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Review Paper

Feasibility Study of Biofuel Incorporated Nanoparticles as Sustainable IC Engine Fuel: Opportunities and Challenges - An overview

Abdullahi Tanko Mohammed[1,2], **Mohd Farid Muhamad Said**[3], **Norazila Othman**[4], **Anthony Chukwunonso Opia**[5], **Ibham Veza**[6]

[1]School of Mechanical Engineering, Universiti Teknologi Malaysia, 81310, Malaysia
[2]Department of Mechanical Engineering, Waziri Umaru Federal Polytechnic Birnin Kebbi, 860262, Nigeria
[3]Institute for Vehicle Systems and Engineering (IVeSE), Universiti Teknologi Malaysia, 81310, Malaysia
[4]UTM Aerolab, Universiti Teknologi Malaysia, 81310, Malaysia
[5]Faculty of Mechanical Engineering, Universiti Teknical Malaysia Melaka, Malaysia
[6]Centre for Automotive Research & Electric Mobility (CAREM), Institute of Transport Infrastructures (ITI), Universiti Teknologi PETRONAS (UTP), 32610 Seri Iskandar, Perak, Malaysia

tanko@gaduate.utm.my

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Abstract

The advent of biofuel as a fossil petroleum substitute has been a revolutionary concept in the realm of combustion, but it lacks some qualities that, if addressed, could improve physio-chemical properties and promote energy sustainability. Recently, introducing nanoparticles (NPs) as an additive in fuel for combustion engines has become an effective practice particularly in the automobile industry, to optimize combustion efficiency and minimize emissions. Previous researchers discovered that adding NPs into biodiesel fuel improved overall engine operation performance. Thus, the objective of the research is to summarize existing research findings on nanoparticles effects on fuel properties and engine performance. The paper investigates biofuels, bio-fuel generation classifications, nano-fuel stability, performance, and limitations, as well as current research on the influence of NPs on combustion fuel properties and engine efficiency. Prior to this, researchers have discovered that employing NPs with appropriate additives and concentrations with optimal solubility significantly reduced emissions. In comparison to basic biofuel, adding CeO_2 NPs to biofuel boosted brake thermal efficiency (BTE) for low and high operation by 4.1 and 12.02%, respectively. Carbon II Oxide and unburnt hydrocarbon emissions were reduced by 16.13 and 17.59%, respectively, in comparison to pure biofuel under C20-D80 + CeO_2 20 ppm. However, due to the biofuel's oxygen concentration, CO_2 and NOx emission reductions were not as significant. The findings indicate that utilizing a single bio-fuel generates minimal effective power, yet by incorporating nanoparticles optimizes the operation. Furthermore, future direction of the related work will be discussed particularly on the potential benefits of incorporating NPs in fuel.

Keywords: Bio-fuel; Biomass; Nanoparticles; Combustion emission; Sustainable

1. Introduction

The progression of global industrialization, lifestyle transformation [1], [2] and vehicular population has substantially increased the demands for petroleum-based fuels [3], [4]. Globally, petroleum-based fuels reach up to 80.3% of the primary energy demand, alongside the transportation sector manipulating a total of 57.7% [5]. Constant overharvesting and exploration of crude oil reserves to meet current demand for energy has resulted in depletion [6] and environmental effects from oil exploration activities [7], [8].

Furthermore, continued consumption will cause fluctuations in crude oil prices, as well as contribute to greenhouse gas (GHG) emissions from their use [9], [10], are having a negative impact on earth's natural environment and human health [11]. Therefore, it is critical to develop new green technologies that are renewable [12], sustainable, environmentally benign, efficient, and commercially feasible [13], [14]. Despite these benefits, there are a number of negatives connected with the feedstocks, such as a lack of available land, competition with the food and scarcity in the market, and high costs. Many of the issues associated with using petroleum and other fossil fuels can be resolved using biomaterials, one of many alternative energy sources. Since it is regarded as the most environment friendly and sustainable energy source, biofuel, a product made from biomass, has attracted interest on a global scale [14], [15].

Biofuel lies under the category of biomaterial liquid, solid, and gas fuels such as methanol, ethanol, bio-diesel, bio-oil, Fisher Tropsch (FT) diesel, hydrogen, and methane [16]–[18]. Unfortunately, the utilization of biofuels as a substitute for petroleum/fossil fuels still has significant issues that require serious consideration in order to achieve its applicability [19], [20]. Therefore, in order to meet the worldwide fuel standard and demand, the main goal of this research is to explore biofuel incorporated nanoparticles, as well as their promising potential and applications, highlight specific constraints and proffer solutions the identified challenges. As globally ascertained that use of biodiesel reduces life cycle of carbon dioxide (CO_2) emissions because the associated CO_2 emitted by combustion of biodiesel is balanced and absorbed by the growing soybeans and other biofuel feedstocks. When compared to petroleum diesel, B100 use reduces carbon dioxide emissions by 74%, according to a life cycle analysis done by Argonne National Laboratory [21]. Through pre-treatment, saccharification and oleaginous microbe-mediated fermentation, lipid extraction, [22], [23] and transesterification, these biofuels (biodiesel, gas, etc.) can be produced from lignocellulosic substrates [24], [25].

2. Biofuel

Due to inadequate and depletion of petroleum fuels, researchers attempt to provide alternatives to cater the current demand by developing derived from renewable materials. Renewable energy sources can supply global energy demand [26], and reduce greenhouse gas emissions [27]. Previously mentioned in International Energy Report 2014 [28] that by 2040, the global demand for energy is projected to increase up to 37%. Despite the fact that there are various technologies for manufacturing gasoline from biodegradable materials, commercial operations are still in development [29]. Due to their limited applicability in food formulation [10], [29], [30], sources of non-edible raw materials have a strong propensity to be converted into biofuel. In addition, primary and secondary biofuels are the two categories predominantly found in this field. Primary biofuels [30] are derived from primary biomass sources like plants, woods, animal manure, and crop byproducts [24], [31], whereas secondary biofuels are derived from a mixture of biomass [32], [33] and microorganisms, classified as first, second, and third generation biofuels [3], [34].

Several publications and scientific journals have addressed significant concerns, such as economic [35], sociological [34], health, and technical problems associated with biofuel production [30]. Among the most important aspects in biofuel production [36], [37] with emissions such as Carbon levels, hydrocarbon (HC) particulate matter, and nitric oxide (NO_2) [15]. Developed countries have established research objectives for the development of biofuel business especially in transport sector. Physiochemical properties of biofuel derived from biomaterials vary based on the feedstock type, form and source, hence differentiating the products, applications, and performance. Biofuel from biomass can be derived from two primary sources, as depicted in **Figure 1**, while the formulation phases and associated biomass feedstock generations are shown in **Figure 2**.

The formulation of bio-fuels provides context for understanding first-generation class limitations, highlight relevant descriptions of second-generation biofuel technologies that are accessible to non-experts, as well as presents key energy, economic variation, and emission content between two bio-fuels generation [35]. These will serve as a tool for speculation towards the future global implication associated with biofuel development and utilization for business, economic development and environmental sustainabilty [17], [38].

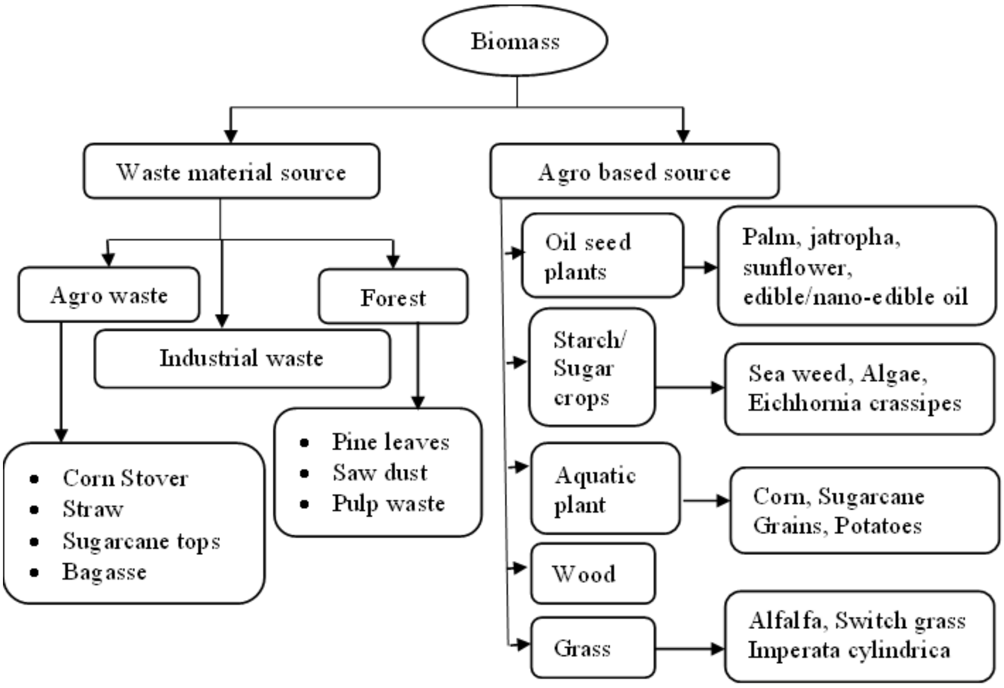

Figure 1. Potential biomass feedstock for biofuel production [19], [29]

