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Effect of Oxy-hydrogen Enrichment into Water-in-Biodiesel Emulsion Towards Performance and Exhaust Emissions of a Diesel Engine

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ABSTRACT

This study aims to evaluate the combined effect of water-in-biodiesel emulsions (WBE) and oxy-hydrogen (HHO) enrichment on diesel engine performance and emissions. Experiments were conducted on a single-cylinder diesel engine fueled with B35 (35% biodiesel–65% diesel), WBE5 (5% water-in-biodiesel emulsion), and their HHO-enriched blends under 1–4 kW loads. Engine performance was assessed through brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), and exhaust gas temperature (EGT), while emissions of NOx, CO, and CO_2 were measured. Results show that WBE5 reduced NOx emissions by up to 30.2% compared with B35 and improved BSFC by 6.2% and BTE by 8.4% at 2–3 kW loads. However, CO emissions increased by about 18% due to lower combustion temperatures. HHO enrichment improved BSFC and BTE at light loads (1–2 kW) by up to 2% and decreased CO emissions through enhanced oxidation, but its influence on NOx was minimal and diminished at higher loads. Overall, WBE–HHO dual-fuel operation provides partial advantages, particularly under light-to-medium loads, offering a feasible pathway toward cleaner and more efficient diesel engine operation without major modifications.

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1. INTRODUCTION

Diesel engines are major contributors to harmful emissions, particularly nitrogen oxides (NOx) and particulate matter (PM), both of which are strongly linked to air pollution and global warming. In response to these concerns, alternative fuels such as biodiesel and water-in-biodiesel emulsions (WBE) have gained significant attention as substitutes for conventional diesel. Biodiesel, derived from renewable sources such as vegetable oils and animal fats, has been shown to reduce carbon monoxide (CO), unburned hydrocarbons (UHC), and PM emissions compared to fossil diesel (Hamasaki *et al*., 2002; Jazair *et al*., 2007; Reham *et al*., 2015). Its inherent oxygen content enhances combustion efficiency and suppresses particulate formation. However, biodiesel suffers from drawbacks such as higher viscosity and lower volatility, which can cause fuel system issues and incomplete combustion, particularly under cold conditions.

To address these limitations, WBE has emerged as a promising alternative. Formed by dispersing water into biodiesel with surfactants, WBE creates a stable heterogeneous mixture that improves combustion and emission characteristics. The presence of water lowers combustion temperatures, thereby suppressing NOx formation, which predominantly occurs under high-temperature conditions (Elsanusi *et al*., 2017; Tamam *et al*., 2025). However, this cooling effect may also increase CO and UHC emissions, particularly at low loads, since effective CO oxidation typically requires temperatures above 1400 K (Tamam *et al*., 2025; Kapadia *et al*., 2019).

Experimental studies with varying water concentrations in WBE (5%, 10%, 15%, and 20%) have demonstrated substantial reductions in NOx and PM across blends (Ithnin *et al*., 2015). Performance tests further showed that even without surfactants, emulsions enhanced engine behavior, with a 3.59% increase in brake thermal efficiency (BTE) and a 3.89% reduction in brake specific fuel consumption (BSFC) compared to diesel (Ithnin *et al*, 2018). Stable emulsions sustained these improvements, achieving a 4.19% decrease in BSFC and a 3.92% increase in BTE relative to neat biodiesel (Sugeng, 2020). Moreover, combustion studies using different water sources—tap, rain, and seawater—reported NOx reductions of 32%, 29%, and 19%, respectively (Ahmad *et al*., 2018).

Parallel to these developments, oxy-hydrogen (HHO), a mixture of hydrogen and oxygen produced by electrolysis, has been proposed as a supplementary fuel for compression-ignition engines. Its enrichment raises the oxygen concentration inside the combustion chamber, improving oxidation and combustion completeness (Masjuki *et al*., 2016). Previous studies demonstrated that dual-fuel engines operating with biodiesel–diesel pilot fuel and inducted HHO reduced CO emissions by 33% (Paparao & Murugan, 2022). Hydrogen and HHO enrichment have also been shown to enhance performance and combustion characteristics while lowering HC and CO emissions (Vellaiyan, 2023; Mahdi *et al*., 2025; Rao *et al*., 2024), with reported gains of 5.5% in BTE, 5.95% in maximum cylinder pressure, and 7.6% in maximum heat release rate compared to diesel (Rao *et al*., 2024). When combined with WBE, HHO enrichment achieved a 6.8% increase in BTE at a 1 kW load (Saputro *et al*., 2025). Furthermore, the addition of nanomaterials has been shown to improve thermal properties, evaporation, and heat transfer of blended fuels (El-Shafay *et al*., 2025).

