HYDROGEN, FUEL CELL & ENERGY STORAGE

Enhanced Cooling System Design for Single and Double Pass Condensers: A Comprehensive Technical, Chemical, Economic, and Environmental Feasibility Study

Mohmmad Danesh Azari | **Seyyed Faramarz Ranjbar*** | **Faramarz Talati** | **Moharram Jafari**

Department of Mechanical Engineering, Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran
* Corresponding author, Email: s.ranjbar@tabrizu.ac.ir

Article Information

Article Type
Research Article

Article History
Received: *15 Jul 2025*
Revised: *10 Oct 2025*
Accepted: *30 Oct 2025*
Published Online: *01 Nov 2025*

Keywords

Ammonium hydroxide
Reactivity-controlled compression ignition engine
Sustainable energy
Nano additive
Performance enhancement

Abstract

The escalating global crises of fossil fuel depletion and emission threats are motivating developed nations to adopt electric vehicles (EVs) as a sustainable transportation alternative. While EVs offer notable advantages, including reduced environmental impact, they also present challenges such as high initial costs, increased electronic waste pollution, and potential electricity supply constraints. Some countries are exploring hydrogen-based fuels for internal combustion engines, but challenges related to hydrogen storage and safety remain significant. To address these issues, research is increasingly focused on transitioning internal combustion engines to low-emission technologies, such as reactivity-controlled compression ignition (RCCI) engines, and incorporating hydrogen-enriched biofuels. This study investigates the performance of RCCI engines using various ammonium hydroxide energy shares (30%, 35%, and 40%) as hydrogen carriers, combined with biodiesel derived from waste lather fat (WLFO) blended with 100 ppm of nanoparticles. The results reveal that a blend comprising 35% ammonium hydroxide and 65% WLFO achieves substantial reductions in nitrogen oxides (9.2%), hydrocarbons (27%), and smoke (26%) compared to conventional diesel in an RCCI engine. Additionally, this blend maintains comparable heat release rates, brake thermal efficiency, and brake-specific energy consumption, demonstrating its potential as a cleaner and efficient alternative fuel.

Cite this article: Danesh Azari, M., Ranjbar, S. F., Talati, F., Jafari, M., (2025). Enhanced Cooling System Design for Single and Double Pass Condensers: A Comprehensive Technical, Chemical, Economic, and Environmental Feasibility Study. DOI: 10.22104/hfe.2024.7178.1328

 Publisher: Iranian Research Organization for Science and Technology (IROST)
DOI: 10.22104/hfe.2024.7178.1328

1 Introduction

People worldwide rely heavily on energy to sustain their daily activities. Moreover, energy consumption continues to rise steadily, driven by population growth and the accelerating pace of globalization. The transportation sector is continually evolving with new technologies, leading to a significant rise in fuel energy demand. However, this growing demand negatively impacts the environment and human health [1–3]. Following the COVID-19 pandemic, many nations have placed a stronger emphasis on improving public health and economic well-being, particularly within the transportation sector, recognizing its vital role in national prosperity. It is widely recognized that approximately 45% of global energy consumption is attributed to the transportation sector, with fossil fuels serving as the primary energy source. This reliance on fossil fuels results in the emission of greenhouse gases, posing significant threats to both the environment and human health [4–6]. In this context, renewable-based fuels are considered a vital solution to address these challenges. Notably, researchers in the transportation sector are focusing on hydrogen-based fuels due to their clean and carbon-free combustion properties. Globally, many nations are advocating for the use of hydrogen-based fuels in internal combustion engines as a sustainable alternative to mitigate fossil fuel shortages and reduce environmental pollution [7–9]. Despite the challenges associated with hydrogen storage, many researchers are increasingly interested in ammonia as a fuel source because it contains 40% hydrogen. Moreover, the storage and combustion of ammonia are considered to be less risky compared to the use of pure hydrogen, making it an attractive alternative for energy applications [10,11].

Since 2020, numerous global studies have focused on the use of ammonia in internal combustion engines and gas turbines. In 2021, a public commission in the USA decided to explore alternatives to diesel generators, specifically considering the potential replacement of diesel generators with ammonia-driven generators. In Japan, significant progress is being made in utilizing ammonia for power generation, particularly in electricity production and as a fuel for marine vehicles [12,13]. Additionally, ammonium hydroxide has been chemically proven to be an optimal renewable source for use in internal combustion engines and gas turbines. The three hydrogen atoms and one nitrogen atom in NH_3 (ammonia) provide versatile support for clean combustion [14].

In India, many researchers are investigating the use of ammonia as a fuel for internal combustion engines. However, studies have identified several drawbacks of using pure ammonia, including its corrosive nature, lower energy density compared to conventional fuels, toxicity, and challenges in starting cold engines [15,16]. The investigator reported that the use of pure ammonia fuel in diesel engines resulted in minimal indicated brake power and higher fuel consumption compared to diesel, primarily due to ammonia's lower calorific value and energy content [17].

Recently, numerous techniques have been introduced to address the drawbacks of pure ammonia combustion. These include dual fuel injection, mixing with nano additives, blending with diesel, water emulsion, combining with biofuel, exploring different fuel injection strategies, and employing various low-combustion-temperature technologies such as Reactivity Controlled Compression Ignition (RCCI), Homogeneous Charge Compression Ignition (HCCI), and Premixed Charge Compression Ignition (PCCI) engines [18–20]. The researcher found that using a dual-fuel engine with a combination of ammonia and biodiesel resulted in smoother operation. Additionally, there was a significant reduction in both NO_x emissions and smoke formation [21].

Sivasubramanian et al. [22], examined the influence of combining ammonia with mustard methyl ester in a diesel engine. The experiment revealed a decrease in brake thermal efficiency (BTE) and oxides of nitrogen (NO_x) formation compared to diesel fuel, which was attributed to the lower energy content and flame speed of the ammonia-mustard methyl ester mixture. However, a lower proportion of NH_3 in the blend led to improved BTE and brake-specific energy consumption (BSEC), due to a higher combustion rate and enhanced air-fuel mixing [22].