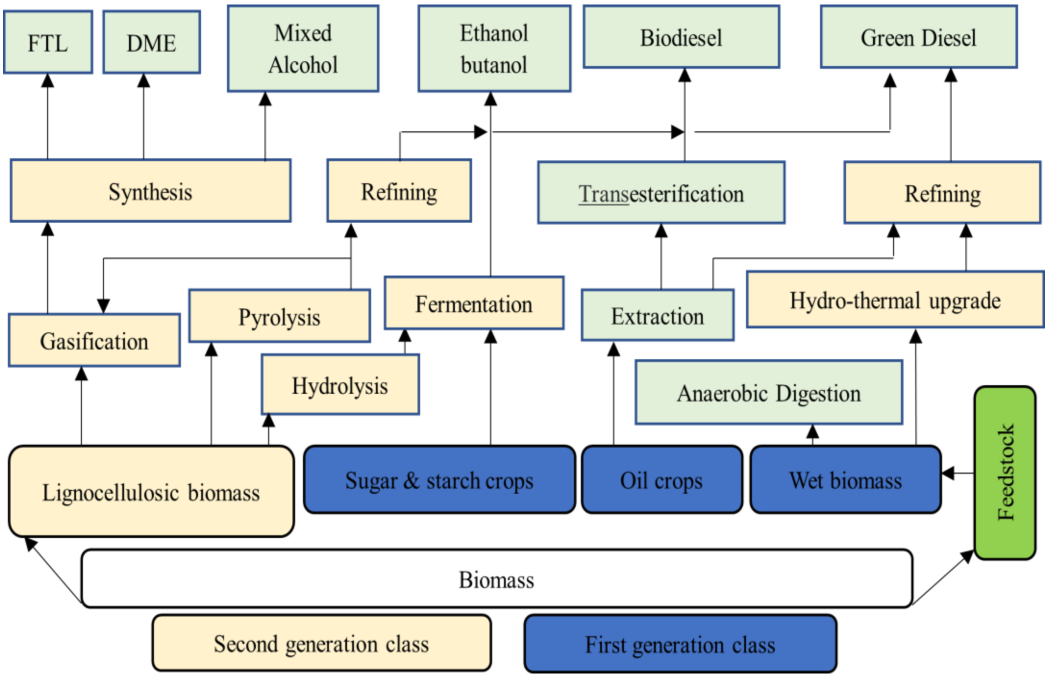

Figure 2. The route of first and second-generation biofuel generation

2.1. *First Generation Biofuel*

The most prevalent biofuel of the first generation is ethanol, which is created by fermenting sugar derived from various sugar sources or starch extracted from corn kernels or other starch-containing plant. Nonetheless, according to Naqvi *et al.*, [34], the 1st generation of biofuels are derived from the previous biomaterial feedstocks using the traditional biochemical conversion routes (fermentation/hydrolysis). As depicted in **Figure 2**, this category includes biodiesel, bioethanol, 2,5-dimethylfuran, and biofuels that have been catalytically cracked. Similar to ethanol, butanol can be produced utilizing variations of fermentation microorganisms [39]. Currently, the commercialization of butanol are ongoing [3], [40], whereas ethanol is already a well-established industry.

Other marginal biomasses used or considered for the synthesis of 1st generation bioethanol include sugarbeets, barley, potato wastes, etc. Sugarcane is known as one of the most prominent feedstock used for biofuel production, and Brazil has the highest usage rate. Producing ethanol from sugarcane is a relatively easy procedure as the sugarcane is pulverised in water to extract sucrose, which is then processed to produce either refined sugar or ethanol [41]. Even though the increase in the prices of sugar are advantegous to the producers, yet they provide challenges for the bioethanol business. As shown in **Figure 1**, corn is known as the key source carbohydrates for ethanol production, but it requires an extensive breakdown of starch compared to sugarcane in order to release sugars that may subsequently be fermented to ethanol [42], [43].

2.2. *Second Generation Biofuel*

Second-generation products are fuels derived from a variety of feedstocks, such as non-edible lignocellulosic substances and others. In general, biomaterials used to manufacture second-generation biofuels are classed as follows: homogeneous, e.g. white wood chips; quasi-homogeneous, e.g. agricultural residues; and non-homogeneous, which includes low-value feedstock such as municipal solid wastes [44]. These biomaterials are considerably less expensive than corn, vegetable oil, and sugarcane, which would be a huge benefit. These biomaterials are far less expensive than corn, and vegetable refining techniques.

The concept of "biorefinery" is supported by the fact that numerous biomasses enable the manufacture of diverse products from similar feedstock. As depicted in **Figure 3**, the conversion of second-generation biofuels often involves three distinct "thermo" or "bio" routes. oil, and sugarcane, which is an enormous advantage. Conversely, these materials appear to be more hard to convert, and their processing is responsive to novel. Bio oil is the main product of pyrolysis obtained by heat application on biomass at elevated temperatures (550 to 750 °C) in the absence of oxygen [45], [46]. Gasification occurs at higher temperatures (750-1,200 °C) with minimal oxygen inputs, producing principally syngas, charcoal, and bio oils [9], [36]. Biochar, a solid biofuel, is gaining popularity in the briquette sector, particularly in regions of the world where lignocellulosic biomass is cheaper [47], [48]. However, the production of syngas or pyrolytic oil is often regarded as more effective and sophisticated for vehicle fuel. Pyrolytic oil, a liquid intermediate that seems similar to petroleum but is chemically distinct. As a result of high level of water-content and caustic nature of the product bio-oil, a second transformation is necessary to produce vehicle gasoline from this intermediate and is deemed as a difficult procedure.

The term "thermal" refers to the process of heating biomass with minimal, if any, oxidizing material. All of the processes in that category convert biomass into three components: solid as bio-char, liquid as pyrolytic oil, and syngas, largely from carbon dioxide, short chain alkanes, carbon monoxide, and hydrogen, as shown in **Figure 3**, whereas the "bio" pathway is similar to a pulping technique with the production of cellulose, hemicellulose, and lignin. Torrefaction occurs when biomass is heated at relatively low temperatures (250 to 350 °C) in deficient air, and the predominant conversion product is charcoal.

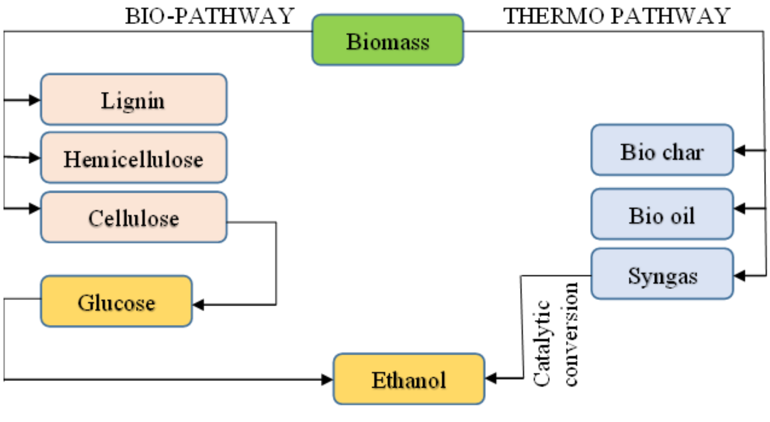

Figure 3. Breakdown of second generation biofuel [49]

Zhang *et al.*, [46] evaluated four feasible transformation systems: 1) hydrodeoxygenation (by removing oxygen, a mixture of alkanes similar to that of fossil petroleum is produced); 2) catalytic cracking; 3) steam reforming; and 4) diesel production using emulsion method. In comparison to pyrolysis, gasification produces syngas, that mainly composed of single carbon molecules and hydrogen. Although syngas can be used to make transportation fuels, it requires a specialised catalysts to stimulate carbon-to-carbon bonds formation. The Fisher-Tropsh technique is one such treatment [50]. Methanol production is one of the simplest methods for commercialising synfuels from syngas. Methanol can be produced directly from hydrogen and carbon IIoxide using suitable reducing catalyst.

Recent research has indicated production rates ranging from 500 to 560 L/ton of biomass using municipal solid, a non-homogeneous biomaterials [44]. Methanol is a finished product, however it cannot yet be used as a gasoline additive. Therefore, more transformation is required. Plenty of end products have been manufactured using methanol as the raw ingredient including alkanes via methanol-to-gasoline (MTG) processes and ethanol via carbonylation procedures [44]. Furthermore, methanol is being investigated for its potential application in the development of emerging biofuels, such as bioDME. The bioDME is synthesized by etherifying two methanol molecules. This is further used as a diesel additive [51] which also added benefit of simplifying the production using acid catalyst [52]. However, the most notably limitation of BioDME is, its low viscosity as compared to diesel fuel, which causes severe degradation in fuel injection systems for vehicles [51].

2.3. *Third Generation Biofuel*

Due to a highly developmental products as compared to typical lignocellulosic biomass, the most popular description of third-generation biofuels has traditionally been fuels obtained from algal biomass [53]. Microalgae flourish under a variety of growth conditions and synthesize a number of renewable bio-based fuels, including biohydrogen, biodiesel, and biogas [3], [53]. Microorganism lipid components are predominantly used in the development of algae-based biofuels. Chlorella species are often promising due to their high lipid potential (60 to 70%) [54] and productivity (6.28 and 2.06 g/L day) for Chlorella protothecoides [55]. There are several issues with algal biomass, such as the geographical nature and composition/ constituents nature [55]–[57]. When extracting lipids from algal biomass, the high moisture content is a significant difficulty, necessitating drying after centrifugation or filtration before separating lipids [58], [59]. Algae lipids might be transesterified utilising the previously reported biofuel procedure or hydrogenolyzed to yield kerosene category alkane suitable for aviation fuels [58].

