Synthesis and Application of the Nano-Additive [Cu2(CN)3.Me3Sn.qox] in Biodiesel-Diesel Blends: Enhancing Combustion Efficiency, Engine Performance, and Emission Reduction in a Single-Cylinder Diesel Engine

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Abstract. This study explores the impact of the nano-additive **[$Cu_2(CN)_3.Me_3Sn$.qox] (NSCP)**, synthesized from quinoxaline (qox), $K_3[Cu(CN)_4]$, and Me_3SnCl, on the performance and emissions of a single-cylinder, water-cooled diesel engine operating at 1500 rpm under varying load conditions. The nano-additives were blended into a fuel mixture of 40% biodiesel and 60% conventional diesel at concentrations of 25, 50, 75, 100, 150, and 200 ppm. The enhancement presented in engine performance showed that the nano additives significantly enhanced combustion efficiency, particularly at 50 ppm. Engine performance metrics, including brake power and brake thermal efficiency (BTE), improved notably, with the highest gains at 50 ppm, while specific fuel consumption (SFC) decreased, indicating better fuel utilization. Emissions of particulate matter (PM) and nitrogen oxides (NO_x) were reduced due to complete combustion, with optimal reductions in carbon monoxide (CO) and unburned hydrocarbons (UHC) observed at 50 ppm. The additives also improved the stability of the biodiesel-diesel blend, preventing phase separation. However, higher concentrations (200 ppm) risked nanoparticle aggregation and engine deposits, potentially affecting long-term performance. The study identifies 50–100 ppm as the optimal concentration range for maximizing engine performance and minimizing emissions while maintaining engine durability. At this values, the engine BTE was enhanced by 21% at 50-ppm NSCP additives, while the reduction of CO emission is reached to 33%, and 57.9 % reduction in soot formation. These findings highlight the potential of nano-additives to enhance diesel engine efficiency and reduce emissions. However, further research is needed to evaluate long-term effects and optimize formulations for commercial use.
Keywords: Nanosized supramolecular coordination polymer (NSCP); Engine emissions; Biodiesel/Diesel blend; Engine performance and emissions

1. Introduction

Considering the profound way our climate has shifted throughout the last 100 years and the fact that the climate remains the greatest risk to the health of humanity, managing the impact of climate change might be considered one of the most significant health concerns of this century. According to immediate impacts such as intense heat, severe storms, dryness, and flooding events towards secondary impacts such as alteration in ecosystem and medical impacts which are less obvious other than could have the greatest influence upon sensitivity and respiratory problems, the impacts of changing the climate on the health of humans are multiple and being more widely recognized [1].

Expectations state that by 2050, the existing quantity of petroleum and petroleum products will be exhausted because natural resource extraction will not keep up with increasing the consumption of humans [2].

Scientists have been looking for replacements because of pollution in the atmosphere which is resulting from the heavy consumption of fossil fuels. It should be physically possible, affordable, ecologically innocent, and commercially viable as an alternative to petroleum fuel. Biodiesel could be extracted from low-quality and naturally occurring materials utilizing an assortment of techniques; therefore, it possesses an opportunity to be an affordable alternative source of energy. It is predicted that the production of biofuels will progressively use low-cost and sustainable catalysts that promote the transesterification of different raw materials [3].

A substitute for diesel fuel that is generated from petroleum-based fuel, biofuel is significantly more environmentally friendly since it can be produced from waste or recyclable materials including biomass, fats from animals, and waste from industries. However, there are still problems with developing methods for manufacturing, identifying raw materials with the highest levels of sustainability, and improving and optimizing the features of biodiesel [4,5].

The majority of transitional nations have started manufacturing biofuels such as ethanol and biodiesel fuel, throughout the last decade, and some even before. The European Union Directive (2003/30/EC) regarding fuel substitutes in motor vehicles and initiatives to promote the use of biofuels show that this current pattern is going to persist in the future [6]. One of the most common and favorable novel sources of energy to minimize the consumption of fossil fuels and damage to the environment is biodiesel. In recent years scientists from an extensive variety of sectors and nations have been placing a lot of thought on biodiesel [7]. As it releases harmful pollutants lower than traditional diesel, bio-diesel represents an improved sustainable source. Based on research utilizing bio-diesel in gasoline engines markedly reduces releases of CO, HC, and particulates [8]. From earlier studies, integrating nanomaterials into diesel and bio-diesel fuels greatly enhances the behavior of igniting and combustion, which improves the performance of engines and minimizes emissions. Also, it can increase a fuel's calorific value and cetane number [9,10].

Currently, the synthesis of nanoparticles and how they are utilized in the development of composite materials has been the most prevalent study. They have several applications which are acquiring prominence [11]. Moreover, nanoparticles (NPs) as a diesel additive have attended important developments because they have many advantages such as improved thermal transfer abilities, higher surface area, and effective catalytic features that enhance combustion and decrease exhaust emission [12-14]. In comparison with pure diesel, the introduction of nanomaterials to the diesel led to a significant enhancement in its radiative and heat/mass transfer features, and the droplets burned at a notably lower temperature [15].

This comprehensive path highlights the importance of multidisciplinary cooperation between materials science, engineering, and ecological studies in order to extend the limits of sustainable energy technologies [16]. A popular method of fuel modification technology is the addition of nanomaterials, alcohols, water, and hydrogen to fuel as fuel additives.

In particular, metal and non-metal nanomaterials have been awarded due to their diversity, high reactive area, high oxygen content, high catalytic activity, and high redox activity, a very much attentiveness [17]. On top of that, biodiesel is a preferable lubricant compared with diesel fuel, consequently, it extends the lifetime of the engine and its wear will be reduced. As well as it notably decreases engine waste because of the rareness of sulfur and the existence of oxygen, leading to more efficient combustion [18]. It's now necessary to turn to the economics of sustainable development to promote the establishment of an identity that is stable and social sustainability and that requires a distinct development model. The novel model of sustainable development as the principal driver and megatrend of resolving environmental challenges involves the management of climate change [19].