Despite these benefits, challenges remain in utilizing HHO as a supplementary fuel. Its high flame speed can elevate in-cylinder temperatures, leading to increased NOx emissions (Subramanian & Thangavel, 2020). In addition, HHO's high auto-ignition temperature and unsuitability as a sole fuel for compression-ignition engines require precise blending control to prevent pre-ignition and knocking. Its production through electrolysis, often involving potassium hydroxide (KOH), also presents safety, energy efficiency, and integration concerns.

The combined use of WBE and HHO offers both opportunities and challenges. WBE lowers combustion temperatures and suppresses NOx, whereas HHO enrichment enhances combustion efficiency but may promote NOx formation. Although biodiesel, WBE, and HHO have been extensively studied individually, limited research has investigated their combined application under practical engine operating conditions.

Therefore, this study aims to evaluate the dual-fuel potential of WBE enriched with HHO in a single-cylinder diesel engine. The experiments were conducted using B35 (35% biodiesel–65% diesel), WBE5 (5% water-in-biodiesel emulsion), and their HHO-enriched blends at different engine loads (1–4 kW). Performance indicators such as brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), and exhaust gas temperature (EGT), along with emissions of NOx, CO, and CO_2, were measured and analyzed. The novelty of this work lies in systematically examining the trade-offs between WBE's NOx reduction capability and HHO's combustion enhancement under dual-fuel operation, providing new insights into the feasibility of achieving cleaner and more efficient diesel engine performance without engine modification.

2. METHODS

2.1. Test Fuels

The base fuel, B35, consisted of 35 vol% palm stearic biodiesel supplied by Pertamina Indonesia blended with conventional diesel. The WBE5 fuel was prepared by adding 5 vol% tap water into B35 and homogenizing the mixture using a Misonix S-4000 Ultrasonic Processor (600 W, 20 kHz) in the presence of surfactants. Tween 80 (HLB 15) and Span 80 (HLB 4.3), both obtained from Merck, were combined to achieve a hydrophilic–lipophilic balance (HLB) value of 8 at a total surfactant concentration of 2%. This value was combination provides optimal stability.

The HHO gas was generated using an OGO-GW25 electrolyzer. In this system, a potassium hydroxide (KOH) electrolyte solution passed through a dry cell composed of 316L stainless steel plates to produce the gas. The generated HHO then flowed through a bubbler tank and a filtration tank to ensure gas purity before entering the engine. A flame arrestor was installed between the filtration tank and the engine to prevent flashback, ensuring safe operation.

For testing, both B35 and WBE5 were enriched with 0.2 L/min of HHO, denoted as B35+HHO and WBE5+HHO, respectively. The physicochemical properties of B35 and WBE5 are summarized in **Table 1**.

Table 1. Fuel properties of test fuels.

Properties	Units	B35	WBE5
Calorific Value	MJ/kg	43.28	41.14
Density (15°C)	kg/m^3	850	858
Viscosity (40°C)	mm^2/s	3.59	4.03
FAME Content	% v/v	35.26	-
Flash Point	°C	82.5	102
Pour Point	°C	3	6

2.2. Experimental Setup

Experiments were conducted using a FIRMAN FDG7800ECA diesel generator with a rated capacity of 4.5 kW. The generator was powered by an 186FA diesel engine, a four-stroke, single-cylinder, air-cooled, direct injection unit with a displacement of 0.418 L, a compression ratio of 19:1, and a rated speed of 3000 rpm. A brush-type alternator was coupled to the engine to apply the required loads.

All tests were performed at a constant engine speed of 3000 rpm under varying load conditions. Performance parameters including brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) were evaluated across loads from 1 to 4 kW. Simultaneously, exhaust gas temperature (EGT) and gaseous emissions (NOx, CO, and CO_2) were measured over the entire load range (0–4 kW). A schematic diagram of the experimental setup is shown in **Figure 1**.