3. Combustion of Pure Biofuel

Over decades, as the world has strived to minimize its carbon footprint or achieve carbon neutrality, the use of renewable energy has progressed significantly [10], [11], [60], [61]. As one of the modern renewable biofuel energy sources [62], it has provided 5.1% of global energy consumption and has continued to develop at a pace of roughly 2% per year in recent years [18]. All of this is aimed at mitigating the problems associated with petroleum counterparts, although some concerns still exist when biofuel is used in combustion processes. Thus, variations of appropriate biofuel advancements are still needed. According to Sandesh *et al.*, [63], the use of biofuel as a replacement for fossil derived fuels is acceptable, although it definitely results in a reduction in combustion performance due to a lack of several required fuel qualities. A slight incline in performance is usually not a problem for small-scale applications, but somehow it causes major concern in the industrial and power sectors [64].

This discovery was confirmed by [65] whom tested the performance of diesel engine tractor running on pure plant oil (PPO). The John Deere 6830 agricultural tractors used in this study had a 6-cylinder, 24-valve engine model 6068HL481 with a power output of 103 kW (140 kM), a high-pressure fuel injection system with 620 Nm torque at 1400 rpm, a displacement of 6790 cm^3, and a working speed range of 1300-2100 rpm fueled with pure rapeseed oil, and a high-pressure fuel injection. According to the study, using the PPO resulted in a significant reduction in torque and power production. The total efficiency of the engine, including specific fuel consumption (SFC) and brake thermal efficiency (BTE), was comparable to that of normal diesel fuel.

Similarly, Karthikeyan *et al.*, [66] investigation on the utilization of Stoechospermum marginatum microalgae biodiesel proved a significant decline in power production with no apparent impact on the overall performance of the biodiesel fuel. The utilization of biofuel in combustion applications is still seen as one of the most realistic options for significantly reducing carbon emissions in the sector. Despite the fact that biofuels offer significant advantages in terms of lower CO_2 emissions, some types of biofuels, particularly pure biofuels, have higher NOx emissions, somewhat lower efficiency, and higher hydrocarbon content (HC) emissions (B100) [67], [68].

Venkatesan et al. [69] evaluated tractor engine performance using hybrid biofuel to determine the performance of pure biofuel in application. In the investigation, diesel-soapnut oil methyl ester was used (fuel = P0SNB100, P25SNB75, P50SNB50, P75SNB25, P100SNB0). The fuels were injected into a Simpson's S217 tractor engine, and its performance, emissions, and combustion properties were all tested and investigated. The results revealed that the hybrid biofuel blend P75SNB25 with 10% exhaust gas regeneration (EGR) reduced SFC, exhaust gas temperature, and HC emissions by 3.44%, 3.90%, and 20%, respectively, when compared to diesel running at maximum load without EGR. Furthermore, BTE and CO emissions increased by 4.44 and 8%, respectively. The HC, NOx emission reduction, and exhaust gas temperature (EGT) values for SNB20 with 10% EGR were around 20%, 10.55%, and 3.12%, respectively. The improved performance of blended biofuel over pure B100 was due to differences in the individual biofuel qualities.

Mc Carthy *et al.*, [70] analyzed the performance of bio-fuel and diesel respective to energy content, emissions, fuel consumption, and exhaust emission in a Kubata V3300 ICE using two biodiesels, A (20% canola oil and 80% tallow) and B (20% canola oil and 80% tallow) (30% waste cooking and 70% chiken tallow methyl ester). According to the research, biodiesel's low energy content results in poor performance (torque and power). Also shows poor power and torque performance for biodiesel fuels, which could be due to the engine used. Furthermore, HC and CO_2 emissions from both biodiesels increase as the volume of biodiesel mixed increases, although CO emission decreases as the volume of biodiesel in the blend increases. Biodiesel B consumes more fuel than Biodiesel A but has a lower energy level. Although gasoline with lower calorific value is consumed more faster [70], biodiesel A emits less pollutants and performs better than Biodiesel B.

Saravanakumar *et al.*, [71] discussed the combustion performance of a diesel incorporating lemon grass oil and methanol. The results revealed that biodiesel BTE outperforms diesel, especially in loading circumstances. According to the graph in **Figure 4a** and **Figure 4b**, increasing the lemongrass biodiesel blend ratio improves the BTE. The BTE of the blended samples L20M30, L20M10, and L20M20 were respectively 20.62 (14%), 19.33 (7.8%), and 20.37 (12%) higher than diesel (17.93). Despite having a lower heating value than diesel, proper fuel blending guarantees complete combustion. This demonstrates that in terms of brake thermal efficiency, dual biodiesel surpasses diesel [71]. The study also indicated that higher load increases the BSFC in all of the fuel samples tested. The BSFC of blended ratio B20 as in L20M10, L20M20, and L20M30 for optimum load operation via compression ratio 17.5 (CR17.5:1) was 0.49, 0.43, and 0.42 kg/kW h, respectively, compared to pure diesel (0.47 kg/kWh) [71]. While analysing the emission effect, as shown in **Figure 5**, blended bio-diesel showed good emission reduction 64) on CO, HC, and CO2, but higher NOx with L20M10 at maximum load (100).

Dhinesh et al., [72], analysed the performance of biofuel, pure diesel, and in comparison to combination of CeO_2 NPs. As opposed to findings by Saravanakumar et al., [71] it was demonstrated that in comparison with other fuels, diesel had a higher BTE as a result of its higher viscosity and higher evaporation rate. C100 gasoline also has a lower BTE compared to other fuels as a result of its reduced volatility and higher viscosity. Apart from diesel fuel, C20-D80 + 20 ppm fuel performed better than other fuels, increasing by 4.1% and 12.02% (low and high load) compared to base bio-fuel. Potentially since the combination action of NPs and oxygenated fuel.

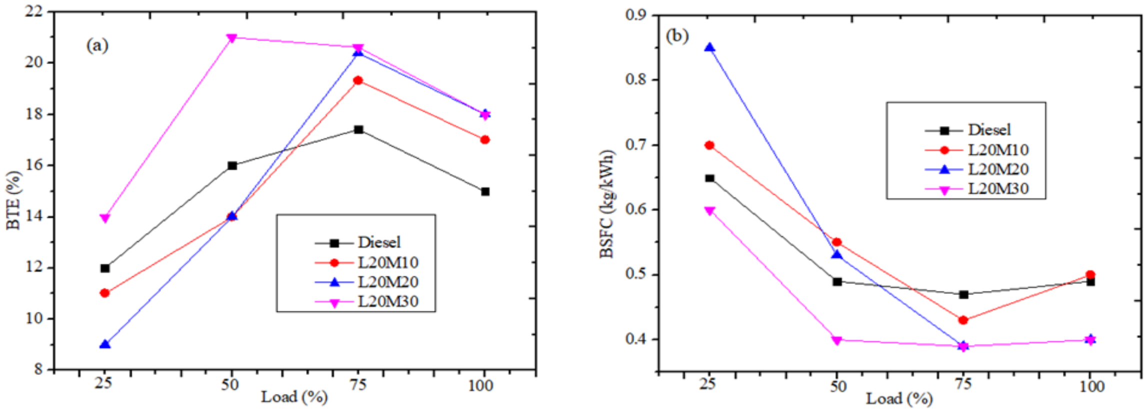

Figure 4. (a) BTE and (b) BSFC against load for various blends [71]

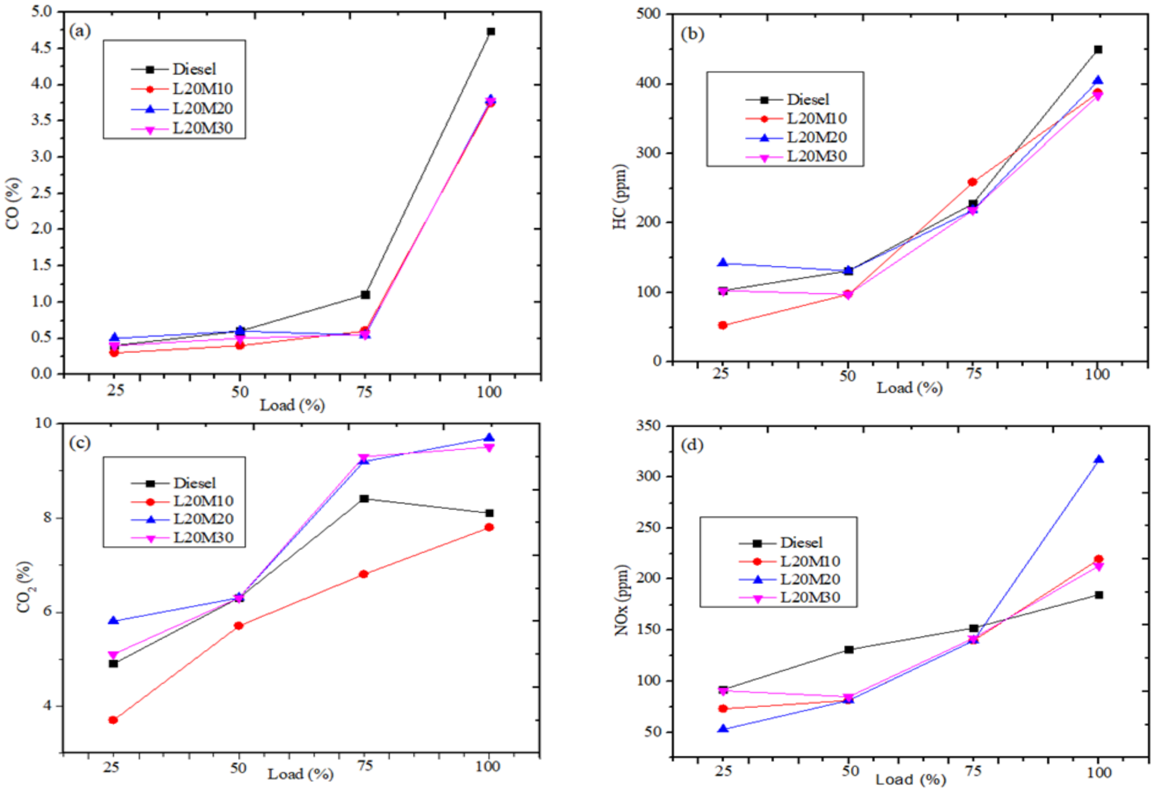

Figure 5. (a) Emissions; (b) HC; (c) CO2; (d) NOx, against loads for various fuels [71]