The novelty of this work lies in the synthesis and application of a unique nano-additive, **NSCP** [$Cu_2(CN)_3.Me_3Sn.qox$] ($C_{14}H_{15}N_5Cu_2Sn$), derived from the coordination of quinoxaline (qox), copper cyanide, and trimethyl tin chloride (Me_3SnCl), for enhancing the performance and emissions of a biodiesel-diesel blend in a single-cylinder diesel engine. This additive, tested at varying concentrations (25–200 ppm), demonstrates unprecedented improvements in fuel combustion temperature, and engine performance, while significantly reducing particulate matter (PM) and nitrogen oxides (NO_x) emissions. The integration of copper, tin, and quinoxaline in a single nanostructured compound represents a groundbreaking approach, offering a sustainable solution for optimizing renewable fuel blends and advancing cleaner combustion technologies in diesel engines.

2. Experimental

2.1. Material and method

$K_3[Cu(CN)_4]$ had been synthesized utilizing the techniques mentioned in the literature [20]. Every preparatory and analytical task was completed in a typical environment. Every reagent used in the synthesis was commercially accessible and used without additional purification [20, 21]. Measurement of XRD single crystal data of NTSCP had been performed using a Kappa CCD Enraf Nonius FR 90 four circle-goniometer with graphite monochromatic MoKα radiation {[λMoKα] = 0.71073Å. Structure refinement parameters and crystal data of NSCP were completely discussed and presented in the previous authors' work [21].

2.2 Synthesis of the nanosized [$Cu_2(CN)_3.Me_3Sn.qox$] ***NSCP***

In 20 mL of hot CH_3CN, 189 mg (0.95 mmol) of Me_3SnCl and 40 mg (0.31 mmol) of quinoxaline (qox) were mixed with a solution of 90 mg (0.31 mmol) of $K_3[Cu (CN)_4]$ in 10 mL H_2O, and they were then exposed to an irradiated ultrasonic for three hours at 30 ºC with a distinct power of 70 W. After a few days, the previously clear solution began to produce orange crystals. There was 79 mg (49.8% referred to as $K_3[Cu (CN)_4]$) of orange crystals after filtration, rinsing with cold H_2O and CH_3CN, and drying. The following are the elemental analysis data for **NSCP** ($C_{14}H_{15}N_5Cu_2Sn$), anal. C, 33.69; H, 3.01; N, 14.04; Cu, 25.49 are the calculated values. C, 33.58; H, 3.08; N, 14.11; Cu, 25.41 were discovered.

2.3 The identification of the structure of the single crystal.

During the earliest phases of the enhancement, all the non-hydrogen atoms were located from the original solution or later electron density difference maps. The crystal structure of **NSCP** was resolved using direct ways. The modelings were performed against F^2, first using isotropic and then anisotropic thermal displacement parameters after finding all non-hydrogen atoms in each structure. The crystallographic data and structure refinement parameters of **NSCP** are given in reference [21]. Following an isotope refinement and estimation of the H atom positions, a final refinement cycle was carried out.

2.4 Preparation of fuel blends using an addition of ***NSCP***

Various concentrations of **NSCP** nanofluids were prepared: 25,50,75,100,150, and 200 ppm by dissolving **NSCP** in DMF, with pH adjusted to 10 using 0.1 M sodium hydroxide NaOH. Biodiesel derived from waste cooking oils was initially blended with diesel fuel at a ratio of 40:60 V/V%, respectively. The resulting diesel/biodiesel blend (B40) was poured into a glass container and stirred for two hours consecutively to guarantee uniform mixing. After that different ratios of **NSCP** nanofluids were added to the prepared B40 and to guarantee proper mixing, the entire mix was subjected to ultrasonic radiation for one hour. Following that, it has been examined the way various NSCP nanofluid concentrations influenced the performance of engines and exhaust features.

The fuel mixture containing 40% biodiesel and 60% diesel exhibits intermediate physicochemical properties between pure diesel and biodiesel. From the tested data of the fuel mixture, the Cetane number 58 improves over diesel of 56, while the calorific value is 39,150 kJ/kg. The flash point of the mixture is about 89°C remains significantly safer than biodiesel but higher than diesel. This blend retains compliance with ASTM standards for key parameters like viscosity (D445) and density (D1298), ensuring compatibility with conventional diesel engines while leveraging biodiesel's renewable benefits and reduced emissions. In addition, the complete chemical and physical properties of the blended mixture can be found in the author's previous work [18, 22].

2.5 Test methodology and engine arrangement

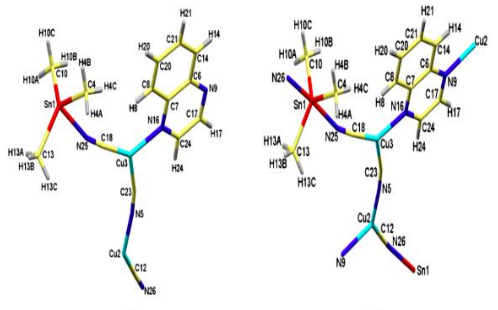
The experimental study was conducted using a single-cylinder, water-cooled diesel engine operating on a steady speed of 1500 rpm under varying load conditions to estimate the impacts of the **NSCP** nano-additive [$Cu_2(CN)_3.Me_3Sn.qox$] on engine performance and emissions. The schematic diagram of the test rig, with an actual photograph of its configuration with different measuring arrangements, was thoroughly investigated and presented by the earlier authors' work [23].