Injecting carbon-free NH_3 and carbon-neutral biofuel into a diesel engine using a dual-fuel mode can significantly reduce CO emissions [23]. However, increasing the proportion of NH_3 in the diesel mix has led to a decrease in thermal efficiency, primarily due to the lower flame speed of NH_3. Nonetheless, a notable reduction in NO_x levels of up to 60% has been observed [24]. When the ammonia ratio in fuel injection is increased, in-cylinder pressure decreases due to the longer ignition delay caused by the lower combustion temperature of NH_3 [25]. However, some studies have reported that higher ammonia energy fractions can lead to increased NO_x formation due to the higher nitrogen content in the fuel bond [26,27]. Yoichi et al. [28] revealed that employing multiple diesel injections was an effective method for reducing nitrogen oxide emissions in a dual-fueled ammonia-diesel engine. Advancing the fuel injection timing was identified as one of the feasible techniques to reduce nitrogen oxide and greenhouse gas emissions in an ammonia-fueled diesel engine [29]. It has been shown that advancing the fuel injection timing can reduce NO_x formation by up to 11% and carbon monoxide (CO) formation by up to 21%, while also enhancing thermal efficiency [30]. An ammonia energy share of approximately 35.9% in a dual-fuel engine significantly reduces emissions such as CO, carbon dioxide (CO_2), particulate matter, NO_x, and unburned ammonia. However, beyond this threshold, the results show an opposite trend, with increased emission levels [31]. The diesel engine, powered by biodiesel mixed with titanium nano oxide as the primary fuel and ammonia injected as the secondary fuel, was investigated. The experiment revealed a significant improvement in BTE compared to using diesel fuel alone.This improvement was attributed to the enhanced fuel-air atomization of NH_3-enriched fuel and the high surface area-to-volume ratio of the nanofluid [32]. The author reports that the combination of ammonia and nanoparticles plays a pivotal role in controlling combustion temperature and enhancing overall engine efficiency [33].

Utilizing ammonia fuel in RCCI engines was an optimal approach to improve the overall performance of internal combustion engines. The charge control technique used in RCCI engines results in lower greenhouse gas emissions while increasing brake power and combustion efficiency [34]. Elumalai et al. [35] evaluated an RCCI engine using algae and ammonium hydroxide as low reactivity fuel (LRF) and high reactivity fuel (HRF), respectively. The experiment revealed

that a 40% ammonia share reduced NO_x by 23%, CO2 by 15%, smoke by 40%, and showed an 11% improvement in brake thermal efficiency (BTE) compared to neat algae fuel [35]. On the other hand, converting waste into useful energy is a critical approach to boosting national economic growth. Extracting biofuel from biomass is one of the promising methods for replacing diesel in internal combustion engines. Recently, many researchers have focused on using waste leather fat to extract oil for use in diesel engines [36,37]. Based on the literature survey, the research was motivated to focus on investigating the low-temperature combustion of RCCI engines fueled with ammonium hydroxide as a LRF in the secondary port and waste lather fat nanofluid as a HRF in the primary port. A 100 ppm A 100 ppm cobalt chromite nano additive was blended with each waste leather fat fuel using an ultrasonicator. Five distinct test fuels were utilized in this study: standard diesel (SDL), waste leather fat oil (WLFO), 30% ammonium hydroxide in WLFO (W70A30N), 35% ammonium hydroxide in WLFO (W65A35N), and 40% ammonium hydroxide in WLFO (W60A40N). The aim was to investigate the impact of ammonium hydroxide on the overall performance characteristics of the RCCI engine.

2 Material

2.1 Extraction of waste lather fate oil

The production of leather fat oil involves two steps using waste materials from the leather industry, such as raw skin, shaving hide, and waste flesh. The first step is hydrolysis treatment, where the collected waste leather flesh, raw skin, and shaving hide are mixed with water at a $1:2$ ratio and heated to 110 °C. This process facilitates the breakdown of proteinaceous substances and the generation of leather fat oil. After this, the oil undergoes acid treatment to remove impurities like gums and residues. Phosphoric acid is applied at 60 °C for 15 minutes to effectively remove these impurities. The fuel preparation process is depicted in Figure 1.

2.2 Synthesis of Cobalt chromite nano powder

The synthesis of cobalt chromite nano powder was carried out using a straightforward combustion technique [38]. Initially, cobalt nitrate and chromium nitrate were separately dissolved in distilled water to create precursor solutions. These solutions were then combined in a $1:2$ ratio to achieve the appropriate cobalt chromite stoichiometry. Glycerine was introduced into the mixture, serving both as a combustion catalyst and an energy source. Following meticulous homogenization, the resulting mixture was transferred to a combustion vessel and gradually heated to initiate the combustion process. At approximately 300 °C, glycerine underwent rapid decomposition, promoting the combustion of the metal nitrates. Once the combustion process was complete, a black powder, identified as cobalt chromite nano powder, was collected from the vessel. The nano powder was then washed and dried to improve its purity. Morphological and chemical analyses of the cobalt chromite nano powder were conducted using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX).

2.3 Test fuel preparation

The diesel fuel was procured from the local market and underwent initial filtration using an oil filter. The waste leather fats were collected from the Ambur, Ranipet, and Arani areas, then extracted through hydrolysis acid treatment and stored in a container at room temperature. The nanofluid was prepared in an ultrasonicator, combining the synthesized cobalt chromite nanopowder with the waste leather fat oil. The nanopowder was consistently added at 100 ppm to all waste leather fat oil blends. Liquid ammonia was

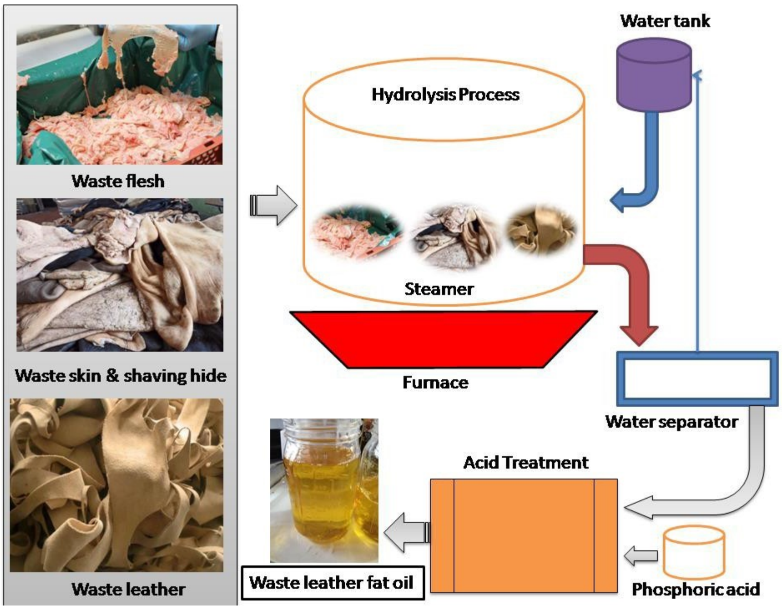

Fig. 1. Fuel preparation setup

procured from Sumisons Scientific Private Ltd. in Ambattur, Chennai. Various shares of ammonia energy were injected into the engine. Table 1 presents a comparison of the physicochemical properties of the test fuels.

Table 1. Property comparison of fuel used in diesel engine.