Cerium (IV) Oxide NPs enable greater atomization and a more suitable air-fuel premix composition as a result of their higher surface area to volume (As/V) ratio.

In comparison to biofuel with C20-D80 + 20 ppm to base diesel, the HC was reduced by 16.13% and 17.59%, at low and full operations, indicating that CeO_2 increased emission reduction [72]. Meanwhile, when compared to base diesel, smoke emission for bio-fuel with C20-D80 + 20 ppm was reduced by 20.31% and 12.28% at low and full operations, demonstrating that base bio-fuel performed better than CeO_2 NPs application. C20-XD80 + 20 ppm increased NOx discharge by 15.15% and 7.96% compared to base diesel at low and full operations. As result of the high oxygen concentration in biofuel, C100 produces more NOx than normal diesel fuel, but C20-D80 + 20 ppm produces less NOx. **Figure 6** depicts the behaviour of engine efficiency and emissions when biofuel, diesel, and NPs are used.

Analysis conducted on pure biofuel indicated that contaminants, quality deterioration and low energy content are area that requires more attention and review, prior to its usage on power generation applications [18]. These obstacles in need of the development of alternative optimization methodologies capable of achieving

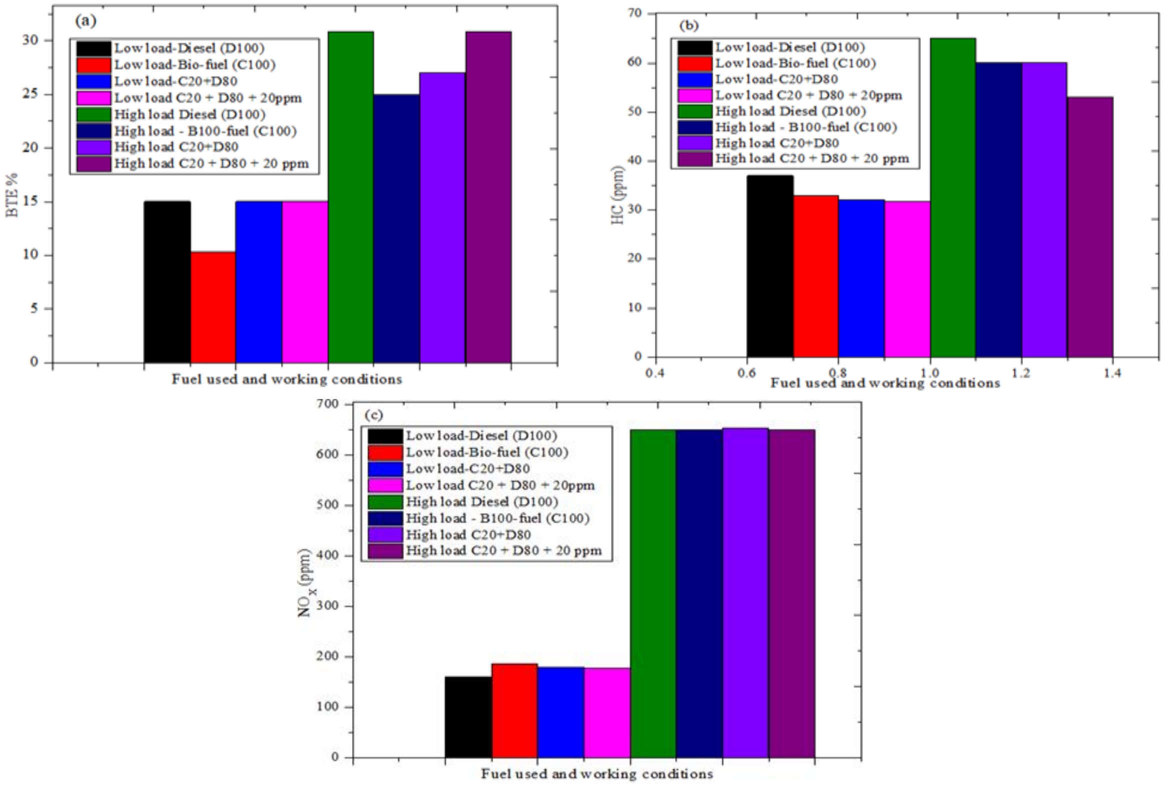

Figure 6. (a) Engine BTE performance; (b) HC; (c) NOx emissions under bio-fuel, diesel and blended with NPs [72]

high process yields as well as the commercialization of biofuels ability to compete with conventional fuels. Some difficulties, such as biofuel surface changes, fuel characteristics (cetane number, oxidation stability) [73] and lowering of combustion activation energy required attentions [74]. Researchers have identified appropriate nanoparticles as a strategy for boosting biofuel performance.

4. Nanoparticles as a Unique Substance in Combustion Engineering

Nanotechnology has gained overwhelming preponderance in recent times as a result of its capacity to handle a wide variations of 1 to 100 nm nanoscale materials [75]–[77]. Therefore, NPs are utilised in multi-industries, such as agriculture, food, cosmetics, medicine, and electronics [75], [77], [78]. The wide application of nanotechnology is partly attributable to the novel properties of NPs, such as their structures, nanoscale dimensions, as well as better reactivity [79]–[81]. Due to the remarkably small size of NPs, they have attracted significant interest for the following reasons: (1) provides a large As/V ratio and an increased number of active sites, both of which are required for providing various reactions [82]; (2) the ability of NPs to exhibit a variety of structures has broaden its applicability in domains such as biomedical, water/environmental remediation, and (3) rapid reactions among nanoscale materials. Moreover, nanoparticles possess a lamellar/crystalline structure for optimal reaction, catalytic activity [83], chemical inertness, and a high adsorption capacity [84]. They could be metallic [85], polymeric in nature [86], and can be synthesized from the top down or bottom up [87]–[89]. Due to their unique features, nanoparticles are desirable materials for improving biofuel processes and enhancing the performance of nano-fuels in service [90], [91]. They are often used as catalytic substance [92] and is important for electron transfer [93], inhibitory compound reduction, and anaerobic consortium activity [94].

The use of NPs in biofuels is still progressing, therefore the review pertinent to this topic is as limited. These reviews describe the many types of NPs-additives used in these bioprocesses to optimize process yields. In order to prevent non-specific bonds and facilitate the identification of certain microbial enzymes, NPs have been functionalized by replacing their large surface area (As) with organic contents via covalent or non-covalent bonds [53]. In this scenario, necessary research needs to be conducted in order to verify the molecular system and behaviour of binding of a specific NP with the AGPase enzyme (ADP-glucose pyrophosphorylase), which improves the formulation's activity. NPs, particularly metal type exposure in various microalgae (including C. vulgaris), may influence the physiological, microbiological or biochemical changes, resulting in increased production, improved biofuel quality, or the activation of some defense, with resulting formation of various pharmaceuticals, nutraceuticals, exopolymers, phytohormones, peptides and pigments.

5. Nanoparticles in Biofuel

5.1. Impact of Nanoparticles in Biofuel Formulation

Nanoparticles are becoming more popular in biofuel production because they have better effects on metabolic responses in many bioprocesses. Nano-products such as nanofibers, nanotubes, and metallic NPs have been found to be used in biofuel synthesis systems [13], [93], [95]. As shown in **Table 1**, incorporating bio based fuel with nanoparticles completely changes the physico-chemical properties of the produced biofuel. Furthermore, the fuel content containing nanoparticles will modify when the effects on several parameters such as cetane number, heating-value, kinematic viscosity, flash point, and specific gravity are examined. The improvement in these fuel qualities considerably increases the biofuel nature, making it comparable to its petroleum counterpart.

In addition, the use of nano-microorganisms aided in the more successful and increased quantity of biofuel generation. This section highlights research that used nanoscale materials as property enhancement catalysts to improve biofuel production and combustion performance [96]–[98]. Ivanova *et al.* [99] immobilized S. cerevisiae cells using magnetic nanoparticles to show bioethanol synthesis using immobilized microorganisms. During fermentation, the immobilized cells generated bioethanol at a high rate, generating 264 g/L.h. Calcium and sodium alginate were also tested for improving bioethanol yields and found to be beneficial [100].