The engine was coupled with a hydraulic dynamometer offering precise control over the load applied to the engine while ensuring a constant rotational speed. By subjecting the single-cylinder diesel engine to incremental loads at a fixed speediness, researchers can simulate real-world operating conditions and scrutinize the engine's response in terms of power output, fuel consumption, and emission levels. Additionally, the test rig includes an RPM indicator to monitor engine speed. A biodiesel-diesel blend (40% biodiesel + 60% diesel) was used as the base fuel, with the nano-additive introduced at concentrations of 25, 50, 75, 100, 150, and 200 ppm. For emissions measurement, an exhaust gas analyzer was employed to quantify carbon monoxide (CO), unburned hydrocarbons (UHC), nitrogen oxides (NO_x), and particulate matter (PM). A smoke meter was used to measure smoke opacity, while the temperature of the exhaust was measured by using K-type thermocouple sensors. Data were recorded under steady-state conditions at different engine loads to ensure comprehensive performance and emissions evaluation. This methodology ensured accurate and reproducible results, providing insights into the additive's impact on combustion efficiency and environmental performance [18].

3. Results and discussion

*3.1. X-ray diffraction structure of [$Cu_2(CN)_3.Me_3Sn.qox$] **NSCP***

The asymmetric unit's ORTEP depiction; According to the NSCP, $^3_\infty[Cu_2(CN)_3.Me_3Sn{\cdot}qox]$ = $^3_\infty[\{(CuCN)_2\mu\text{-}(CN)\mu\text{-}(Me_3Sn)\}\mu\text{-}(qox)]$ shows that NSCP is made up of one $[Me_3Sn]^+$, one $[Cu_2(CN)_3]$ fragment, and one qox molecule, which stands for the asymmetric unit, Figure 1a. Through binding to two cyanide groups and one qox ligand, both Cu(I) sites assume a distorted trigonal planer (TP-3) shape, Figure 1b. The structures of NSCP extend to 3D-network have been mentioned in the literature [21]. The transmission electron microscopy image of NSCP displays uniform circular-shaped nanostructures with a narrow range of particle sizes ranging from 5.33 to 10.31 nm, Figure 2.



(a) *(b)*

Figure 1. *(a) Asymmetric unit of* ***NSCP*** *(b) ORTEP drawing indicating coordination of copper atoms.*

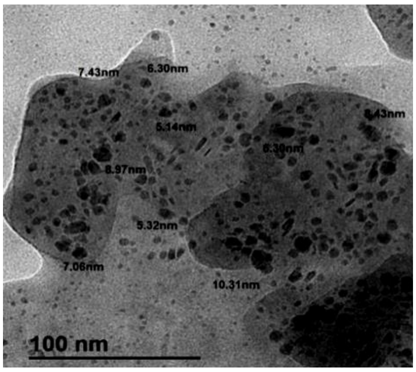


Figure 2. *TEM image of* ***NSCP*** *showing the nanoparticle sizes.*

3.2. Engine attributes at different operating conditions

This study aimed to evaluate the performance of a single-cylinder diesel engine under various operational conditions using eight distinct fuel formulations. Comprehensive measurements of Brake Specific Fuel Consumption (BSFC), Brake Thermal Efficiency (BTE) being calculated, and exhaust gas temperatures (T_{exh}) were conducted, with T_{exh} measured at the exhaust manifold outlet to provide insights into combustion characteristics. Tests were performed at a constant rotational speed of 1500 rpm and varying engine loads, ranging from no load to maximum capacity. The study focused on analyzing the effects of fuel blend components, **NSCP** nano-additive concentration, and engine load on performance metrics. Weighted average values were computed for each experiment to facilitate comparative analysis across all tested fuel blends, enabling a holistic understanding of the impact of fuel composition and operating conditions.

Figure 3 illustrates the BSFC for different blends, revealing that BSFC decreases significantly as engine load increases. The minimum BSFC was observed at a 50-ppm concentration of the nano-additive in the diesel-biodiesel blend. However, BSFC increased when the additive concentration was raised beyond 100 ppm, potentially due to adverse effects on fuel system components and fuel spray characteristics at higher concentrations. The results highlight a notable improvement in engine performance with the incorporation of nanomaterials, particularly at 50 ppm **NSCP** concentration, which significantly reduced BSFC. This enhancement is attributed to improved combustion efficiency and fuel atomization, demonstrating the potential of nano-additives in optimizing diesel engine performance. Throughout the experiment, it was observed that engine performance, as reflected by Brake Specific Fuel Consumption (BSFC), showed unsatisfactory results with increased BSFC values.

Figure 4, presents the outcomes for Brake Thermal Efficiency (BTE) across different nanomaterial concentrations in the tested fuel blends. The results indicate that the most optimal engine efficiency was achieved at an **NSCP** concentration of 50 ppm, where BTE reached its peak. However, as the concentration of the nano-additive increased beyond this level, engine performance declined, leading to lower BTE values. This decline in efficiency at higher nano-additive concentrations may be attributed to potential adverse effects on fuel atomization, combustion characteristics, or fuel system components. These findings underscore the importance of optimizing nano-additive concentrations to achieve the best engine performance, with 50 ppm **NSCP** emerging as the most effective concentration for enhancing BTE in this study.

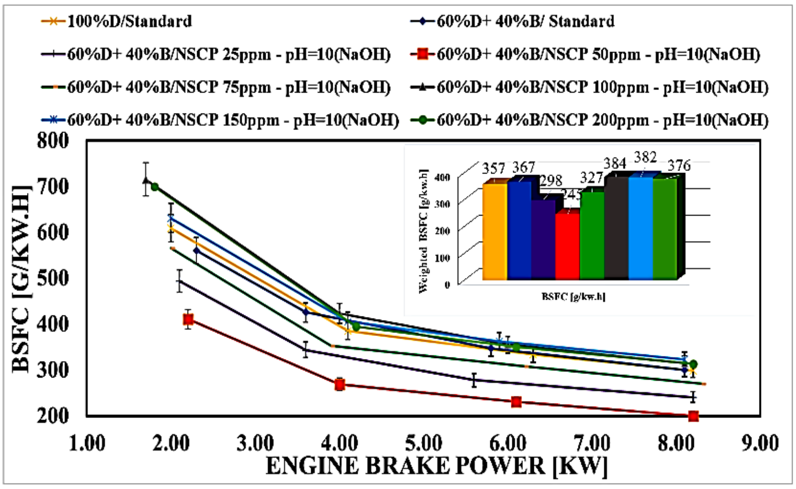


Figure 3. Variance of BSFC with brake power.