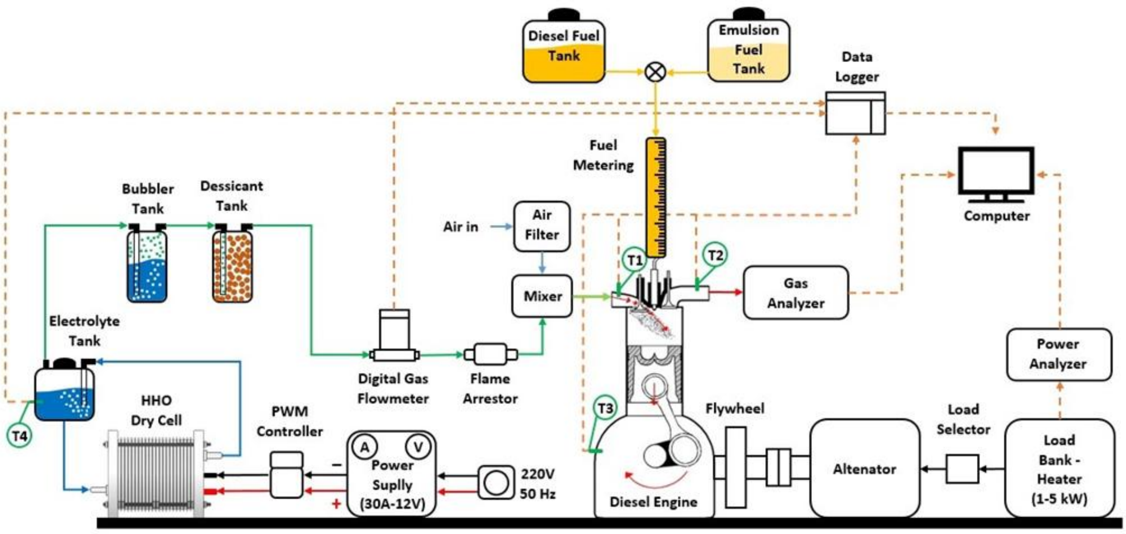

Figure 1. Schematic diagram of the experimental setup.

3. RESULTS AND DISCUSSION

3.1. Engine Performance

As illustrated in **Figure 2**, B35 exhibited the highest BSFC across all load conditions, despite possessing a higher calorific value (43.28 MJ/kg) and lower viscosity (3.59 mm^2/s). This behavior can be attributed to its relatively high density (850 kg/m^3), which leads to incomplete atomization and, consequently, higher fuel consumption per unit of power output. At a 2 kW load, the BSFC of B35 was approximately 6.2% higher than that of WBE5.

The addition of HHO to B35 reduced BSFC by 1–2%, as the supplementary energy contribution from hydrogen partially offset the liquid fuel requirement. WBE5 consistently demonstrated lower BSFC compared to B35, highlighting the benefits of secondary atomization caused by water-induced micro-explosions, in agreement with previous findings (Ithnin *et al*., 2015; Ithnin *et al*., 2018; Sugeng *et al*., 2020; Ahmad *et al*., 2018). At light loads (1–2 kW), HHO enrichment further reduced the BSFC of WBE5 by up to 2.5%. However, at higher loads (3–4 kW), BSFC increased by 1–1.5% with HHO addition, likely due to the heat absorption effect of water evaporation, which disrupted combustion stability.

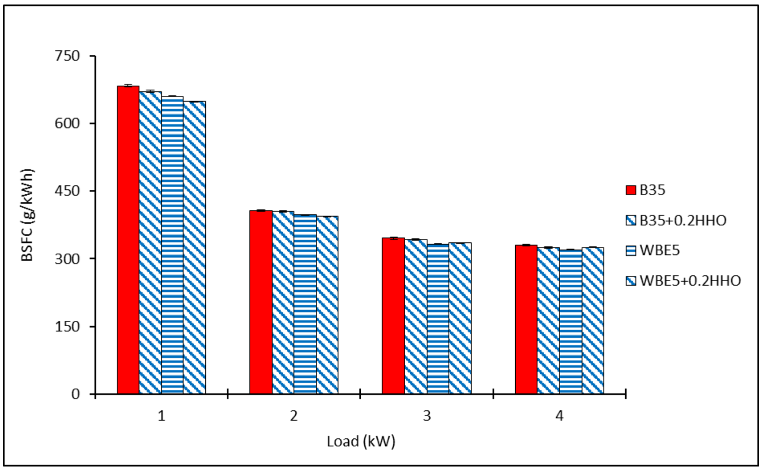

Figure 2. Variation of brake specific fuel consumption (BSFC) with engine load for different fuels.