Lee *et al.* [101] used S. cerevisiae cells entrapped in calcium alginate to increase bioethanol production. The immobilized cells produced 100% ethanol, whereas the free-suspended cells produced 88% ethanol. It should be noted that no inhibitory metabolites were discovered in the processes. Subsequently, [102] discovered that cells cultured in an alginate matrix produced 50% more ethanol than cells grown in free suspension. Duarte *et al.*, [103] evaluated S. cerevisiae implementation utilizing both chitosan and calcium alginate as immobilization matrix in a comparable study. It generated optimal bioethanol amounts of 32.9 1.7 and 30.7 1.4 g/L, respectively [103]. Due to the protection provided by the immobilization barrier, the cells are eight times reusable without being contaminated.

Several other immobilizing agents have been found to be quite effective in bio-refineries and modification, including apple peels [104], corncob [105], orange peels [106], sorghum, and sugarcane [107]. Inorganic carriers includes mineral clays, alumina, natural polymers such as chitosan, and synthetic polymers like; polyvinyl alcohol and polyacrylamide [81]. Alginate matrices are favoured as an alternative since they use moderate fermentation conditions, cost-effective, allow cell reusability, resistant to pollutants, and have high porosity [81]. Zymomonas mobilis is another ethanologenic organism with very significant economic potential for bioethanol production as a result of the benefits of such as high specific rate of sugar uptake, enhanced bioethanol production output, and absence of need on aerobic conditions [108].

Furthermore, there are novel metabolic approaches at immobilizing this bacterium for massive and improved bioethanol yield [109]. For example, commercially produced ethanol from a Z. mobilis strain can ferment xylose and other sugars [108]. Moreover, by better understanding the role of NPs in microalgal cellular processes, solutions to improve the quality and value of biofuel cellular products can be developed. **Figure 7** depicts the advantages of using nanoparticles in biofuel formulation.

5.2. Factors Influencing Nanoparticle Performance in Biofuel Manufacturing Processes

There are numerous determining factors that affect the behavior of NPs in biofuel formulation processes. These determinants include synthesis

Table 1. Summary of some key properties of bio-fuel incorporated NPs

Nanoparticle	Biofuel	Fuel properties					Ref.
		Cetano No	**Density (Kg/m^3)**	**Calorific value**	**Viscosity (sCt)**	**Flash point (°C)**	
CNT25	Honge oil methyl ester	-	-	34.56	5.7	166	[110]
CNT50		-	-	35.1	5.8	164	
AgO 5	Palm stearin biodiesel	-	804	38.35	3.86	134	[111]
AgO 10		-	797	38.54	3.71	132	
-	Neem oil biodiesel	43.5	828	41.9	37.4	65	[112]
CeO_2 50 ppm		43.7	830	41.94	3.71	66	
-	Sardine oil methyl ester (SOME)	45	890	37.41	4.5	58	[113]
CeO2 25 ppm		56	894	45.37	5.6	191	
ZnO 100	Grapeseed oil biodiesel (GSO)	59	-	38.9	4.42	-	[114]
CeO_2 100		57	-	38.76	4.47	-	
-		-	-	39.07	4.06	-	
CNT25	Diesel fuel	49.09	841	49.09	3.99	-	[115]
CNT 50		50.18	846	50.18	3.86	-	
CNT 100		51.27	850	51.27	3.83	-	
Al_2O_3 25		48.20	853	48.20	3.70	-	
CuO 50	Diesel fuel	54.5	834.1	-	3.5	60	[116]
Al_2O_3 50		55.4	856	55.3	3.81	-	
Al_2O_3 100		55.4	873	55.4	4.12	-	
CeO_2 30 ppm	Lemongrass oil emulsion fuel	48.8	916.4	36.2	4.99	67	[117]
TiO_2 50 ppm	*Calophyllum inophyllum biodiesel*	53	869.2	37.12	4.73	123	[118]
TiO_2 100 ppm		55	870.4	37.54	4.75	124	
ZnO 50 ppm		54	871.1	37.02	4.76	123	
ZnO 100 ppm		56	872.4	37.32	4.78	126	
CeO 20 ppm	*C20-D80*	48.3	840	42.88	3.30	53	[72]

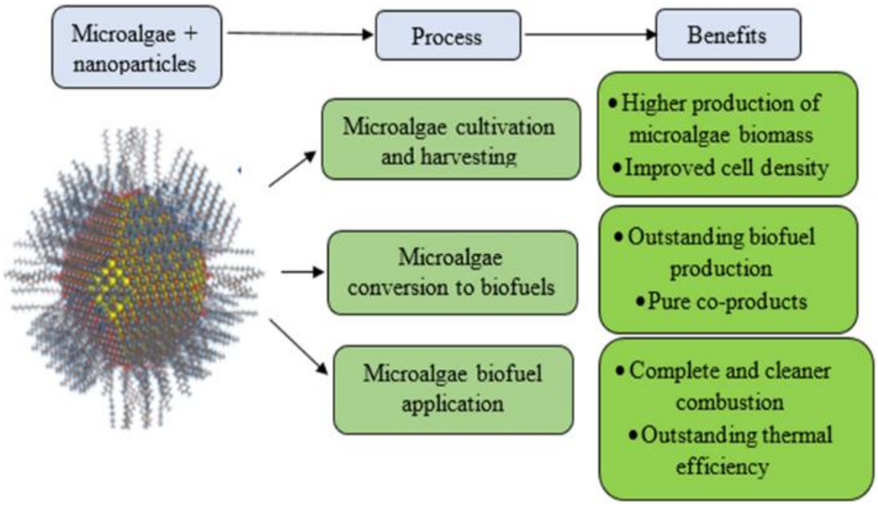

Figure 7. Illustration of the benefit of nanoparticles and microorganisms in bio-fuel production

temperature, medium pH, strategy, pressure, size, and so on [87]. These process conditions are described as the following.

5.2.1. *NPs Synthesis Temperature and Pressure*

Temperature is a critical factor in the production of NPs [119]. The calcination temperature of metallic NPs varies depending on the technique of synthesis from 100 to 700 °C. Physiochemical procedures typically employ high temperatures (>300 °C), whereas biological approaches use moderate temperatures (100 °C) or even room temperature condition. The production temperature has effect on the overall structure (pore size, shape, and stability) of NPs [120]. Pressure is another variable that can be manipulated during the production of NPs which are applied to the reaction media [81] to accomplish the desired size, shape, and aggregation in NPs. It can be observed that, when treated to high pressure, the size of NPs expanded.

5.2.2. *NPs Size*

Based on literature, several nanoparticle sizes ranging from 5 to 100 nm have been utilized for biofuel manufacturing methods [87], [119]. A multitude of factors influence production outputs, including nanoparticle size, and each process necessitates the determination of an optimal set of operating parameters [87]. The quantity and size of NPs achieved throughout the manufacturing process are critical attributes [121], [122].

5.2.3. *NPs Synthesis PH*

It has been demonstrated that the medium pH during NPs production, influences the behaviour of the metallic NPs (Au, Ag, Cu, Pd, Zn, etc.) [123]. Particle aggregation occurs at pH values less than 7, which increases NP stability. Thus, the size and geometry of NPs can be modified by adjusting the medium's pH value during production [87].

5.2.4. *NPs Synthesis Strategy*

As mentioned in previous literature, several researchers [83], [124] has been conducted involving co-precipitation, thermal breakdown, micro-emulsion, hydrothermal synthesis, synthesis with biological organisms (fungi and algae), synthesis with plant materials, and so on [87], [119]. These techniques have advantages and disadvantages. Biological techniques, on the other hand, are strongly recommended due to their non-toxic, environmentally friendly process and chemicals and have proven minimal inhibitory influence on biocatalysts especially during the biofuel generation [83], [123]. Furthermore, nanoparticles derived from biomass plants [119] and microorganisms [123], [125] are favoured because they consume less energy and so inexpensive.

In synthetic technique, semiconductor quantum dots (QDs) NPs with extremely high photocatalyst that have attracted considerable interest in different field of engineering [78]. This methanol diffusion and diameter precipitation procedure is evaluated until the size distribution cannot be narrowed any more, as evidenced by a refinement of the optical absorption spectrum [78]. A similar approach was used, along with a suitable organometallic compound, to coat the native CdSe core with another semiconducting with greater band gaps. **Figure 8** illustrates the TOP/TOPO production technique and surface modification of NPs using cadmium oxide (CdO) as a precursor.

Consequently, researchers have found that the morphology and performance of these particles are also heavily influenced by the synthesis techniques. Therefore, [126] proposed a new technique for producing composite magnetic NPs with a gold surface, a silica core, and an electrostatic inner layer (**Figure 9**). Based on this work, in step 1, the positively charged amino-modified SiO particles are cross-linked with negatively charged hydrophilic Fe_3O_4 NPs (15±1 nm) water-soluble magnetite NPs that is super paramagnetic. As a result, SiO_2-Fe_3O_4 NPs nanoparticles are generated (see step 2). Because of the reduction of chloroauric acid (HAuCl), the Au NP seeds (1-3 nm) function as colloidal particles for the development of subsequent Au-shell surrounding the SiO_2-Fe_3O_4 NPs [126]. This innovative strategy improved NPs synthesis as well as its application performance.

