Mechanical Technology and Engineering Insights

www.mtei.reapress.com

Mech. Technol. Eng. Insights . Vol. 3, No. 1 (2026) 29–38.

Paper Type: Original Article

Experimental Study on the Influence of Biodiesel Diesel Blends on Engine Performance and Exhaust Emissions

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Citation:

Received: 19 September 2025 *Revised: 25 November 2025* *Accepted: 27 January 2026*	Seyedi, M., & Nekoufar, K. (2026). Experimental study on the influence of biodiesel diesel blends on engine performance and exhaust emissions. *Mechanical Technology and Engineering Insights*, *3*(1), 29-38.

Abstract

The increasing demand and rising cost of fossil fuels, coupled with the depletion of their reserves and the growing environmental pollution they cause, have motivated researchers to explore alternative fuels. Among these alternatives, biodiesel has emerged as a promising renewable option. Given the ongoing fossil fuel crisis and the numerous advantages of biodiesel, its widespread adoption in the near future appears inevitable. Therefore, it is crucial to investigate the effects of biodiesel–diesel blends on engine performance and environmental emissions. This study experimentally examines the impact of various biodiesel–diesel blend ratios on the performance parameters, exhaust emissions, and vibration characteristics of a diesel engine. Biodiesel was produced from waste cooking oil through the transesterification process and blended with conventional diesel at volumetric ratios of 10%, 20%, 30%, 40%, and 50%. Pure diesel was used as the reference fuel. The performance, emission, and vibration characteristics of these blends were evaluated in accordance with the ECE-R49 standard (constant speed mode) at engine speeds of 1500 and 2200 rpm under four load levels: 25%, 50%, 75%, and 100% of full load. The results indicate that increasing the biodiesel fraction in the blend reduces the emissions of Carbon Dioxide (CO_2), Nitrogen Oxides (NO_x), and soot, while increasing the oxygen content in the exhaust gases. However, no clear trend was observed for unburned hydrocarbon emissions. Engine torque and power remained nearly constant with increasing biodiesel content, whereas exhaust gas temperature decreased and the lambda value increased. Time-domain vibration analysis revealed that vibration levels increase with engine speed and load, whereas higher biodiesel content in the fuel blend leads to reduced vibration and noise levels. Frequency-domain analysis further showed that the dominant vibration frequencies for all fuel samples lie in the range of 0–320 Hz. The peak vibration frequencies varied with engine speed but remained unaffected by biodiesel ratio or engine load; however, vibration amplitudes decreased with higher biodiesel content and lower engine load.

Keywords: Alternative fuels, Biodiesel, Engine performance, Exhaust emissions, Vibration and noise, Diesel engine.

1 | Introduction

Energy plays a pivotal role in economic development, industrial progress, and the overall quality of human life. However, the rapid increase in global energy consumption, coupled with the depletion of fossil fuel reserves and the growing environmental degradation associated with their use, has become one of the most pressing challenges of the modern era [1–3]. The combustion of fossil fuels contributes significantly to air pollution and global warming by emitting large quantities of greenhouse gases, such as Carbon Dioxide (CO_2),

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https://doi.org/10.48313/mtei.vi.36

Nitrogen Oxides (NO_x), and Particulate Matter (PM) [4–6]. As a result, both researchers and policymakers have increasingly turned their attention toward renewable, sustainable, and environmentally friendly energy alternatives [7], [8].

Among the wide range of renewable energy sources, biodiesel has emerged as one of the most promising substitutes for conventional diesel fuel [9], [10]. Biodiesel is a renewable, biodegradable, and non-toxic fuel that can be produced from various natural feedstocks, including vegetable oils, animal fats, and waste cooking oils, through a chemical process known as transesterification [11–13]. Compared with fossil diesel, biodiesel has a higher cetane number, better lubricating properties, and contains oxygen in its molecular structure, which promotes more complete combustion [14–16]. These advantages lead to reductions in emissions of unburned Hydrocarbons (HC), Carbon Monoxide (CO), and soot, contributing to cleaner and more sustainable engine operation [17], [18].