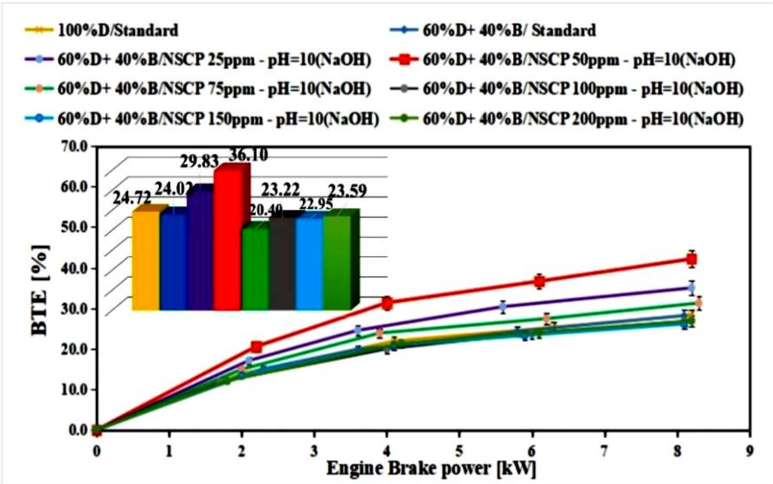


Figure 4. Variation of BTE with brake power.

In Figure 5, T_{exh} resulting from the combustion of various fuel blends tested in the laboratory are presented. These tests were conducted at varying engine loads and a fixed speed of 1500 rpm. The results indicate that T_{exh} generally increased with higher concentrations of nanomaterials, with a particularly significant rise observed at a 50-ppm concentration of **NSCP** across all tested fuel blends. This increase in exhaust gas temperature can be attributed to the role of nanomaterials in enhancing the combustion process. Nanomaterials, such as **NSCP**, increase the surface area for combustion reactions, acting as catalysts that promote the breakdown of fuel molecules and lead to more complete combustion. This results in higher temperatures within the combustion chamber. Additionally, nanomaterials improve heat transfer efficiency, further accelerating the combustion rate and contributing to elevated exhaust gas temperatures. These findings highlight the significant influence of nano-additives on combustion dynamics and their potential to optimize engine performance through enhanced thermal and catalytic effects.

The obtained results indicate that, the addition of nanomaterials (**NSCP**) to fuel blends significantly influences combustion dynamics and engine performance. At higher concentrations, particularly 50 ppm, T_{exh} increases due to enhanced combustion efficiency. This is attributed to the nanomaterials' ability to increase the surface area for combustion reactions, acting as catalysts that promote the breakdown of fuel molecules, leading to more complete combustion and higher combustion chamber temperatures. Additionally, nanomaterials improve heat transfer, further accelerating the combustion process. However, while higher nano-additive concentrations improve combustion and increase T_{exh}, they may also lead to increased Brake Specific Fuel Consumption (BSFC) and reduced Brake Thermal Efficiency (BTE) at very high concentrations (e.g., 200 ppm), likely due to adverse effects on fuel atomization or system components. The optimal concentration for balancing performance and efficiency was found to be 50 ppm, where BTE peaked and BSFC was minimized, demonstrating the importance of optimizing nano-additive levels for enhanced engine performance.

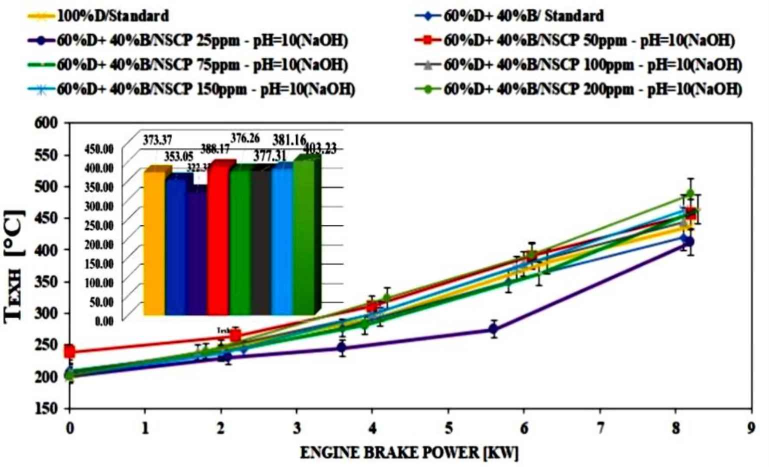


Figure 5. Variance of T_{Exh}. With engine brake power.

The oxygen storage capacity of **NSCP** nanomaterials can also help maintain the proper oxygen-to-fuel ratio, influencing the exhaust gas temperature. The current study demonstrates the potential of nanomaterial additives, specifically **NSCP** additives, in improving combustion characteristics such as BSFC, BTE, and T_{exh}. By reducing ignition delay and promoting uniform mixing of fuel and air, these additives can contribute to more consistent and controlled combustion. This, in turn, can lead to enhanced combustion efficacy and ultimately affect the temperature of the exhaust gases. The positive findings in this study indicate that incorporating **NSCP** additives into fuel blends shows promise for enhancing combustion performance. It highlights the real possibility of achieving better combustion efficiency and higher exhaust gas temperatures with **NSCP** nanomaterial additives.