Properties	Units	Diesel	WLFO
Formula	-	$C_{12}H_{23}$	–
Calorific Value	MJ/kg	44	28
Flash point	°C	66	85
Density	kg/m^3	820	907
Auto ignition temp	°C	230	–
Storage temp	°C	25	25 to 35
Storage Method	–	Liquid	liquid

2.4 Test setup and procedure

The schematic layout of the engine test setup is illustrated in Figure 2. The study utilized a Kirloskar TV-1 diesel engine, which is a single-cylinder, direct injection engine with a 4-stroke cycle. The engine is equipped with a water-cooling system to maintain ideal operating temperatures even during extended periods of usage. The engine has a bore of 86.6 mm and a stroke of 112 mm, with a compression ratio of 17.6 : 1, which represents the ratio between the maximum and minimum volume of the cylinder. It has a rated power output of 5.2 kW at a rated speed of 1500 rpm, making it suitable for its intended purposes. The injection timing is set to occur 23 degrees before top dead center (TDC), ensuring precise fuel delivery to achieve optimal combustion efficiency. The engine is fitted with three nozzles, each with a diameter of 0.3 mm, ensuring an even distribution of fuel throughout the combustion chamber. Additionally, the piston bowl is designed with a hemispherical shape, which improves the efficiency of air-fuel mixing and enhances combustion effectiveness. The smoke meter (AVL India Pvt. Ltd.) was used to measure smoke intensity, with readings in the range of 0 to 100 Hartridge Smoke Units (HSU). Additionally, a five-gas analyzer (Krypton 290, SMS Auto Line Equipment's Private Limited) was employed to measure multiple emissions simultaneously. This included carbon monoxide (CO) within the range of 0 to 10%, carbon dioxide (CO_2) from 0 to 20%, hydrocarbons (HC) from 0 to 10,000 parts per million (ppm), oxygen (O_2) levels from 0 to 25%, and nitrogen oxides (NO_x) from 0 to 5000 ppm. These tools jointly contribute to enhancing the engine's performance and are integral to the experimental setup of the study.

The base fuels, including SDL and WLFO, were delivered to the combustion chamber via the HRF injection system. Ammonium hydroxide was supplied through the LRF injection system. Before injection into the combustion chamber, both fuels were blended. Prior to starting the engine, it is important to check the coolant flow and engine oil level. Initially, the engine was fueled with diesel and operated under various loads at a speed of 1500 rpm. Once it stabilized, the diesel fuel was replaced. Subsequently, experiments were conducted at different loads, as specified in the graphical fuel matrix. Parameters such as fuel consumption, exhaust gas temperature, and emissions were evaluated once the engine reached a stable condition. Each experiment was repeated up to five times to ensure accuracy. Additionally, a decarbonizing device was used for each test fuel to remove engine residues.

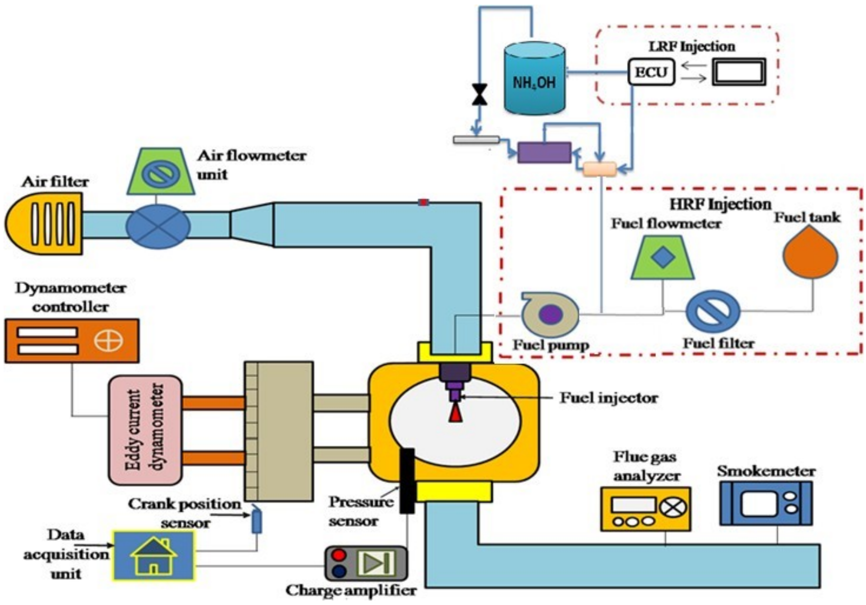

Fig. 2. Schematic layout of engine test setup.

2.5 Uncertainty examination

The errors were identified based on various factors, including labor errors, calibration errors, instrument errors, and atmospheric conditions. Uncertainty treatment was applied to eliminate errors associated with the final results. The experimental setup has the following uncertainty values for the observed parameters: BTE - 0.5%, BSEC - 0.7%, HC - 0.4%, CO - 0.14%, NO_x - 0.7%, and smoke opacity - 0.7%. The total uncertainty of the experimental results is calculated as ±1.378 using the following method:

$$\text{Total uncertainty} = \sqrt{(\text{total performance deeds})^2 + (\text{total emission deeds})^2}\,, \tag{1}$$

$$\text{Total uncertainty} = \sqrt{(\text{UC}_{\text{BTE}})^2 + (\text{UC}_{\text{BSFCE}})^2 + (\text{UC}_{\text{HC}})^2 + (\text{UC}_{\text{CO}})^2 + (\text{UC}_{\text{NO}_x})^2 + (\text{UC}_{\text{smoke}})^2}\,. \tag{2}$$

2.6 Novelty

In cold seasons, the temperature of the cooling water exiting the cooling tower is lower, which results in improved performance of the condenser. Additionally, the pressure drop across the condenser is reduced, leading to a decrease in the work consumption of the power plant. This is because the condenser pump, which is one of the primary energy consumers in the plant, experiences a reduced load. In hot seasons, utilizing a double-pass cooling flow helps maintain the proper performance of the condenser, although it leads to an increase in the work required by the condenser pump. However, over the course of the entire year, compared to the usual configuration, the overall work consumption within the power plant is reduced, resulting in an increase in both overall power output and efficiency.

3 Result and discussion

3.1 Cobalt chromite characterization

The SEM image of cobalt chromite nanoparticles, shown in Figure 3, along with the corresponding EDX analysis in Figure 4, offer valuable insights into the nanoparticles' characteristics. The images reveal that the nanoparticles predominantly exhibit a spherical shape with a varied size distribution across the sample. While some agglomeration is noticeable, the overall dispersion remains relatively uniform. Surface features such as irregularities and permeability are also visible, indicating potential opportunities for surface modification. The EDX analysis confirms the presence of cobalt, chromium, and oxygen in the nanoparticles, providing insights into their composition and crystal structure. Additionally, the images indicate a high level of purity, with minimal contamination observed. This thorough characterization helps refine synthesis techniques and assess the nanoparticles' suitability for various applications, particularly in energy-related fields.

