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# A novel emulsion fuel containing aqueous nano cerium oxide additive in diesel–biodiesel blends to improve diesel engines performance and reduce exhaust emissions: Part I – Experimental analysis

Esmail Khalife [a,b,c], Meisam Tabatabaei [b,d,*], Bahman Najafi [a,*], Seyed Mostafa Mirsalim [e], Ayat Gharehghani [e], Pouya Mohammadi [b], Mortaza Aghbashlo [f,*], Akram Ghaffari [c], Zahra Khounani [b,d], Taha Roodbar Shojaei [g], Mohamad Amran Mohd Salleh [g]

[a] Department of Biosystems Engineering, Faculty of Agricultural Technology and Natural Resources, University of Mohaghegh Ardabili, 56199-11367 Ardabil, Iran
[b] Biofuel Research Team, Karaj, Iran
[c] Young Researchers and Elite Club, Boukan Branch, Islamic Azad University, Boukan, Iran
[d] Agricultural Biotechnology Institute of Iran (ABRII), Agricultural Research, Education, and Extension Organization (AREEO), 31535-1897 Karaj, Iran
[e] Department of Mechanical Engineering, Amirkabir University of Technology, 424 Hafez Avenue, P.O. Box 15875-4413, Tehran, Iran
[f] Department of Mechanical Engineering of Agricultural Machinery, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran
[g] Institute of Advanced Technology (ITMA), Universiti Putra Malaysia, Serdang, Malaysia

## HIGHLIGHTS

- Aqueous nano-emulsion of cerium oxide improved combustion quality.
- Impacts of low-level water containing cerium oxide in B5 on engine performance and characteristics were first investigated.
- bsfc of $B5W3_m$ was 5% and 16% lower than those of neat B5 and neat B5W3, respectively.
- $B5W3_m$ increased bte by over 23 and 11% compared with B5W3 and B5, respectively.
- $B5W3_m$ considerably reduced CO, HC, and $NO_x$ emissions by 51, 45, and 27% compared with B5W3, respectively.

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## ABSTRACT

Improving fuel combustion in engines and consequently reducing environmentally-unfavorable emissions is of prominent importance in addressing some of the main challenges of the current century, i.e., global warming and climate change. Fuel additives are considered as efficient way for improving fuel properties and to diminish engine emissions. In line with this, the present research was focused on the simultaneous application of water (3, 5, and 7 wt.%) and cerium oxide nano particles (90 ppm) as metal-based additive into biodiesel/diesel fuel blend (B5) and their impacts on the performance and emission characteristics of a single cylinder four stroke diesel engine were investigated. The findings revealed that the aqueous nano-emulsion of cerium oxide improved the overall combustion quality. More specifically, the brake specific fuel consumption (bsfc) of B5 containing 3% water and 90 ppm cerium oxide ($B5W3_m$) was measured 5% and 16% lower than those of neat B5 and neat B5 containing 3% water (B5W3), respectively. Moreover, the $B5W3_m$ fuel blend increased brake thermal efficiency (bte) by over 23 and 11% compared with B5W3 and B5, respectively. $B5W3_m$ also considerably reduced CO, HC, and $NO_x$ emissions by 51, 45, and 27% compared with B5W3. To the best of our knowledge, this is the first report exploring the impacts of low-level water containing cerium oxide in B5 on engine performance and emission characteristics.



## 1. Introduction

One of the major challenges faced by the transportation sector is to meet the increasingly stringent exhaust gas emission standards set to protect the environment and to reverse the

* Corresponding authors at: Biofuel Research Team, ABRII, Karaj, Iran (M. Tabatabaei).
*E-mail addresses:* meisam_tab@yahoo.com, meisam_tabatabaei@abrii.ac.ir (M. Tabatabaei), najafib@uma.ac.ir (B. Najafi), maghbashlo@ut.ac.ir (M. Aghbashlo).
*URL:* http://www.brteam.ir (M. Tabatabaei).

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unfavorable impacts of this sector on climate change. In fact, global transportation is responsible for more than 25% of the total greenhouse gases (GHGs) emissions. Improvements in engine technologies as well as exploring less polluting energy carriers have been among the main solutions constantly considered to overcome these challenges [1,2]. Biodiesel is the most extended alternative for diesel fuel offering unique advantages such as biodegradability and non-toxicity, inherent lubricity, low emission characteristics, as well as similar properties to those of mineral diesel fuel [3,4].

Biodiesel could be produced from various vegetable oils and animal fat feedstock [5]. However, waste oriented resources such as waste cooking oil (WCO) are more favorable from both economic and food security point of views [6,7]. The most commonly-practiced method for biodiesel production is alkali-catalyzed transesterification [8,9]. Transesterification is in fact an alcoholysis process (using methanol or ethanol) taking place in the presence of a basic catalyst (commonly NaOH or KOH) and through which triglycerides are converted into fatty acid methyl/ethyl esters [10–12].

Numerous studies exist on the exhaust emissions of neat biodiesel as well as various biodiesel/diesel blends when combusted in diesel engines [13–15]. Generally, these studies claim that the combustion of biodiesel and its blend led to decreases in unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) emissions while unfavorable increases in nitrogen oxides (NOx) were also observed compared with pure diesel fuel [4,16,17]. A large variety of fuel additives have been put to test over the last decades aiming to further decrease exhaust emissions caused by biodiesel-diesel blends and in particular to overcome the general deterioration in $NO_x$ emissions caused by biodiesel inclusion [8,9,18–21].