3.3 Engine exhausts emissions at different operating conditions

Figure 6 represents the levels of CO emissions during various engine loads for various fuel conditions, including B40, B40 + 25 ppm **NSCP**, B40 + 50 ppm **NSCP**, B40 + 75 ppm **NSCP**, B40 + 100 ppm **NSCP**, B40 + 150 ppm **NSCP**, and B40 + 200 ppm **NSCP**. According to the data in Figure 6, it is important to point out that the highest levels of CO emissions were recorded for B40 across all engine loads. However, when B40 was modified with 50 ppm of NSCP, the CO emission levels were lower compared to B40, implying a potential reduction in CO emissions. The data also suggests that increasing the concentration of **NSCP** to 200 ppm led to higher CO emissions compared to B40 + 50 ppm and lower than standard B60. On the other hand, when the fuel blends of B40 + 75 ppm **NSCP** and B40 + 100 ppm **NSCP** were tested, the CO emissions gradually increased with higher **NSCP** additive concentrations. Additionally, the data presented in Figure 6 highlights that CO emissions tend to decrease with increased engine load used for all examined fuels owing to the elevated temperature of combustion during higher load conditions, leading to complete combustion of carbon and lower CO emissions. Finally, among the examined fuels, B40 + 50 ppm recorded the lowest CO emission levels.

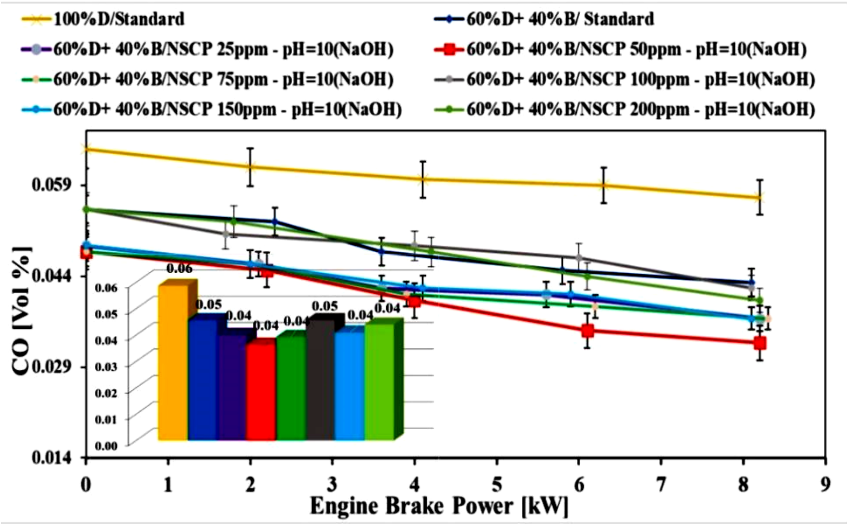


Figure 6. Variance of CO with Engine Brake Power.

Based on the information appeared in Figure 7, it is noted that the CO_2 emission levels during different engine loads were analyzed for the same used fuel blends, where using of **NSCP** nano-additives showed an average rise in CO_2 emissions values at different concentrations compared to the standard diesel and B40 blend.

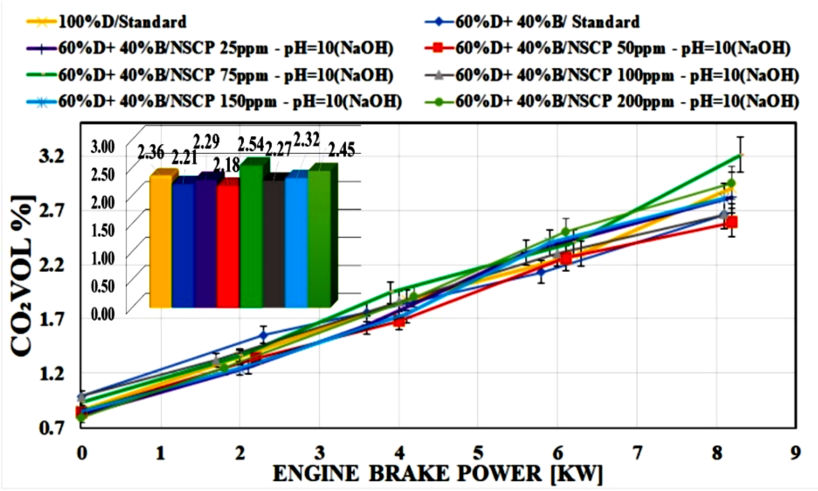


Figure 7. Variance of CO_2 with Engine Brake Power.

The highest CO_2 emission value was recorded for B40 + 200 ppm. This indicates that the addition of **NSCP** nano-additives boosted the rate of combustion, leading to higher CO_2 emissions. Using **NSCP** as a nano-additive is suggested to upgrade the chemical and physical features of the fuel blend, including flash points and other combustion-related factors. It is also mentioned that **NSCP** can enhance combustion by increasing the surface area-to-volume ratio, which aids in the combustion process. Furthermore, increasing CO_2 emissions can be attributed to the higher reactivity of the fuel blend when **NSCP** is added. These results in increased mass and heat transfer, due to the improved thermal conductivity of the fuel blend mixed with **NSCP**. Generally, the data from Figure 7 suggests that adding **NSCP** nano-additives to the fuel blend increased CO_2 emissions, indicating a boost in the rate of combustion and improvements in the fuel's physical and chemical characteristics.

Figure 8 represents the information about the O_2 emission levels during different engine loads and the impact of various additives on these emissions. The figure illustrates that O_2 emission levels decrease by increasing the load of the engine. This is ascribed to sufficient combustion due to a higher combustion temperature at higher loads. 100% D standard fuel recorded the lowest O_2 emissions across the full engine load range. While, when it was mixed with different concentrations of **NSCP**, O_2 emissions continued to increase compared to being alone. Among the mixtures, B40 + 50 ppm **NSCP** recorded the highest O_2 emission levels. However, NO_x formation is affected by the temperature and concentrations of O_2, and N_2. The weighted average value of O_2 emissions is inversely proportional to the average value of emitted NO_x, depending on the presence and concentration of **NSCP** additives. The presence of O_2 also affects the average value of O_2 emissions. Lower O_2 emission values can be attributed to their exhaustion during the oxidation process and the formation of NO_x.