5.3. *Nanoparticles Stability in Bio-fuel*

Nano-fuel has a high surface energy because of its immense surface area, which promotes coagulation and the formation of micro-sized particles prior to deposition. A more stable and uniform nanofluid mix is required for its suitability in various technical applications. The stability of a nanofluid influences both its performances as a heat carrier and its thermos-physical properties [79]. Many methods for improving the stability of NPs in a base fluid have been documented in the literature, such as ultrasonication techniques, surface modification, surfactant incorporation and manipulation of pH-value.

According to Hong *et al.*, [127], the stability of nanofluids can be increased using longer sonication period. Their studies revealed that extending the sonication period minimizes particle agglomeration. Subsequently, Ali and Salam [128] discovered comparable results in their

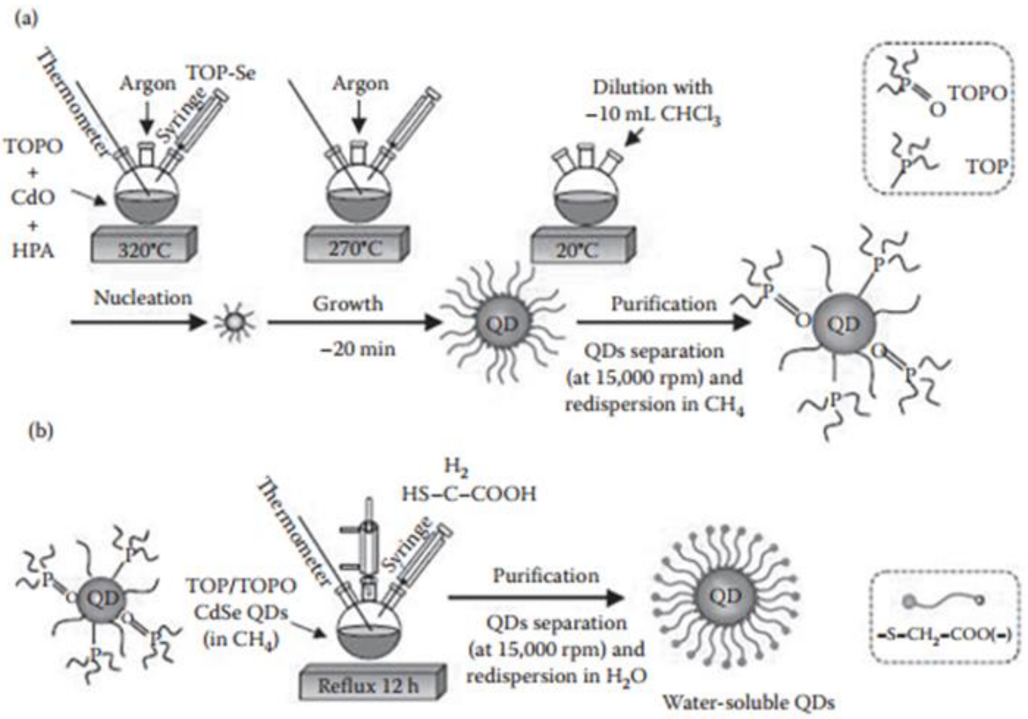

Figure 8. Synthesis approach and surface-modification of (CdO) as precursor: (a) NPs synthesis and (b) surface modification [78]

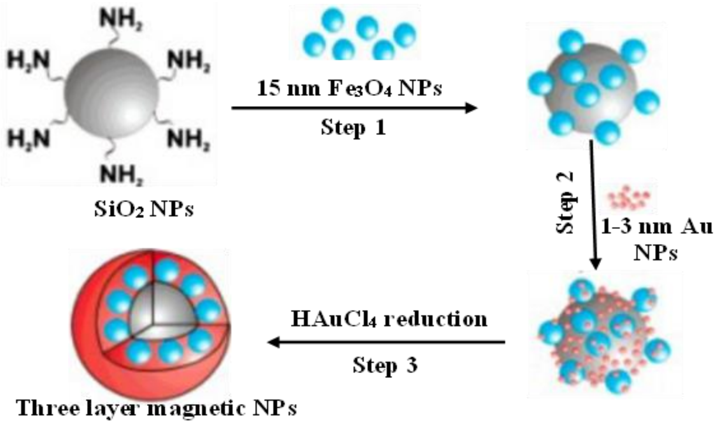

Figure 9. Synthesis technique steps for three-layer magnetic SiO_2–Fe_3O_4 NPs formulation through $HAuCl_2$ reduction [126]

experiments; the longer sonication times, the better NP stability in both trials. According to Ruan *et al*., [129] employing ultrasonic to break down particle buildup for possible agglomeration support stability and improve NPs dispersion in the base-fluids was advantageous. The findings showed that thermal physicochemical properties of MWCNT-ethylene glycol nanofluid are greatly dependent on the length of ultrasonication. Furthermore, Opia *et al*., [130] studies on the effect of surfactants on particle stability in nanofluid and performance showed a similar outcome on the physiochemical alteration of the formulation, leading to excellent performance.

Surfactants and additives are commonly used to address the problem of nanoparticle aggregation (**Figure 10**). These are chemical compounds that are added to NPs to reduce surface tension and improve particle absorption [131]. Surfactants are utilized in some works to slow down the deposition rate; nevertheless, in some works, an appropriate surfactant must be used with the NPs [132], [133]. According to [134] theory, the quantity of van der Waals pull and electrical repulsive forces that occur among molecular/ionic particles when they are pulled onto one another due to Brownian motion is used to calculate particle's stability in solution. As a

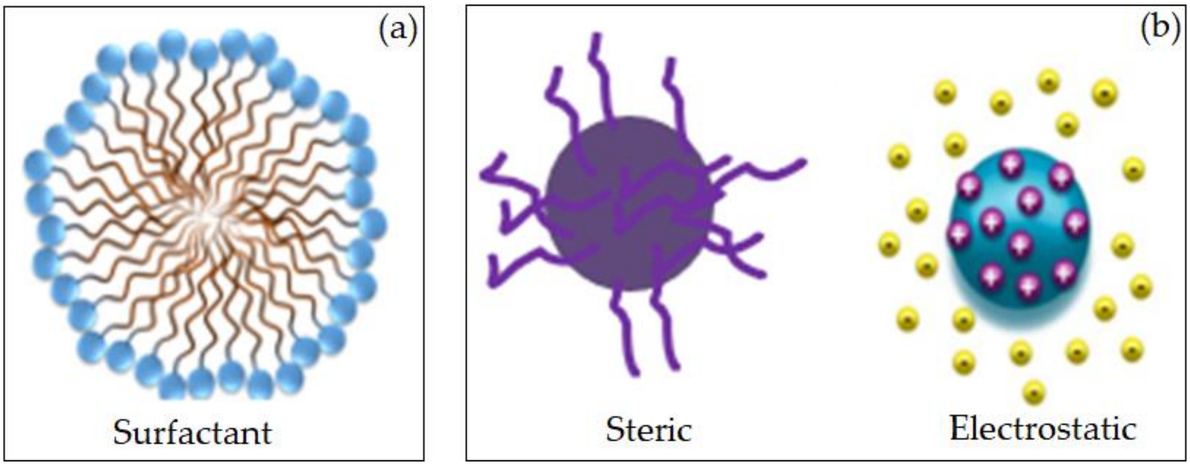

Figure 10. (a) Structure of surfactant's and (b) Colloidal stabilization of nanofluids [89]

result, when the pulling force surpasses the repelling force, the two particles clash and the suspension become unstable. Suspensions will be stable if the particles have a stronger repulsive force. Nanofluids or colloids must be stable due to the dominance of repulsive forces between particles. Based on the kind of repulsion (steric repulsion and electrostatic repulsion), the basic processes that determines the colloidal stability are classified into two groups [89], that operates based on the amphipathic tendency.

5.4. Operation of NPs in Biofuel during Combustion

The injection system (injection timing, injection pressure, injection rate), fuel spray system (atomization, angle of injection and spray penetration), and combustion formation (ignition delay, exhaust temperature, in-cylinder temperature and pressure) all influence engine combustion characteristics in terms of performance and emissions [135]–[137]. The utilization of nano-fuels can affect major changes in these processes particularly due to: (1) the activities and transformations of nanoparticles, (2) changes in the physicochemical parameters of the biofuel such as modification of heating value, cetane number, flash point, viscosity, specific gravity and others [138]. Considering combustion ignition delay and cetane number are interdependent, the incorporation of nanoparticles to the bio-based fuel may result in shortening ignition delays as a result of higher cetane numbers [2], [139], [140]. Moreover, changes caused by nanoparticles are affected by the type of combustion engine used. This means that a vast number of influencing parameters should be highlighted while assessing nano-fuel impacts. In this context, it is hard to draw reliable conclusions based on data presented from varied literature [140].

Praveen *et al.* [2] investigated the effect of TiO_2 NPs in Calophyllum inophyllum biodiesel on fuel characteristics, combustion behaviour, engine performance, and emissions. They discovered that adding TiO_2 NPs to the biodiesel enhanced its kinematic viscosity, calorific value, and cetane number as higher cetane numbers improved BTE due to increased oxygen abundance. The NOx and HC emissions were reduced when nanoparticles were added to the plain biodiesel. Similar outcomes were obtained in research on the impact of TiO_2 NPs in Calophyllum inophyllum biodiesel [2]. Similarly, Yusof et al., [93] employed CeO_2 nanoparticles as a fuel additive to lower emissions from an ethanol-gasoline blend. The thermal brake performance of NPs using biofuels was improved. However, the results showed that CO_2, HC, and NOx emissions all fell drastically in the test, with a significant rise in O_2 content in all mixes.