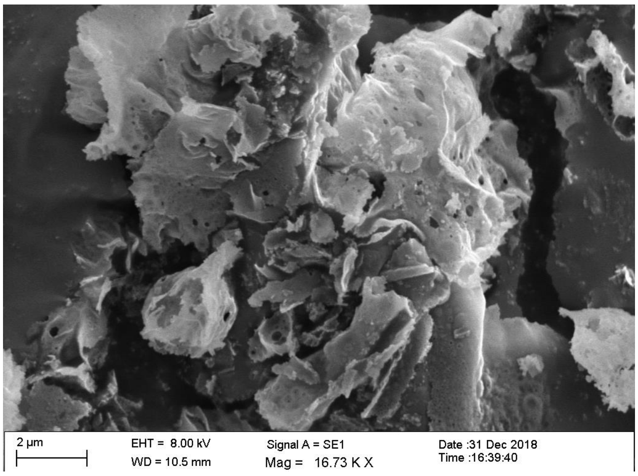

Fig. 3. SEM image of Cobalt chromite nanoparticles.

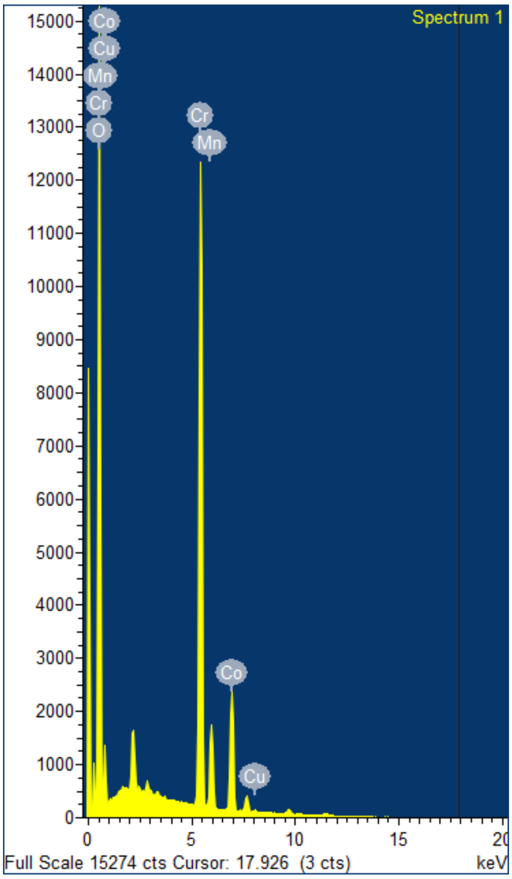

Fig. 4. EDX image of Cobalt chromite nanoparticles.

3.2 Performance report

Examining the output response of Brake Thermal Efficiency (BTE) is a crucial method for determining the energy gained from the combustion of test fuels [39]. Figure 5 illustrates the relationship between BTE and Brake Mean Effective Pressure (BMEP) for five test fuels: SDL, WLFO, W70A30N, W65A35N, and W60A40N. The BTE steadily increases with the load for all test fuels. At low and medium loads, diesel exhibited a higher BTE than the other fuels by 2 to 3%. The researchers also observed that diesel had a higher BTE at loads up to 40% compared to biodiesel and biofuels. This could be attributed to the longer ignition delay of biodiesel and biofuels [40]. At peak load, W70A30N demonstrated a higher BTE than all other test fuels, with diesel showing an increase of about 2%. This could be attributed to the enhanced air/fuel mixture, the high surface area-to-volume ratio of the nanofluid, and complete combustion facilitated by the presence of oxygen. The WLFO blend exhibited lower BTE than the other test fuels due to its lower calorific value and higher viscosity. These properties lead to poorer atomization and incomplete combustion, resulting in less efficient energy conversion.

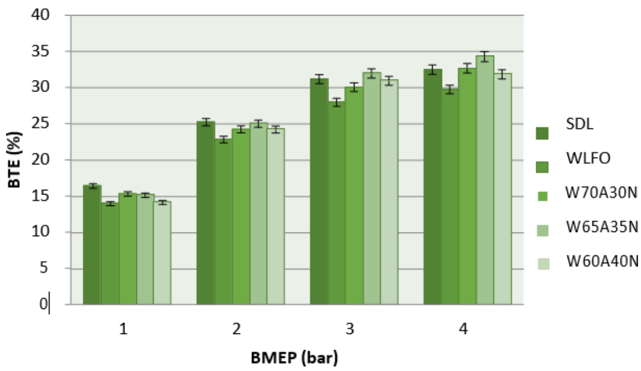

Fig. 5. BTE analysis of test fuels.

Additionally, the longer ignition delay and slower combustion process associated with waste leather fat oil further reduce combustion efficiency. The BTE results were as follows: SDL at 32.6%, WLFO at 29.8%, W70A30N at 32.7%, W65A35N at 34.3%, and W60A40N at 31.9% under maximum load conditions. Interestingly, except for WLFO and SDL, the other test fuels exhibited higher BTE at all maximum loads due to these blends being burned in RCCI mode. The addition of nanoparticles to a blend of ammonium hydroxide and diesel fuel improves the BTE of the engine by enhancing fuel atomization, acting as catalysts for combustion, and accelerating the combustion process. This results in a higher degree of combustion and improved fuel efficiency. Nanoparticles enhance the mixing of fuel and air, improve thermal conductivity, and minimize heat losses to the engine walls. The cumulative impact of these factors results in an elevated maximum pressure and temperature throughout the combustion process, enhanced energy conversion efficiency, and a reduced duration of combustion, all of which contribute to an increased BTE. However, higher quantities of nanoparticles in diesel fuel blended with ammonium hydroxide can negatively impact performance characteristics, potentially leading to undesirable effects such as increased engine wear or reduced overall efficiency if not carefully managed. This is primarily due to issues such as particle clumping, higher fuel viscosity, unstable combustion, reduced catalytic effects, and increased mechanical wear. These findings align with those of the researcher [35], who conducted studies on an RCCI engine fueled with ammonia. This outcome can be attributed to increased charge homogeneity, combustion rate, and heat release rate.

Figure 6 illustrates the relationship between BSEC and BMEP for five test fuels. BSEC consistently decreases with load for all the test fuels. At low and medium loads, diesel exhibited a lower BSEC compared to other fuels by 3 to 4%. It is commonly observed that the trend of BSEC consistently mirrors the trend of BTE for all the test fuels [41]. This correlation arises because an improvement in efficiency typically results in lower fuel consumption, thereby leading to better fuel economy. The BSEC results were as follows: SDL at 11.8 MJ/kWhr, WLFO at 11.66 MJ/kWhr, W70A30N at 10.42 MJ/kWhr, W65A35N at 9.41 MJ/kWhr, and W60A40N at 10.7 MJ/kWhr for maximum load. Interestingly, except for WLFO and SDL, the other test fuels exhibited lower BSEC at all maximum loads, as these blends were burned in RCCI mode. Overall, the W65A35N blend showed the best fuel economy among all the test fuels. This outcome can be attributed to improved charge homogeneity, combustion rate, and heat release rate, which enhance combustion efficiency and reduce the amount of fuel required to produce the same output.