As shown in **Figure 3**, B35 consistently exhibited the lowest BTE under all load conditions. At 3 kW, its BTE was 8.4% lower than that of WBE5. This reduction is attributed to the higher density and viscosity of B35, which hinder atomization and fuel–air mixing, thereby reducing combustion efficiency (Sahoo *et al*., 2009; Mofijur *et al*., 2013). The addition of HHO improved BTE for B35 by 1–1.5%, primarily due to enhanced oxidation from the increased oxygen concentration in the combustion chamber, although the calorific contribution of HHO was not included in the energy balance.

Among the tested fuels, WBE5 achieved the highest BTE across all loads, benefitting from micro-explosions that promoted finer atomization and more complete combustion. At light loads, HHO enrichment further increased the BTE of WBE5 by up to 2%. However, at higher loads, BTE decreased by approximately 1% with HHO addition, likely due to excessive water evaporation that interfered with flame propagation and combustion stability.

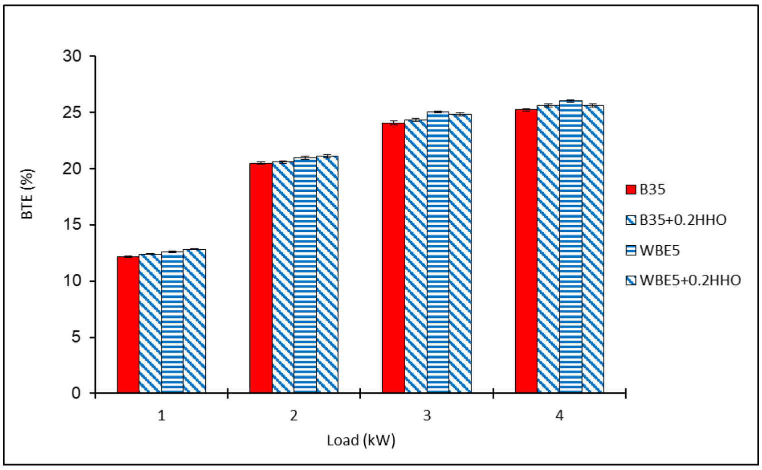

Figure 3. Brake thermal efficiency (BTE) at varying engine loads for different fuels.

As illustrated in **Figure 4**, WBE5 consistently produced lower EGT compared to B35 across all load conditions. At 3 kW, the EGT of WBE5 was approximately 11% lower than that of B35. This reduction can be attributed to its lower calorific value (41.14 MJ/kg) and the heat-absorbing effect of water evaporation, which reduced the overall combustion temperature. The addition of HHO to WBE5 resulted in negligible changes in EGT (<1%), indicating that the dominant cooling influence of water evaporation overshadowed the relatively minor thermal effect of hydrogen combustion.

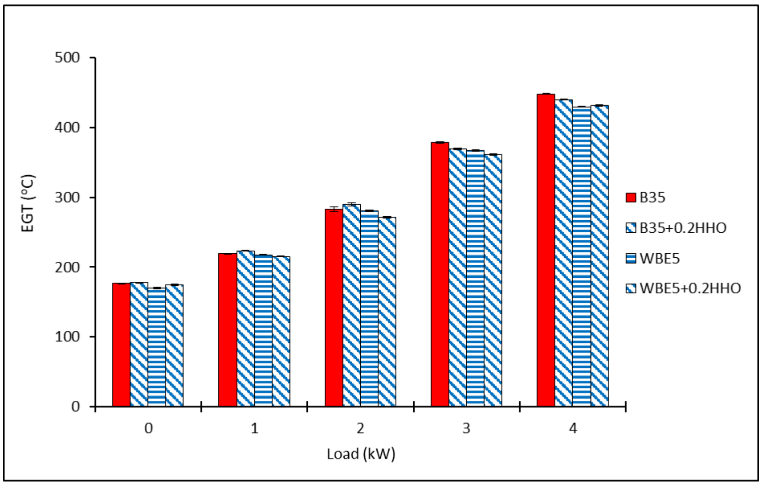

Figure 4. Exhaust gas temperature (EGT) variation with engine load for B35 and WBE5, with and without HHO enrichment.