Do *et al.*, [141] used a four-stroke cycled, single-cylinder CI engine for testing the effects on different TiO_2 nanoparticles in terms of emission behaviour of diesel fuel. The results showed an increment of calorific values by 0.4 and 0.68% under 50 and 100 ppm, respectively. Similarly, the flashpoint of biodiesel was increased by 4.4 and 6.67 % under 50 and 100 ppm, respectively. Inclusion of TiO_2 to diesel fuel minimized CO, HC, NOx, and smoke emissions significantly. Research with CeO_2 has been used as an oxygen absorber, thus inducing oxidation of hydrocarbons (HCs) while decreasing nitrogen dioxide emissions [93].

Subsequently, Narasiman *et al.* [113] used soybean methyl ester (SOME) biofuel to investigate the impacts of CeO_2 NPs as an additive in diesel and sardine oil methyl ester. The mass fracture of the NPs utilized was 25 parts per million. A single-cylinder, four-stroke cycle, air-cooled diesel engine was utilized at constant speed with varying loads in all of the samples tested. According to the test results, the NPs might be utilized as a desirable additive in diesel and biodiesel to accelerate complete combustion of fuel and decrease exhaust emissions. The findings are consistent with prior study [2], [81]. Conversely, a comprehensive review of the available test results allows researchers to draw some broad conclusions about the key components for maximum engine performance, which are described below.

5.4.1. *Brake Thermal Efficiency, BTE (η_{th}).*

Many researches [112], [142], [143] investigated the improvement of BTE of a CIE by nanoparticles incorporation in fuels. According to their findings, appropriate nanoparticles aided in facilitating complete combustion due to increase in-cylinder temperatures, a faster evaporation rate, and a shorter ignition delay. This is nearly identical to the presentation given in a similar location [11], [110], [144]. Similarly, Mohamed et al., [145] discovered comparable results in their examination of pure oil fuel and the introduction of Al_2O_3/TiO_2. The outcome demonstrated that Al_2O_3 /TiO_2 nano-lubricants showed improvement on brake thermal efficiency by 3.9–8.6%, respectively, when compared to reference oil fuel. The mentioned effects are significantly amplified suitable nanoparticles through better atomization [138], [146] and improved catalytic activity [72], [147]. According to Devarajan *et al.*, [148] based on testing of the BTE, all fuels improved as the engine load increased. As shown in **Figure 11a**, the BTE of neat neem oil biodiesel is lower than that of diesel at all engine loads. In addition, as shown in **Figure 11b**, the SFC of neat diesel was lower than that of the other samples. This is could be attributed to the fact that diesel has a higher heating value and a lower viscosity compared to neem oil biodiesel [149].

5.4.2. *Effective Power (Pε)*

When suitable NPs are used in fuels, the effective power (Pe) is not significantly changed. Despite this, a slight increase in maximal effective power (Pe,max) was observed [77]. As presented with the addition of NPs, that either trigger micro-explosions, increasing the overall calorific value of nano-fuels [150], or lead to increased nano-fuel viscosity and density, therefore reducing pump leakage [93].

5.4.3. *NOx Emissions*

It is commonly known as the most harmful emission pollution. Based on prior research, about one-third of the studies on fuel incorporated nanoparticles demonstrated increases in NOx emissions, while the other two-third showed slight to lower decreases in NOx emissions. Moreover, parameters that influences the most are interactions between adiabatic flame temperature, cetane number, enthalpy of vaporisation, oxygen mass fraction in a nano-fuel, ignition delay, and amounts of nano-fuel consumed in premixed and mixing-controlled combustion phases. It is also worth noting that the effect of nano-fuels on NOx emissions is highly dependent on engine type, specific engine setup settings, and operating state.

Nanoparticles that increase the rate of heat release, in-cylinder pressure, and temperature may increase NOx emissions [112]. These are affected due to the catalytic effects of NPs [77], [148], which accelerates the combustion process [148]. In contrast, if the NPs heat sink effect is significantly stronger, NOx emissions can be reduced [77]. In addition, other researchers indicated that NOx reduction was induced by the catalytic activity of NPs, that allows NOx to be converted into oxygen and N_2 during engine operation [151]. Consequently, NPs can reduce in-cylinder temperature because of NOx emissions, while raising the cetane number of nano-fuels and decreasing the amount of fuel consumed during the premixed combustion phase [95], [118].

5.4.4. *HC Emissions*

The addition of different NPs to different base fuels often reduces HC emissions. Because of their oxygen concentration, NPs have a significant impact on reducing HC emissions when used as oxidation catalysts [11], [152]. Also, accelerated combustion due to the catalytic actions of NPs [72], [77] and improved secondary atomization [138]. However, when coupled with specific base fuels, NPs with carbon in their elemental composition can also increase HC emissions [115]. According to Devarajan *et al.*, [148] it can be observed that HC emission formations were lesser at lower brake power on all the tested fuels with NPs while pure bio-fuel and diesel produced higher values as shown in **Figure 11c**.

5.4.5. CO Emissions

In most circumstances, the addition of NPs reduces CO emissions, however it may potentially have negative implications. NPs with improved catalytic activity [153], improved its activity as oxidation catalyst, capable of transforming CO into CO_2 during the combustion process [142], and NPs that promote secondary atomization, all lead to CO emission reduction. CO emission may increase if NPs composed of oxygenic functional groups over carbon quantum dots [77]. As illustrated in **Figure 11d**, pure bio-fuel and diesel yielded higher CO emission but inclusion of 10 ppm Ag_2O reduced CO more than with 5ppm Ag_2O concentration [148]. **Table 2** shows the summary of some results of nano-fuel during combustion.

6. Challenges and Opportunities

The challenges include confronting several commercialization challenges, such as consistent feedstock supply, innovation management, and affordability. This usage of more extensive supply chain and storage facility raises the risk of feedstock degradation and warehouse investment expenses [17], [18]. The raw material issue could be solved by implementing a pre-treatment technology that decreases the likelihood of degradation and adjusting the procedure of incorporating the feedstock based on its availability. Challenges connected with nanofluid solubility that result in agglomeration [154], [155]. Thus, the usage of nano-fuels requires careful consideration; in particular, greater study into the application of more effective surfactant additives [156] is required.

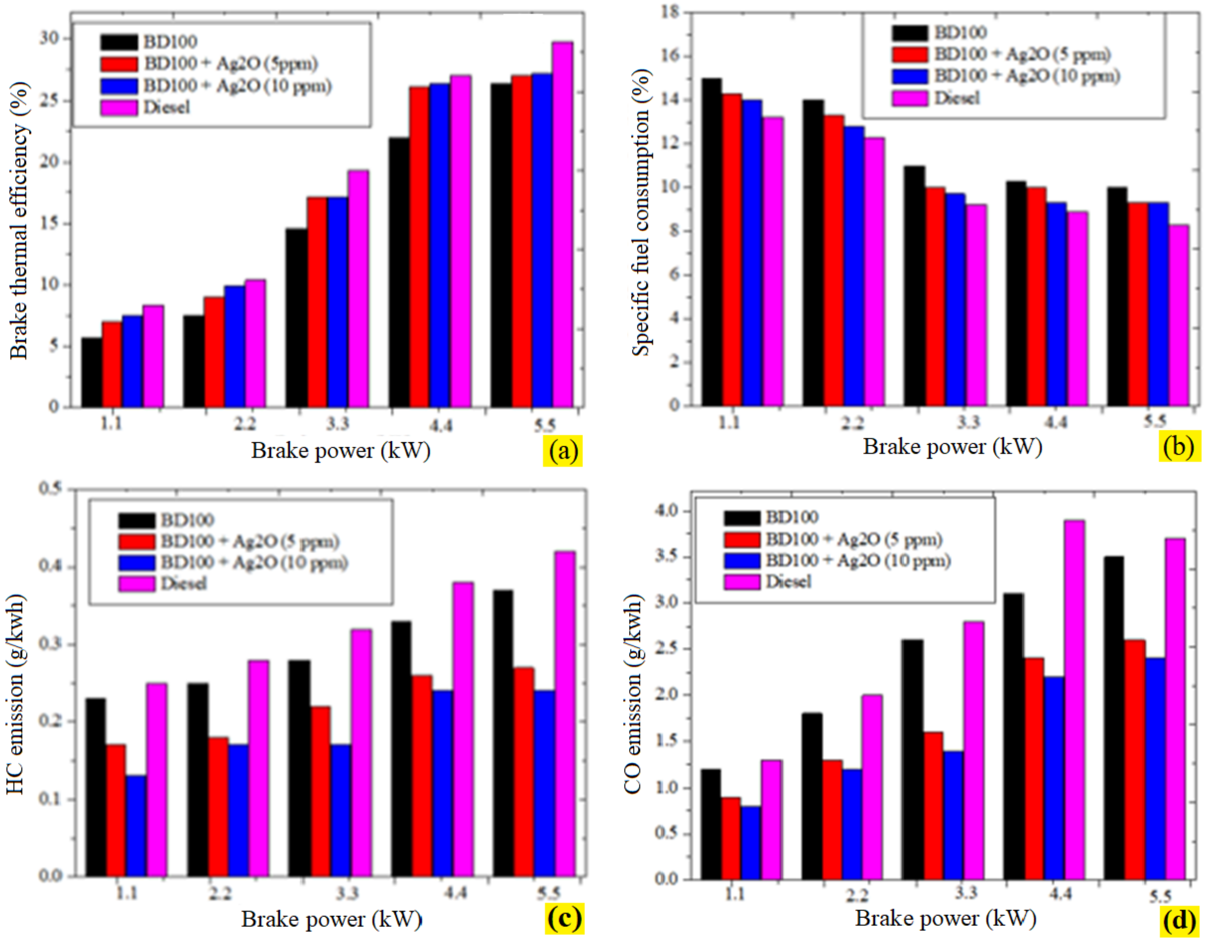

Figure 11. (a) Brake thermal efficiency; (b) Specific fuel consumption; (c) HC emission; (d) CO Emission; Performance of VCR Engine running with Lemon Grass Oil and Methanol Mixed with Diesel [148]