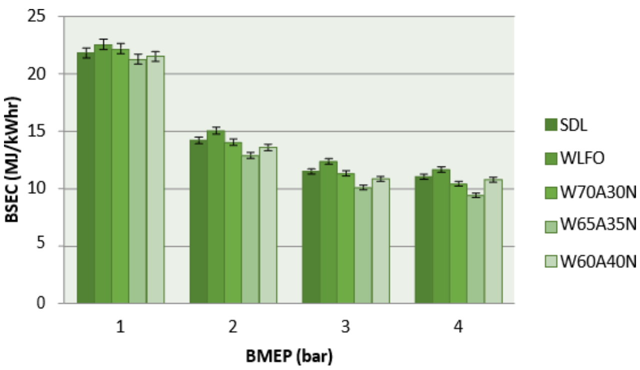

Fig. 6. BSEC analysis of test fuels.

3.3 Emission report

Figure 7 illustrates the relationship between unburned hydrocarbon (HC) emissions and brake mean effective pressure (BMEP) for different test fuels. HC emissions consistently decrease with increasing load for all the test fuels. SDL fuel exhibited higher HC emissions than all other blends across all load states. This can be attributed to its higher aromatic content, lack of intrinsic oxygen, and less favorable atomization characteristics. In addition, the increased viscosity and density of biodiesel improve fuel atomization and the mixing of fuel with air, leading to a further reduction in HC emissions [42].

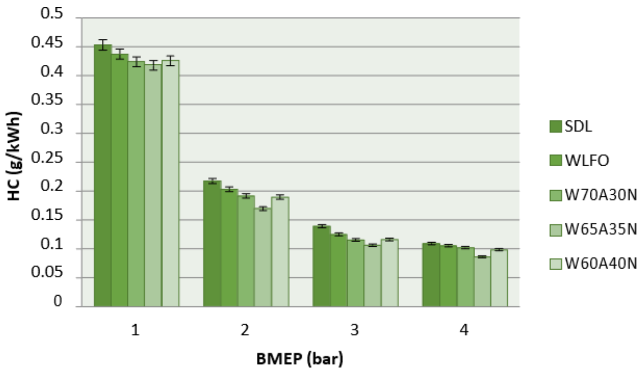

Fig. 7. HC emission analysis of test fue.

The HC results were as follows: SDL at 0.109 g/kWh, WLFO at 0.105 g/kWh, W70A30N at 0.102 g/kWh, W65A35N at 0.086 g/kWh, and W60A40N at 0.0986 g/kWh for the maximum load state. Interestingly, except for WLFO and SDL, other test fuels exhibited lower HC emissions at all maximum loads due to these blends being burned in RCCI mode. Nanoparticles added to an ammonium hydroxide-diesel fuel blend reduce HC emissions by improving fuel atomization, acting as combustion catalysts, and enhancing combustion efficiency. They facilitate better fuel-air mixing, reduce ignition delay, enhance thermal conductivity, and increase the heat release rate. The synergistic effects of these factors lead to improved combustion efficiency and a reduction in hydrocarbon emissions. At higher concentrations, nanoparticles tend to aggregate or form clusters, which hampers their dispersion within the fuel. This results in an uneven combustion process, where some areas may have an excess or a deficiency of fuel. Inadequate dispersion leads to incomplete combustion, which in turn increases HC and CO emissions. Overall, the W65A35N blend exhibited better HC formation than all other test fuels due to the presence of the nanoadditive, which enhances the surface area-to-volume ratio. These findings align with those of the researcher [34], who conducted investigations in an RCCI engine fueled with ammonia. This outcome can be attributed to improved charge homogeneity, a faster combustion rate, and more complete combustion.

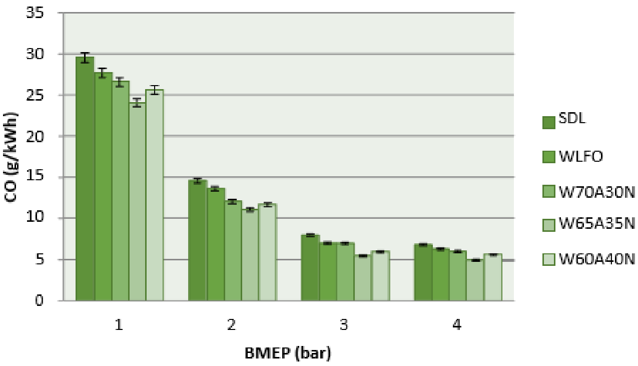

Fig. 8. CO **emission analysis of test fuels.**

Figure 8 illustrates the relationship between CO emissions and BMEP for different test fuels. CO emissions consistently decrease with load for all test fuels. SDL fuel exhibited higher CO emissions compared to all other blends at all load states. This can be attributed to incomplete combustion, which is likely caused by a lack of oxygen. The CO results are as follows: SDL at 6.82 g/kWh, WLFO at 6.29 g/kWh, W65A30N at 6.014 g/kWh, W65A35N at 5.07 g/kWh, and W60A40N at 5.65 g/kWh at maximum load state. Interestingly, except for WLFO and SDL, all other blends exhibited lower CO emissions at maximum loads due to being burned in RCCI mode. Nanoparticles improve fuel atomization and enhance mixing with air, resulting in more efficient and complete combustion. Their catalytic properties facilitate the oxidation of CO to less harmful CO_2 during combustion, thereby reducing the amount of CO emitted in the exhaust.

Additionally, nanoparticles contribute to a more stable combustion process by reducing ignition delay and improving thermal conductivity, which helps maintain a uniform temperature distribution within the combustion chamber. This optimized environment minimizes the formation of CO by ensuring more thorough fuel combustion and more effective utilization of oxygen.

The W65A35N blend exhibited superior CO reduction compared to all other test fuels, primarily due to the inclusion of nanoadditives, which led to an increased surface area to volume ratio. These observations are consistent with those of researchers [34], who conducted investigations in an RCCI engine fueled with ammonia fuel. This outcome can be attributed to the increased charge homogeneity, combustion rate, and complete combustion, all of which contribute to more efficient fuel utilization and lower CO emissions.

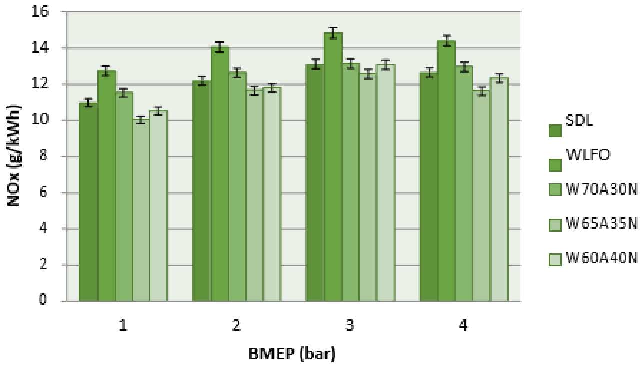

Fig. 9. NO_x **emission analysis of test fuels.**

Figure 9 illustrates the relationship between NO_x emissions and BMEP for the different test fuels. NO_x emissions consistently increase with load for all the test fuels, which can be attributed to the high peak temperatures at medium and maximum loads [43]. The NO_x results were as follows: SDL at 12.66 g/kWh, WLFO at 14.42 g/kWh, W70A30N at 12.97 g/kWh, W65A35N at 11.62 g/kWh, and W60A40N at 12.35 g/kWh for the maximum load state. Interestingly, except for WLFO in the alternate fuel group, all other blends exhibited lower NO_x emissions at all maximum loads due to these blends being burned in RCCI mode. Nanoparticles enhance combustion efficiency by improving fuel atomization and promoting superior air-fuel mixing, which helps reduce peak combustion temperatures and consequently mitigates the formation of thermal NO_x. Furthermore, nanoparticles possess catalytic properties that facilitate the conversion of NO_x into less harmful nitrogen and oxygen molecules.