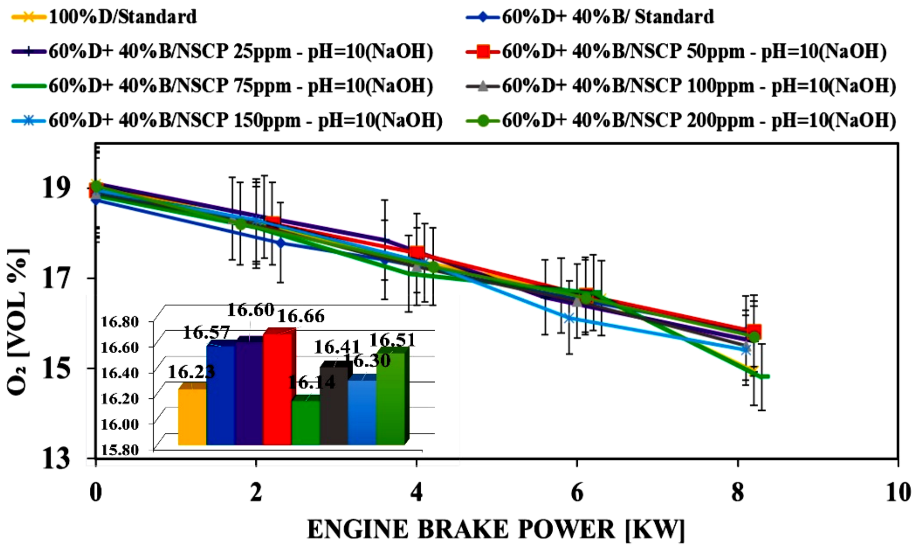


Figure 8. Variance of O_2 with Engine Brake Power.

According to the information presented in Figure 9, the data of the engine soot formation can be compared with the rapid creation of NO_x emissions. The formation of NO_x requires a high combustion temperature, which dramatically reduce the soot formation. Therefore, the increasing in soot formation can lead to NO_x creation reduction. In Figure 9, it is observed that soot emission levels increase with increasing engine load. This is attributed to insufficient combustion due to a shorter combustion period at higher engine loads. 100% diesel fuel recorded the highest soot emissions across the full engine load range. While, when B40 fuel is mixed with different concentrations of **NSCP**, soot emissions continue to decrease compared to B40 alone. In addition, B40 + 50 ppm recorded the lowest soot emission levels.

The decreased soot emissions observed when using the blend mixed with **NSCP** nano-additive can be ascribed to improved combustion, increased O_2 content, shorter soot formation duration, and potential effects on the ambient temperature of soot formation.

Based on the provided information in Figure 10, the NO_x emissions levels were examined for various engine loads and fuel conditions. B40 + 100 ppm was recorded as the highest NO_x emissions across the entire engine load range. In comparison, the lowest NO_x emissions were recorded for B40 + 25 ppm. This suggests that adding the lowest concentrations of the **NSCP** nano-additives to a mixture of the fuel resulted in lowering NO_x emissions. The release of NO_x emissions is known to be influenced by various factors, including combustion temperature, oxygen concentrations, and combustion duration.

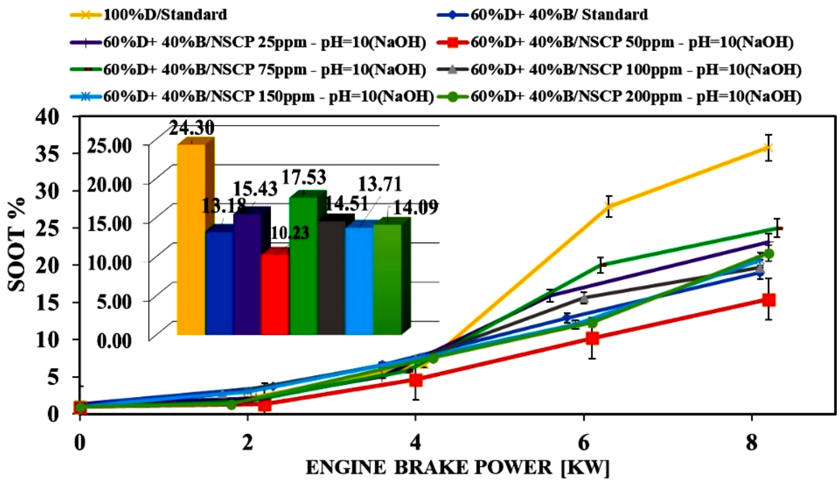


Figure 9. Variance of Soot with Engine Brake Power.

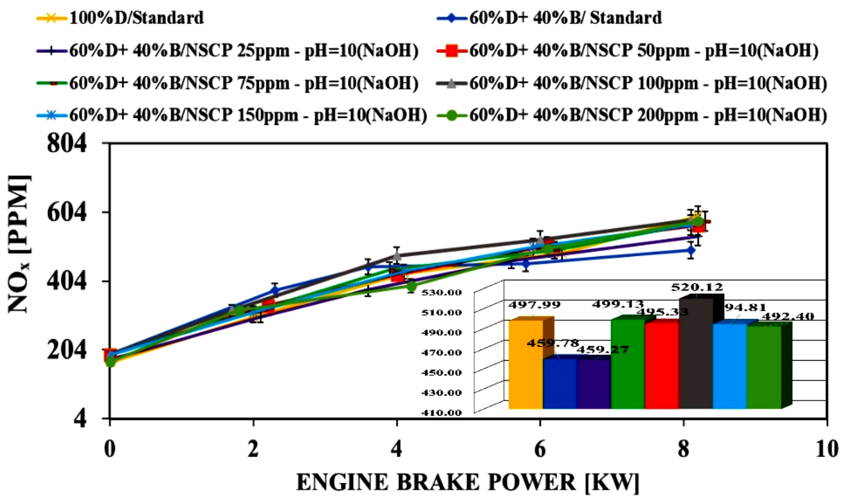


Figure 10. Variance of NO_x with Engine Brake Power.