Table 2. Summary of some results of nano-fuel during combustion

Nanoparticles	Base fuel used	Amount of NPs	Emission result	Engine performance	Ref.
CeO_2	Neat biodiesel (lemongrass oil)	50 ppm	Significant reduction on smoke, CO, NOx, HC	Produced higher BSFC and BTE compared to pure B20	[117]
CeO_2 & ZnO	Neat biodiesel (lemongrass oil)	30 ppm	Emission of CO, NOx and HC were reduced	BSFC were lowered slightly but increased BTE	[142]
CeO_2	Biodiesel (Karanja oil)	40 and 50 ppm	Lowered formation of NOx, CO, HC and CO_2	Low BSFC recorded	[157]
Al_2O_3	Diesel fuel	25, 50 & 100 ppm	Reduced NOx, smoke and CO emission in all application	Increased BTE of the operation	[116]
Al_2O_3	Diesel fuel	1wt% & 1.5 gl	Minimized HC content, lowered NOx in all loads studied	Improved BTE of the engine	[158]
Al_2O_3	Diesel fuel	30 & 60 ppm	Emission HC under Al_2O_3 + SiO_3 were reduced by 1.76% with no change in NOx, but increased CO, CO_2 with Al_2O_3 + CNT	Lower BSFC, higher BTC in all cases, also CNT improved BSFC by 19.85%	[159]
Al_2O_3	Zizipus jujube methyl ester blended fuel	25 & 50 ppm	Lowered HC, CO and smoke for the two used concentrations	Better performance under 100 ppm on BTE & BSFC than 25 ppm	[160]
CeO_2 & ZnO	Biodiesel (Grapeseed oil)	100 ppm	CeO_2 and ZnO reduced NOx emission by 74.16% and 80.06%, respectively	CeO_2 & ZnO increased BTE by 1.4% & 1.7%. Decreased BSFC of CeO_2 to 0.30 kg/kWh while ZnO reduced by 0.29 kg/kWh.	[114]
CeO_2	SOME oil biodiesel	25 ppm	Harmful emission of exhaust reduced	Lower BSFC and higher BTC	[113]
CeO_2, ZrO_2, TiO_2	Garcinia gummi-gutta biodiesel	25 ppm	Emissions lowered in all samples	Enhanced BTE performance	[95]
CeO_2	Ginger grass oil	30 ppm	Reduced smoke, NOx and CO emission	Lower BSFC and higher BTC	[153]
CeO_2 & $CeO_{0.5}CO_{0.5}$	Waste cooking oil biodiesel	100 ppm	Reduced NOx emission by 15.4%, but no reduction on HC	Improved BTE and BSFC under low loads	[161]
Al_2O_3	Rubber seed oil	10, 15, 20 ppm	Emission reduction of NOx, CO, smoke and HC were 7.76%, 6.09%, 6.2% and 12.24% respectively	Lower BSFC, enhanced BTC and brake power in all samples	[92]
Al_2O_3	Jatropha biodiesel oil	10, 30, 60 ppm	Harmful emissions reduced significantly. Little increase in Nox under CeO_2	Lower BSFC and higher BTE at higher engine load	[162]
Al_2O_3	Soybean biodiesel	10, 15, 20 ppm	Higher CO emission with 20 ppm, higher NOx with 10ppm, compared to others	Lower BSFC and higher BTE under higher load	[163]
Al_2O_3	Pongamia methylester	50, 100 ppm	Lower formation of NOx, CO and HC	Enhanced BTE	[164]
Al_2O_3	Petrol diesel	25, 50 ppm	Lower smoke, HC, CO, with little NOx emission	With 25 ppm, BSFC were similar to pure diesel fuel. Reduced BSFC by 6% using 50 ppm, while BTE increased	[120]
TiO_2	Corn methyl ester biodiesel	100, 200, 300 ppm	Lower NOx, CO, CO_2, smoke and HC emissions	Higher BTE and heat release	[165]
TiO_2	Canola biodiesel	300 ppm	Reduced gas emission at the exhaust	Enhanced efficiency of the combustion	[143]
TiO_2	Cottonseed oil methyl ester	20 and 40 ppm	CO_2 and NOx emission higher, with lower HC, CO and smoke opacity	Increased heat release and higher BTE with lower BSFC	[166]
TiO_2	Mustard oil methyl ester	50, 100,150, 200 ppm	Reduced HC, smoke and CO emission with 50 and 100 ppm	Higher BTE and heat release	[167]

Though several nano-fuels have demonstrated enormously intriguing potential benefits, some significant challenges must be solved before nano-fuels can be commercialised. Again, due to the multipurpose of nano products and demand, nanotechnology research is capital intensive [82]. More experimental and analytical research is needed on the primary complicated aspects influencing the effectiveness of nano-fuels, particularly the differences in emission values among the NPs under consideration. Therefore, it is critical to identify these factors, since there is currently a lack of unanimous among the findings obtained by different groups. Conversely, the increased viscosity generated by the use of some nano-fuels is a considerable drawback due to the required pumping force. Nano-fuels with low viscosity and high conductivity have a great deal of potential for increasing bio-fuel efficiency. One technique could be to change the interface properties of two phases to optimise the interaction of NPs and biofuels. Also, reviews of the toxicological consequences of nanoparticles used in nanofluids are conflicting. According to a pilot study [168], some NPs exhibit asbestos-like pathogenicity when they interact with the lungs and cause granulomas to grow on the lungs' mesothelium cells after being injected into mice's abdominal cavities within a week.

The Air Transport Action Group's goal of cutting carbon emissions by 50 % by the end of year 2050 create good fortunes for 1.5 Gbbl of aviation fuel per year. Many researchers are already intrigued in bio-jet fuel derived from abundant low-cost lignocellulose feedstock [169]. The use liquid biofuels as a fuel source can also result in the production of heat and electricity. In spite of this, the rate of consumption in this sector is relatively low because alternative sources of power are readily available. Butanol is a type of advanced biofuel that may be blended in any proportion with gasoline or diesel fuel. Compared to ethanol, butanol has a larger energy content and is less corrosive. Combining biodiesel with fatty acid methyl ester, often known as FAME, which provides characteristics that are comparable to diesel [60], [170], with diesel allows it to be used on ships and other combustions. In IC engines, combining up to 5-7% is effective with no engine modifications necessary. Since the cold flow qualities banned its use in particular places, this fuel suffers a considerable setback [93], [171]. These biomasses are affordable due to limited local demand, but the cost of collecting, sorting, and transportation are substantial. To demonstrate the sustainability of bioenergy, significant efforts have been made to construct distribution networks and establish business models. Bioethanol synthesis from agricultural residues using hydrolysis and fermentation processes is successfully implemented with an annual output capacity of 1 billion litres [169]. Despite this, the plant's production is significantly lower due to testing and optimization of process conditions. Currently, the acetone-butanol-ethanol (ABE) fermentation needs feedstock with a high sugar concentration [172], efforts should be aimed toward creating technology that produces butanol from low sugar feedstock, reducing feedstock prices.

7. Conclusions and Future Work

Over the last few decades, many remarkable features of biofuels and nano fuels have been revealed. This research provides an overview of literature advances in the domain of bio-fuels and the application of NPs as enhancement additives, such as classifications, bio-fuel modification, combustion effects, nano-fuel stability, and the distinctive performance of NPs as emission reduction additive, among other things. The study found that NPs reduced CO, CO_2, NOx, HC emissions in all of the analysed biofuels, except that CO and NOx increased by less than 20ppm and 10ppm, respectively, when tested on soybean oil. Thus, engine performance was improved with biofuel with NPs and pure diesel in comparison to pure bio-fuel, as a result of the lower of cetane number in pure bio-fuel, which NPs improves. Because of higher cetane numbers, the inclusion of suitable NPs can result in shorter ignition delays.

To the best of our knowledge, there has not been a significant amount of research on the thermal performance of nano-fuels at high temperatures, that could increase the spectrum of applications for nano-fuels, such as high-energy storage in ships and other high-energy storage systems. In contrast, high temperatures may speed the breakdown of surfactants used as dispersants in nanofluids, resulting in more foams. The structure and behaviour of new nanoparticles can be used to enhance and extend nanofuels research. As mentioned in recent work, 2D monatomic layer graphene is a feasible candidate material for improving the thermal conductivity of base biofuels. Furthermore, the morphology of the NPs additives is crucial for their qualities; hence, creating new nano-fuels manufacturing techniques with a controllable microscopic structure will be an exciting research endeavour [173]. Consequently, suspension stability is an essential consideration for various technical applications. The application phase change materials broaden the concept of nanofluids beyond simply increasing a fuel's thermal conductivity and therefore aids in improving nano-fuel performance especially from power production view point and emission reduction.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors readand approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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