Nanoparticles, when combined with ammonium hydroxide, act as selective catalytic reduction (SCR) catalysts, effectively reducing NO_x emissions by converting them into nitrogen and water vapor. This catalytic process helps lower the environmental impact of nitrogen oxides. Moreover, nanoparticles assist in better control of combustion heat, minimizing the formation of localized high temperatures that typically promote the production of nitrogen oxides (NO_x). High quantities of nanoparticles can disrupt the combustion process by affecting the spread and stability of the flame. Irregular combustion cycles may occur, leading to incomplete combustion and higher emissions of HC and CO. Furthermore, changes in combustion temperature can contribute to increased NO_x emissions. These observations are consistent with the findings of [20], who conducted investigations in an RCCI engine fueled with ammonia. This outcome can be attributed to improved charge homogeneity, combustion rate, and more complete combustion.

Figure 10 illustrates the relationship between CO_2 emissions and BMEP for different test fuels. CO_2 emissions consistently increase with load for all the test fuels. This can be attributed to higher oxidation rates at middle and maximum load conditions [44]. The CO_2 emission results were as follows: SDL at 971.27 g/kWh, WLFO at 918.90 g/kWh, W70A30N at 937.83 g/kWh, W65A35N at 989.40 g/kWh, and W60A40N at 999.23 g/kWh for the maximum load state. Interestingly, except for WLFO in the alternate fuel group, all other fuels exhibited higher CO_2 emissions at all maximum loads due to these blends being burned in RCCI mode. The addition of nanoparticles to diesel fuel blends containing ammonium hydroxide reduces CO_2 emissions by improving combustion efficiency, optimizing the mixing of fuel and air, catalyzing complete fuel oxidation, and reducing fuel consumption [26]. The W65A35N blend exhibited superior CO_2 formation compared to all other test fuels, primarily due to the inclusion of nanoadditives in ammonium hydroxide.

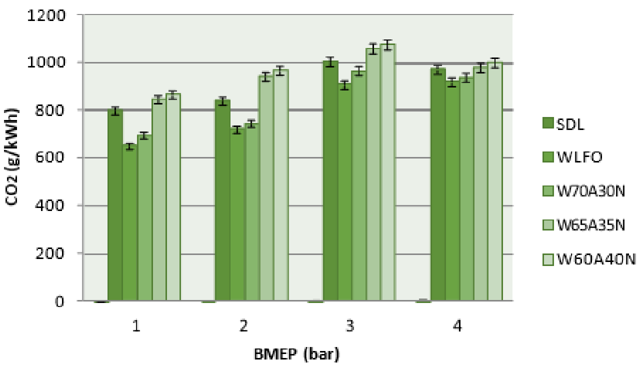

Fig. 10. CO_2 **emission analysis of test fuels.**

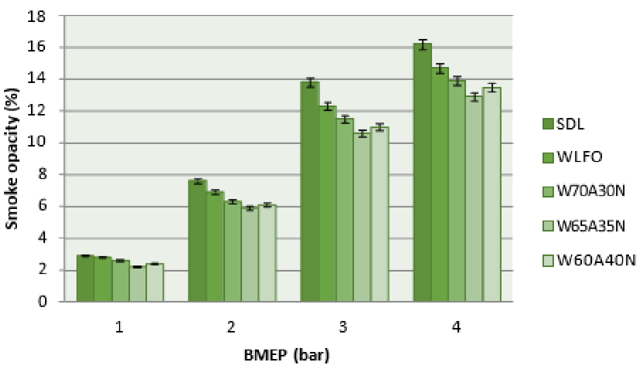

Fig. 11. Smoke opacity analysis of test fuels.

Figure 11 illustrates the relationship between smoke opacity and BMEP for different test fuels. The smoke results were as follows: SDL at 16.2%, WLFO at 14.7%, W70A30N at 13.9%, W65A35N at 12.9%, and W60A40N at 13.5% for the maximum load state. Smoke emissions consistently increase with load for all the test fuels due to a shortage of burning time. The researchers also noted that smoke output increased with an increase in load. This may be due to the absence of sufficient oxygen and the limited time available for complete combustion [45]. Interestingly, except for WLFO in the alternate fuel group, all other blends exhibited lower smoke emissions at all maximum loads due to these blends being burned in RCCI mode. Overall, the W65A35N blend had the best smoke formation compared to all other test fuels, primarily due to the presence of nanoadditives, which resulted in a higher surface area-to-volume ratio.

3.4 Combustion report

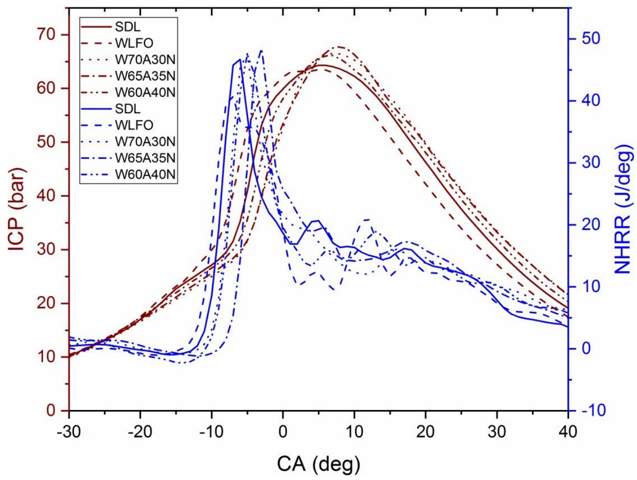

Fig. 12. Combustion parameter analysis of test fuels.