As shown in **Figure 5**, NOx emissions increased with engine load for all fuels, primarily due to higher in-cylinder combustion temperatures. At 1 kW, the addition of HHO to B35 increased NOx emissions by 5.7%, reflecting hydrogen's faster flame propagation and elevated local flame temperatures [18]. However, at higher loads (3–4 kW), NOx emissions with B35+HHO were 2–3% lower than with B35 alone, indicating that thermal stabilisation at elevated loads mitigated the effect of HHO. WBE5 achieved the greatest reductions in NOx, lowering emissions by up to 30.2% compared with B35. This outcome is attributed to the reduced combustion temperatures caused by water evaporation. With WBE5+HHO, further reductions of 2–4% were observed at low loads, although this benefit diminished at higher loads.

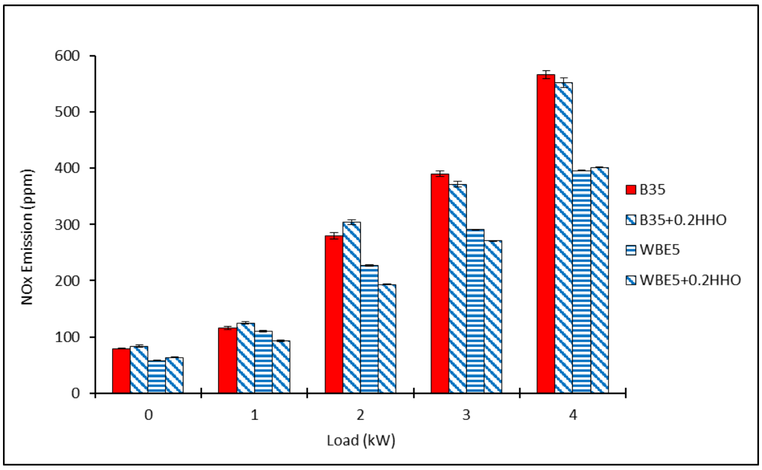

Figure 5. Nitrogen oxides (NOx) emissions versus engine load for B35 and WBE5, with and without HHO enrichment.

Figure 6 shows that WBE5 generated higher CO emissions than B35 across all engine loads. At 2 kW, CO emissions for WBE5 were approximately 18% higher than those of B35, primarily due to incomplete oxidation at reduced combustion temperatures. In contrast, HHO enrichment lowered CO emissions by 5–10% for both B35 and WBE5, attributed to the additional oxygen and faster oxidation promoted by hydrogen.

As illustrated in **Figure 7**, HHO enrichment also reduced CO_2 emissions at low to medium loads by 4–6%, reflecting the reduced demand for carbon-based fuel when hydrogen partially supplied the energy. However, at 4 kW, CO_2 emissions increased slightly (by 2–3%) relative to baseline conditions, likely due to enhanced oxidation of CO into CO_2 at elevated combustion temperatures.

Overall, WBE5 demonstrated improved performance and emissions characteristics compared with B35. BSFC decreased by up to 6.2% and BTE increased by up to 8.4%, while NOx emissions were reduced by as much as 30.2%. These benefits, however, were offset by higher CO emissions (up to 18% higher) caused by lower combustion temperatures. HHO enrichment contributed positively at low loads, improving BSFC and BTE by up to 2–2.5% and reducing CO emissions by 5–10%. Nevertheless, its advantages diminished at higher loads, with negligible effects on EGT and only limited influence on NOx.

These findings highlight that WBE–HHO dual-fuel operation offers partial but significant benefits, particularly under light-to-medium load conditions. However, further optimisation of fuel formulation and HHO supply rate is necessary to balance efficiency improvements with emission control.