Among various fuel additives investigated, water addition has attracted a great deal of attention due to its remarkable impacts on diminishing $NO_x$ emissions [22]. Three strategies have been introduced for using water in internal combustion engine including water-diesel (or biodiesel-diesel) emulsion (WDE), inlet manifold water injection (or fumigation) and direct water injection into the cylinder [23,24]. Amongst these strategies, WDE is of more interest owing to this fact that its application not only could effectively diminish hazardous gaseous emissions but also requires no engine modifications [25–27]. More specifically, it has been well documented that the combustion of WDE fuels can efficiently reduce $NO_x$ and PM emissions simultaneously without causing significant increases in brake specific fuel consumption (bsfc) [25,28,29]. However, WDE combustion could reportedly increase the amount of HC emissions as a result of in-cylinder temperature reduction caused by high latent heat of vaporization of water [30]. In a study, Yang et al. investigated the performance and emission characteristics of a four cylinder turbocharged diesel engine and reported that the addition of 15% water into diesel fuel at full load and 3200 rpm engine speed reduced the exhausted $NO_x$ emissions by 30% while negligible increases in bsfc were observed [27].

Contrary to the above-mentioned studies, Liang et al. claimed that bsfc was increased by 12% when a diesel fuel emulsion containing 30% (v/v) water was used [31]. Similar findings were reported by Koc and Abdullah who studied water inclusion into biodiesel and found that 15% water in biodiesel increased bsfc by 7.2% at 2800 rpm. They also attributed increased CO emission and reduced $NO_x$ emission to the presence of water in the fuel blend [32].

Another group of diesel fuel additives increasingly used as combustion improver in diesel engines is metal-based additives [33–35]. The metals contained in the structure of these additives include manganese, iron, copper, barium, cerium, calcium, and platinum which offer catalytic activities during the combustion process. Metal-based additives could reportedly increase combustion quality simultaneously leading to reduced diesel fuel emissions and bsfc. In the year 2008, Kao et al. studied a diesel fuel containing nano aluminum and claimed higher heat release and lower $NO_x$ emission compared with neat diesel fuel [36]. In a more recent study, Venkatesan and Kadiresh investigated on the addition of 50 ml cerium oxide into diesel and biodiesel/diesel blend fuels and reported that bte and bsfc were improved while HC and $NO_x$ emissions were reduced compared with neat diesel fuel [37].

As mentioned earlier, using water in fuel blends could potentially result in increases in fuel consumption and some of emissions, e.g., CO. Therefore, in order to take advantage of the $NO_x$ reducing feature of WDE fuels, the combination of metallic-based additive with WDE has been put forth as an effective strategy to simultaneously overcome the disadvantages of using water in diesel engines and to covering its benefits [30]. For instance, Farfaletti et al. in the 2005 explored the effects of cerium oxide addition into a WDE fuel containing 20% water (v/v) and reported that in comparison with the WDE without metal-based additive, the new emulsion fuel could simultaneously reduce PM, CO, and HC [38]. Keskin et al. also argued that metal-based additives when reacting with water could result in the production of hydroxyl radicals which in turn led to lower soot oxidation temperature [39]. Recently, Vellaiyan and Amirthagadeswaran studied on the addition of 50 and 100 ppm zinc into diesel fuel containing 10% water, and reported reductions in HC, CO, and $NO_x$ emissions [40].

As mentioned above and to the best of our knowledge, the studies conducted on the combined application of water and metal-based additives in diesel fuel are only limited to high water addition levels, i.e., >5%. Moreover, little information is available on the impact of nano cerium oxide addition into water-biodiesel-diesel emulsion (WBDE) blends on engine performance and emissions characteristics. Therefore, the present study was set to investigate the engine performance and emissions features of aqueous nano cerium oxide (90 ppm) addition into B5 containing low-level water (3, 5, and 7% wt.) using a single cylinder diesel engine.

## 2. Material and methods

### 2.1. Biodiesel production

Biodiesel production was carried out by transesterification of pre-treated WCO with methanol and in the presence of potassium hydroxide (KOH) as catalyst in a stirred tank reactor at 60 °C for 1 h. After the reaction was completed, the mixture was allowed to settle for 1 h in order to separate methanol–biodiesel fractions by gravity. The acid value of the bottom layer was then measured and if it was at above 0.5 mg KOH/g, the pretreatment step was repeated before the transesterification reaction. The resultant biodiesel was washed three times. Water consumption throughout the washing and purification steps to remove residuals was minimized by following the method described by Jaber et al. [41]. Some of the properties of the produced WCO biodiesel were bioprospected based on the fatty acid composition profile of the oil by using "Biodiesel Analyzer© Ver. 1.1" (available on "http://www.brteam.ir/biodieselanalyzer") [42].

### 2.2. Fuel samples preparation

Three different levels of water (i.e., 3, 5, 7% wt.) with and without 90 ppm cerium oxide were emulsified in 1 L of B5 (labeled as B5W3, B5W5, B5W7, B5W3$_m$, B5W5$_m$, and B5W7$_m$, respectively). Emulsification of water and cerium oxide in B5 was achieved by including 75 ml of a 1:2 blend of two known surfactants of Tween 80 and Span 80 (Merk, Germany) into B5 prior to the addition of

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