Figure 12 demonstrates the correlation between BMEP, internal cylinder pressure (ICP), and net heat release rate (NHRR) for various test fuels. SDL shows the highest peak in-cylinder pressure (ICP) and net heat release rate (NHRR), indicating rapid and efficient energy release. WLFO shows slightly lower and delayed peaks compared to SDL, maintaining a similar combustion profile. Introducing 30% ammonium hydroxide and nanoparticles (W70A30N) reduces the ICP and NHRR peaks, suggesting a moderated combustion intensity. Increasing the ammonium hydroxide concentration to 35% (W65A35N) and 40% (W60A40N) further reduces these peaks, indicating a more controlled combustion process. The maximum ICP and NHRR values were recorded as 66.32 bar & 47.4 J/deg, 67.6 bar & 48.2 J/deg, 66.10 bar & 47.1 J/deg, and 63.2 bar & 40.61 J/deg for ammonia energy fractions of 30%, 35%, 40%, and biofuel, respectively. The W65A35N blend demonstrates an improved ICP compared to the other test fuels. This improvement can be attributed to the presence of NH_3 in the test fuel, which enhances premixed combustion. Additionally, the W65A35N blend also exhibits a higher NHRR output, likely due to a reduced diffusion phase. These findings are consistent with those of researchers [35], who investigated RCCI engines fueled with ammonia-based fuels. This outcome is attributed to the increased charge homogeneity, combustion rate, and complete combustion facilitated by the ammonia blends.

4 Conclusion

The research focused on deriving WLFO and blending it with various concentrations of ammonium hydroxide, along with 100 ppm of cobalt chromite nanoadditive. The fundamental characteristics of the nanoparticles were examined using SEM and EDX techniques, and the physicochemical properties of the test fuels were assessed. These test fuels were then evaluated in an RCCI engine under different load conditions and compared with SDL. The key findings are summarized as follows: The synthesized cobalt chromite nanoparticles were comprehensively characterized, providing valuable insights into their composition and properties. The proposed fuel blends met standard physicochemical property limits, confirming their suitability for use. The W65A35N blend (65% WLFO, 35% ammonium hydroxide, and 100 ppm of cobalt chromite) demonstrated a BTE of 34.3%, significantly outperforming the other test fuels. It also demonstrated the lowest BSEC at 9.41 MJ/kWh, indicating optimal fuel economy. Additionally, the W65A35N blend exhibited substantial reductions in emissions. Unburned HC emissions were 0.086 g/kWh, and CO emissions were 5.07 g/kWh, both lower than those of conventional diesel fuel. NO_x emissions were also notably reduced to 11.62 g/kWh. The combustion parameters of the W65A35N blend were comparable to those of SDF, ensuring efficient and smooth combustion processes. In conclusion, using WLFO as a substitute for SDF proves to be an economically viable strategy.

The integration of ammonium hydroxide and nanoparticles in WLFO can lead to more moderated and potentially more efficient combustion, with significant implications for reducing emissions and enhancing engine performance. Further research and development aimed at optimizing these alternative fuels could yield even greater efficiency and environmental benefits, contributing to a more sustainable energy landscape.

References

[1] Vellaiyan S, Kandasamy M, Nagappan B, Gupta S, Ramalingam K, Devarajan Y. Optimization study for efficient and cleaner production of waste-derived biodiesel through fuel modification and its validation. Process Integration and Optimization for Sustainability. 2024;8(3):939–952.

[2] Ramalingam K, Venkatesan EP, Vellaiyan S, Mukhtar A, Sharifpur M, Yasir ASHM, et al. Substitution of diesel fuel in conventional compression ignition engine with waste biomass-based fuel and its validation using artificial neural networks. Process Safety and Environmental Protection. 2023;177:1234–1248.

[3] Vellaiyan S, Chandran D, Venkatachalam R, Ramalingam K, Rao R, Raviadaran R. Maximizing waste plastic oil yield and enhancing energy and environmental metrics through pyrolysis process optimization and fuel modification. Results in Engineering. 2024;22:102066.

[4] Vellaiyan S, Kandasamy M, Chandran D, Raviadaran R, Ramalingam K, Devarajan Y. Characterization and optimization of waste-derived biodiesel utilizing CNT/MgO nanocomposite and water emulsion for enhanced performance and emission metrics. Case Studies in Thermal Engineering. 2024;55:104173.

[5] Ramalingam K, Vellaiyan S, Venkatesan EP, Khan SA, Mahmoud Z, Saleel CA. Challenges and opportunities of low viscous biofuel – a prospective review. ACS omega. 2023;8(19):16545–16560.

[6] Vellaiyan S. Recent advancements in water emulsion fuel to explore efficient and cleaner production from various biodiesels: A retrospective review. Renewable and Sustainable Energy Reviews. 2023;187:113704.

[7] Vellaiyan S, Kandasamy M, Subbiah A, Devarajan Y. Energy, environmental and economic assessment of waste-derived lemon peel oil intermingled with high intense water and cetane improver. Sustainable Energy Technologies and Assessments. 2022;53:102659.

[8] Ramalingam K, Vellaiyan S, Kandasamy M, Chandran D, Raviadaran R. An experimental study and ANN analysis of utilizing ammonia as a hydrogen carrier by real-time emulsion fuel injection to promote cleaner combustion. Results in Engineering. 2024;21:101946.

[9] Hosseini SH, Tsolakis A, Alagumalai A, Mahian O, Lam SS, Pan J, et al. Use of hydrogen in dual-fuel diesel engines. Progress in Energy and Combustion Science. 2023;98:101100.

[10] Dimitriou P, Javaid R. A review of ammonia as a compression ignition engine fuel. International Journal of Hydrogen Energy. 2020;45(11):7098–7118.

[11] Zamfirescu C, Dincer I. Ammonia as a green fuel and hydrogen source for vehicular applications. Fuel processing technology. 2009;90(5):729–737.

[12] Erdemir D, Dincer I. A perspective on the use of ammonia as a clean fuel: Challenges and solutions. International Journal of Energy Research. 2021;45(4).

[13] Wategave S, Banapurmath N, Sawant M, Soudagar MEM, Mujtaba M, Afzal A, et al. Clean combustion and emissions strategy using reactivity controlled compression ignition (RCCI) mode engine powered with CNG-Karanja biodiesel. Journal of the Taiwan Institute of Chemical Engineers. 2021;124:116–131.

[14] Manigandan S, Ryu JI, Kumar TP, Elgendi M. Hydrogen and ammonia as a primary fuel–A critical review of production technologies, diesel engine applications, and challenges. Fuel. 2023;352:129100.

[15] Şahin Z, Akcanca İZ, Durgun O. Experimental investigation of the effects of ammonia solution (NH3OH) on engine performance and exhaust emissions of a small diesel engine. Fuel. 2018;214:330–341.

[16] Klüssmann JN, Ekknud LR, Ivarsson A, Schramm J. Ammonia Application in IC Engines. Advanced Motor Fuels Technology Collaboration Programme; 2020.

[17] Starkman ES, James G, Newhall H. Ammonia as a diesel engine fuel: theory and application. SAE Transactions. 1968;p. 3193–3212.

[18] Subramani AK, Duraisamy G, Govindan N, Hossain AK. An innovative method of ammonia use in a light-duty automotive diesel engine to enhance diesel combustion, performance, and emissions. International Journal of Hydrogen Energy. 2024;49:38–58.

[19] Zhang R, Chen L, Wei H, Li J, Ding Y, Chen R, et al. Experimental investigation on reactivity-controlled compression ignition (RCCI) combustion characteristic of n-heptane/ammonia based on an optical engine. International Journal of Engine Research. 2023;24(6):2478–2488.