Higher combustion temperatures and oxygen concentrations in the fuel blend have been found to significantly increase NO_x emissions. The reduction in NO_x emissions with the use of **NSCP** nano-additives in the fuel blends can be attributed to a distinct reduction in the engine combustion duration.

The addition of **NSCP** nano-additives may have altered the combustion characteristics, leading to fast combustion and subsequently reduced NO_x emissions. Generally, data from Figure 10 indicates that adding the lowest concentrations **of NSCP** nano-additives in the fuel blends resulted in reduced NO_x emissions compared to B40, potentially due to the altered combustion characteristics.

According to the information provided in Figure 11, UHC emission levels were examined for different engine loads and fuel conditions. UHC emission levels were observed to reduce with increasing engine load, indicating sufficient combustion due to a higher combustion temperature. Among the fuel conditions tested, 100% D standard and B40 recorded the highest UHC emissions across the entire engine load range. However, when B40 was mixed with different concentrations of **NSCP** nano-additives, the emission levels of UHC decreased compared to B40. The lowest UHC emissions were recorded for B60 + 50 ppm. The decrease in UHC emissions with the addition of **NSCP** nano-additive can be ascribed to different reasons.

Firstly, the improved ignition can be ascribed to the oxygen content of biodiesel existing in the fuel blend. The oxygen content helps in enhancing the combustion process, leading to more complete combustion and reduced UHC emissions. Furthermore, the nano-additions of **NSCP** may have improved the fuel's features such as fragmentation and viscosity, contributing to better combustion efficiency and reduced UHC emissions.

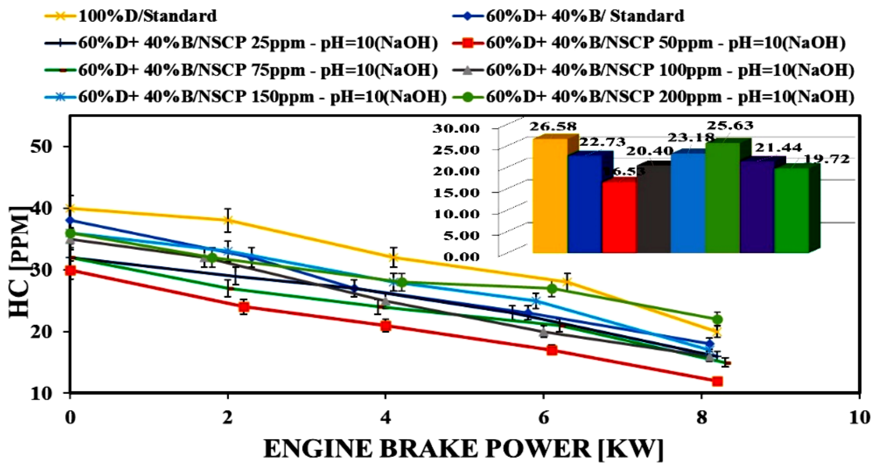


Figure 11. Variance of HC with Engine Brake Power.

The data presented in Figure 11 suggested that adding **NSCP** as nano-additives in the fuel blends, particularly in B40, can be used to upgrade combustion efficacy with decreased UHC emissions. The content of O_2 in biodiesel and the enhanced fuel characteristics facilitated by the nano-additives play crucial roles in achieving these effects.

4. Conclusion

Single crystals of **NSCP** [$Cu_2(CN)_3.Me_3Sn.qox$] ((qox)=quinoxaline) have been self-assembly and synthesized using ultrasonic radiation. The structure of **NSCP** has been investigated using X-ray diffraction XRD of single crystals, also it has a significant catalytic property. In current work, biodiesel that has been generated from a waste cooking oil source was blended as a nanoparticle enhancer, with 60:40 v/v% (D60B40) (e.g., 60% diesel, 40% biodiesel) and containing 25 ppm, 50 ppm, 75 ppm, 100 ppm, 150 ppm, and 200 ppm of nanocatalyst in the form of nanofluids. The main findings of this study were listed as follows:

- The experimental data elucidated that, the 50 ppm **NSCP** blend emerged as the most effective, optimizing fuel combustion efficiency, and emission reduction. However, higher concentrations (e.g., 200 ppm) showed diminishing returns, with increased BSFC, CO, and NO_x emissions.
- These findings underscore the importance of optimizing nano-additive concentrations to achieve a balance between improved engine performance and reduced environmental impact, making **NSCP** a promising candidate for enhancing biodiesel-diesel blends in diesel engines. However, the experimental results demonstrate that the addition of **NSCP** nano-additives to B40 (40% biodiesel + 60% diesel) significantly influences engine performance and emission levels.
- The **50-ppm NSCP** concentration yielded the lowest BSFC, indicating improved fuel combustion efficiency, while higher concentrations (e.g., 200 ppm) led to increased BSFC, likely due to adverse effects on fuel atomization and combustion.

- T_{exh} increased with higher **NSCP** concentrations, peaking at **50 ppm**, due to enhanced combustion efficiency and heat transfer facilitated by the nano-additive. While the lowest CO emissions, indicate combustion that is more complete.
- Lowering NO_x emissions at the **25 ppm NSCP** blend resulted in the lowest NO_x emissions, while the **100-ppm** blend recorded the highest. Lower **NSCP** concentrations reduced NO_x formation by shortening combustion duration and altering combustion dynamics.