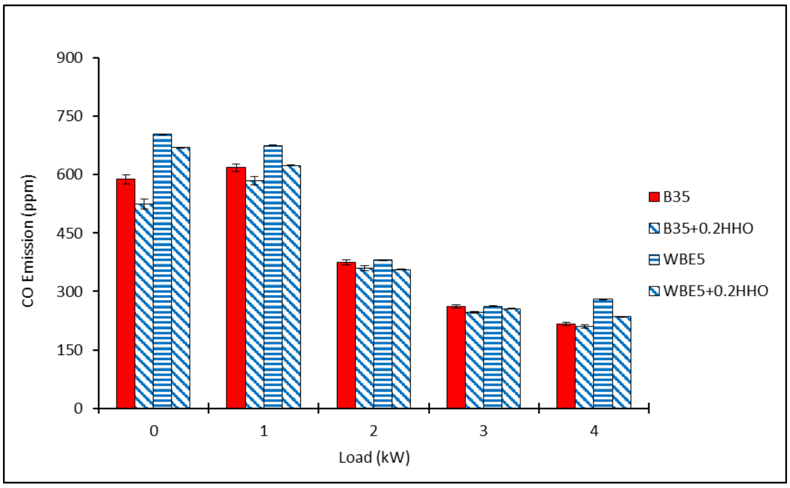

Figure 6. Carbon monoxide (CO) emissions versus engine load for B35 and WBE5, with and without HHO enrichment.

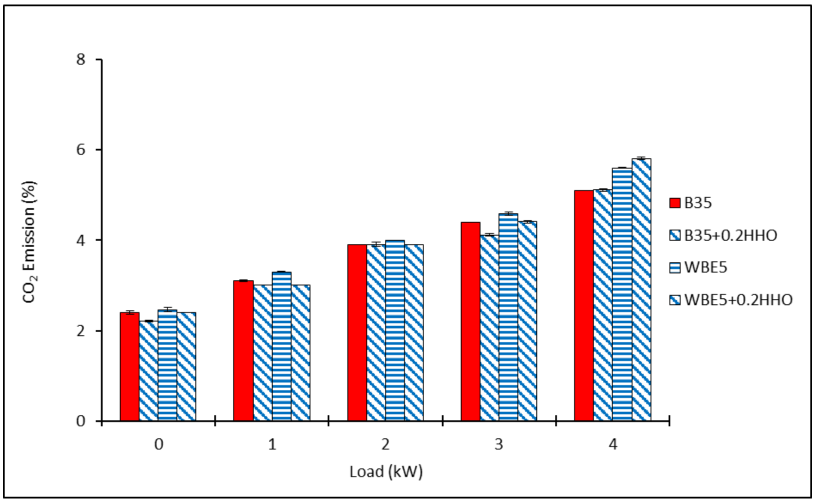

Figure 7. Carbon dioxide (CO_2) emissions versus engine load for B35 and WBE5, with and without HHO enrichment.

4. CONCLUSION

This study investigated the combined effects of water-in-biodiesel emulsion (WBE) and oxy-hydrogen (HHO) enrichment on diesel engine performance and emissions under varying load conditions. WBE enhanced fuel economy and combustion efficiency, achieving up to 6.2% lower BSFC and 8.4% higher BTE compared with B35, while reducing NOx emissions by as much as 30.2%. These benefits were offset by increased CO emissions (up to 18%) due to reduced combustion temperatures. HHO enrichment proved most effective at low loads, reducing CO by 5–10% and improving BTE by up to 2%, though its influence diminished at higher loads, with only marginal effects on NOx and negligible impact on EGT.

The findings demonstrate that WBE–HHO dual-fuel operation offers selective rather than universal advantages, with the greatest potential under light-to-medium load conditions. The novelty of this work lies in systematically assessing the combined application of WBE and HHO, which has been scarcely reported in previous studies. Future research should optimise WBE formulation and HHO flow rates, explore calibration strategies (e.g., injection timing and compression ratio), and conduct long-term durability assessments. With such optimisation, WBE–HHO dual-fuel systems could contribute to cleaner and more efficient diesel engine operation, supporting renewable fuel adoption and alignment with emission reduction targets.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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