[20] Ramachandran E, Krishnaiah R, Vellore Gangadharan S, Perumal Venkatesan E, Chandramurthy SR, Medapati SR, et al. Multicriteria Decision-Making Technique for Choosing the Optimal Ammonia Energy Share in an Ammonia–Biodiesel-Fueled Reactivity-Controlled Compression Ignition Engine. ACS omega. 2024;9(5):5203–5214.

[21] Xu L, Xu S, Bai XS, Repo JA, Hautala S, Hyvönen J. Performance and emission characteristics of an ammonia/diesel dual-fuel marine engine. Renewable and Sustainable Energy Reviews. 2023;185:113631.

[22] Sivasubramanian R, Sajin J, Omanakuttan Pillai G. Effect of ammonia to reduce emission from biodiesel fuelled diesel engine. International Journal of Ambient Energy. 2022;43(1):661–665.

[23] Nithya S, Chinnathambi A, Alharbi SA, Minofar B. Carbon neutrality with ammonia: An analysis of its feasibility as a fuel for diesel engines fuelled with spirulina microalgae and oxygenated additives. Fuel. 2024;361:130628.

[24] Reiter AJ, Kong SC. Combustion and emissions characteristics of compression-ignition engine using dual ammonia-diesel fuel. Fuel. 2011;90(1):87–97.

[25] Reiter AJ, Kong SC. Diesel engine operation using ammonia as a carbon-free fuel. In: Internal combustion engine division fall technical conference. vol. 49446; 2010. p. 111–117.

[26] Reiter AJ, Kong SC. Demonstration of compression-ignition engine combustion using ammonia in reducing greenhouse gas emissions. Energy & Fuels. 2008;22(5):2963–2971.

[27] Kishore K, Kurien C, Mittal M. Experimental and numerical analysis of engine characteristics of an ammonia-substituted dual-fuel CRDI diesel engine. Fuel. 2024;366:131354.

[28] Niki Y, Nitta Y, Sekiguchi H, Hirata K. Diesel fuel multiple injection effects on emission characteristics of diesel engine mixed ammonia gas into intake air. Journal of Engineering for Gas Turbines and Power. 2019;141(6):061020.

[29] Okumuş F, Kanberoğlu B, Gonca G, Kökkülünk G, Aydın Z, Kaya C. The effects of ammonia addition on the emission and performance characteristics of a diesel engine with variable compression ratio and injection timing. International Journal of Hydrogen Energy. 2024;64:186–195.

[30] Liu J, Wang X, Zhao W, Sun P, Ji Q. Effects of ammonia energy fraction and diesel injection parameters on combustion stability and GHG emissions characteristics in a low-loaded ammonia/diesel dual-fuel engine. Fuel. 2024;360:130544.

[31] Ramachandran E, Krishnaiah R, Perumal Venkatesan E, Saleel CA, Shaik S. Investigation on ammonia–biodiesel fueled RCCI combustion engine using a split injection strategy. ACS omega. 2023;8(34):30990–31001.

[32] Pugazhendhi A, Alharbi SA, Loganathan K, Subbiah G, Nithya S. Enhancing sustainable fuel solutions: Castor oil biodiesel with nanoparticles and ammonia, utilizing as a green substitute for diesel engines. Fuel. 2024;368:131597.

[33] Manimaran S, Athimoolam A, Albeshr MF, Praveenkumar T, Beata G. Effects of nanoadditives and ammonia on performance and emission characteristics of diesel engine fueled with Aleurites moluccanus. Fuel. 2024;363:130787.

[34] Zhang R, Chen L, Li J, Wang W, Wei H, Pan J. Effects of injection timings and energy ratios on the combustion and emission characteristics of n-heptane/ammonia RCCI mode. Energy & Fuels. 2024;38(4):3491–3502.

[35] Elumalai R, Ravi K. Optimization of ideal engine parameters to adopt ammonia and algae biodiesel for reactivity controlled compression ignition engine using response surface methodology. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2024;238(6):2456–2473.

[36] Mohanrajhu N, Sekar S, Jayabal R, Sureshkumar R. Screening nano additives for favorable NOx/smoke emissions trade-off in a CRDI diesel engine fueled by industry leather waste fat biodiesel blend. Process Safety and Environmental Protection. 2024;187:332–342.

[37] Özmen S, Şen M, Emiroğlu A, Keskin A. Evaluation of the diesel engine behaviors of premixed hybrid biodiesel obtained from tannery waste fat and canola oil. International Journal of Environmental Science and Technology. 2024;21(9):6567–6582.

[38] Krishnamoorthy R, Asaithambi K, Balasubramanian D, Murugesan P, Rajarajan A. Effect of cobalt chromite on the investigation of traditional CI engine powered with raw citronella fuel for the future sustainable renewable source. SAE International Journal of Advances and Current Practices in Mobility. 2020;3(2020-28-0445):843–850.

[39] Ramalingam K, Kandasamy A, Balasubramanian D, Palani M, Subramanian T, Varuvel EG, et al. Forcasting of an ANN model for predicting behaviour of diesel engine energised by a combination of two low viscous biofuels. Environmental Science and Pollution Research. 2020;27:24702–24722.

[40] Ramalingam K, Venkatesan EP, Vellaiyan S, Mukhtar A, Sharifpur M, Yasir ASHM, et al. Substitution of diesel fuel in conventional compression ignition engine with waste biomass-based fuel and its validation using artificial neural networks. Process Safety and Environmental Protection. 2023;177:1234–1248.

[41] Ramalingam K, Kandasamy A, Joshua Stephen Chellakumar PJT. Production of eco-friendly fuel with the help of steam distillation from new plant source and the investigation of its influence of fuel injection strategy in diesel engine. Environmental Science and Pollution Research. 2019;26:15467–15480.

[42] Asaithambi K, Krishnamoorthy R, Balasubramanian D. A Comparative assessment of tailpipe emission characteristics on diesel engine using nanofluid with R-EGR setup. SAE Technical Paper; 2020.

[43] Ramalingam K, Balasubramanian D, Chellakumar PJTJS, Padmanaban J, Murugesan P, Xuan T. An assessment on production and engine characterization of a novel environment-friendly fuel. Fuel. 2020;279:118558.

[44] Ramalingam K, Kandasamy A, Subramani L, Balasubramanian D, Thadhani JPJ. An assessment of combustion, performance characteristics and emission control strategy by adding anti-oxidant additive in emulsified fuel. Atmospheric Pollution Research. 2018;9(5):959–967.

[45] Lingesan S, Annamalai K, Parthasarathy M, Ramalingam KM, Dhinesh B, Lalvani JIJ. Production of Garcinia gummi-gutta Methyl Ester (GGME) as a potential alternative feedstock for existing unmodified DI diesel engine: combustion, performance, and emission characteristics. Journal of Testing and Evaluation. 2018;46(6):2661–2678.