References

[1] Batista V S, Chagas J V S, Da Silva A K D, Da Silva Y A, Monteiro E C B and Campos-Takaki G M 2023 *Sustainable solutions for clean energy production*. Seven Editora chapter **48** pp 1–13

[2] Lapuerta M, Rodríguez-Fernández J, Oliva F and Canoira L 2009 Biodiesel from low-grade animal fats: diesel engine performance and emissions. *Energy & Fuels*. **23** pp 121-9

[3] Topare N S, Gujarathi V S, Bhattacharya A A, Bhoyar V M, Shastri T J, Manewal S P, Gomkar C S, Khedkar S V, Khan A and Asiri A M 2023 A review on application of nano-catalysts for production of biodiesel using different feedstocks. *Materials Today: Proc*. **72** pp 324-35

[4] Morshedy A S and Guibal E 2024 *Royal Society of Chemistry* vol. 84, in Developments in Biodiesel Feedstock, Production, and Properties ed R G Balakrishna et al., chapter **15** pp 322-39

[5] Malabadi R B, Sadiya M R, Kolkar K P and Chalannavar R K 2023 Biodiesel production: An updated review of evidence. *Inter. J. of Biological and Pharmaceutical Sciences Archive*. **6** pp 110-33

[6] Mustapić Z, Krička T and Stanić Z 2006 Biodiesel as alternative engine fuel *J. of Energy-Energija*. **55** pp 634-57

[7] Madiwale S and Bhojwani V 2016 An overview on production, properties, performance and emission analysis of blends of biodiesel. *Procedia technology.* **25** pp 963-73

[8] Suhara A, Karyadi, Herawan S G, Tirta A, Idris M, Roslan M F, Putra NR, Hananto A L, Veza I 2024 Biodiesel sustainability: review of progress and challenges of biodiesel as sustainable biofuel. *Clean Technologies*. **6** pp 886-06

[9] Razzaq L, Abbas M M, Waseem A, Jauhar T A, Fayaz H, Kalam M A, Soudagar M E, Silitonga A S and Ishtiaq U 2023 Influence of varying concentrations of TiO_2 nanoparticles and engine speed on the performance and emissions of diesel engine operated on waste cooking oil biodiesel blends using response surface methodology. *Heliyon*. **9** e17758

[10] Ahmed M M, Pali H S and Khan M M 2024 Allometry of nanoparticles in diesel-biodiesel blends for CI engine performance, combustion and emissions. *Archives of Thermodynamics*. **45** pp 99-108

[11] Shilar F A, Ganachari S V and Patil V B 2022 Advancement of nano-based construction materials-A review. *Construction and Building Materials (Elsevier)* **359** p 129535

[12] Haq M ul, Jafry A T, Ali M, Ajab H, Abbas N, Sajjad U and Hamid K 2024 Influence of nano additives on Diesel-Biodiesel fuel blends in diesel engine: A spray, performance, and emissions study. *Energy Conversion and Management: (Elsevier)* **23** p 100574

[13] Hamzah A H, Akroot A, Wahhab H A, Ghazal R M, Alhamd A E and Bdaiwi M 2024 Effects of Nano-additives in Developing Alternative Fuel Strategy for CI engines: A Critical Rev. with a focus on the Performance and Emission Characteristics. *Results in Engineering (Elsevier)*. **22** p 102248

[14] Jin C and Wei J 2023 The combined effect of water and nanoparticles on diesel engine powered by biodiesel and its blends with diesel: A review. *Fuel* **343** p 127940

[15] Shaafi T, Sairam K, Gopinath A, Kumaresan G and Velraj R 2015 Effect of dispersion of various nanoadditives on the performance and emission characteristics of a CI engine fuelled

with diesel, biodiesel and blends—a review. *Renewable and Sustainable Energy Reviews*. **49** pp 563-73

[16] Selvam A J and Arunraj R 2024 An Experimental Study on Algae Biodiesel with Nano-additives for Engine Performance and Emission Reduction. *J. Environ. Nanotechnol*. **13** pp 361-73

[17] Zheng F and Cho H M 2024 The Comprehensive Effects of Nano Additives on Biodiesel Engines—A Review. *Energies* **17** p 4126

[18] Elkelawy M, Alm ElDin M H, Abo-Samra S and Elshennawy A I 2023 Nanoparticles Additives for Diesel/Biodiesel Fuel Blends as a Performance and Emissions Enhancer in the Applications of Direct Injection Diesel Engines: A comparative Review *J. of Engineering Research*. **7** pp 112-21

[19] Voronkova V, Oleksenko R and Nikitenko V 2023 Environmental problems solving as a factor in the formation of a sustainable and balanced development paradigm. *Int. Multidisciplinary Scientific GeoConf. SGEM.* **23** pp 215-25

[20] Etaiw S E H and Abdou S N 2017 Long Chain Aliphatic Diamine as Template for the Construction of Host–Guest Copper–Cyanide 3D-Network. *J. of Inorganic and Organometallic Polymers and Materials* **27** pp 1901-10

[21] Etaiw S E H et al. 2011 Synthesis, Characterization and Crystal Structure of New Organotin Copper Cyanide Three-Dimensional Supramolecular Coordination Polymer Containing Quinoxaline Molecule. *J. of Inorganic and Organometallic Polymers and Materials*. **21** pp 36-42

[22] El-Sheekh M M, El-Nagar A A, ElKelawy M et al. 2023 Solubility and stability enhancement of ethanol in diesel fuel by using tri-n-butyl phosphate as a new surfactant for CI engine. *Sci Rep* **13** p 17954. https://doi.org/10.1038/s41598-023-45252-7

[23] Elkelawy M, Alm ElDin M H, El Shenawy E A and Ouda M M 2024 A Greening the Diesel: Vegetable Oil Biodiesel Blends for Cleaner Emissions and Improved Direct Injection Diesel Engine performance. *J. of Engineering Research*. **8** pp 1-17