Despite these benefits, the widespread adoption of biodiesel faces several technical and economic challenges [6], [7], [19]. These include its relatively high production cost, differences in physical and chemical properties compared to diesel (such as viscosity and volatility), and its potential influence on engine durability and operational stability [2], [12], [14]. Additionally, although biodiesel generally produces lower emissions of CO and PM, it may lead to slightly higher emissions of NO_x depending on engine conditions [4], [8], [10]. Therefore, understanding the trade-offs between performance efficiency, emission behavior, and mechanical characteristics is crucial before biodiesel can be fully integrated into existing diesel-based energy systems [5], [8], [10].

The experimental assessment of biodiesel–diesel blends has gained significant attention in recent years. Researchers have demonstrated that blending biodiesel with conventional diesel in appropriate proportions can improve combustion characteristics, enhance energy efficiency, and reduce harmful emissions without requiring major engine modifications [10], [12], [16]. However, the influence of biodiesel content on engine vibration and noise behavior remains relatively underexplored, despite its importance for evaluating engine health and user comfort. Vibration analysis, both in the time and frequency domains, provides valuable insights into combustion stability, fuel combustion quality, and the dynamic behavior of engine components under varying operating conditions [13], [14], [18].

In light of these considerations, this study experimentally investigates the effects of biodiesel–diesel fuel blends on the mechanical performance, exhaust emissions, and vibration characteristics of a compression-ignition diesel engine [3], [5], [12]. Biodiesel was produced from waste cooking oil via transesterification, representing a cost-effective and environmentally responsible approach to biodiesel production. The obtained biodiesel was blended with diesel fuel at volumetric ratios of 10%, 20%, 30%, 40%, and 50%, while pure diesel was used as the reference fuel [1], [2].

The experiments were conducted under the ECE-R49 test standard at constant speeds of 1500 and 2200 rpm and at four load levels (25%, 50%, 75%, and 100%) [4], [8], [10]. The study comprehensively evaluated engine torque, power output, exhaust gas temperature, and emission concentrations of CO_2, NO_x, unburned HC, and PM. Moreover, engine vibration and acoustic responses were analyzed in both the time and frequency domains to assess how biodiesel blending influences combustion-induced mechanical behavior [14], [15].

The findings of this study are expected to provide a deeper understanding of the suitability of biodiesel–diesel mixtures as sustainable alternatives for diesel engines. The results also offer practical insights for optimizing fuel compositions to minimize emissions and vibration while maintaining desirable performance characteristics. Ultimately, this research contributes to the global pursuit of cleaner, renewable, and more efficient energy solutions for the transportation and industrial sectors [3], [4], [17].

3 | Materials and Methods

3.1 | Biodiesel Production Process

Among the various methods for biodiesel production, the transesterification process was adopted in this study due to its high yield, operational simplicity, and minimal equipment requirements. This method also preserves oxygen atoms within the biodiesel molecules, which enhances combustion efficiency and reduces emissions, thus classifying biodiesel as an oxygenated fuel, as shown in *Fig. 1*.

The feedstock used in this research was waste cooking oil, collected from local restaurants and food industries, a cost-effective and environmentally sustainable raw material in Iran. The transesterification process was carried out using ethanol (98.7% purity) as the alcohol and Sodium Hydroxide (NaOH) as the catalyst.

Fig. 1. Purified waste oil, NaOH, Ethanol.

3.1.1 | Purification of waste oil

Prior to the transesterification reaction, the waste oil was purified to remove water and food residues, which can inhibit or even prevent the reaction. Two main dehydration techniques are commonly used: settling and evaporation. In this study, the settling method was employed due to its lower energy consumption. The oil was heated to 60°C for 15 minutes, then allowed to rest for 24 hours, enabling complete water separation by density difference. The clarified oil was then filtered to remove remaining solid impurities.

3.1.2 | Preparation of ethoxide solution

Temperature plays a key role in reaction efficiency. The oil was heated to 60°C and continuously stirred at 600 rpm. The ethoxide solution was prepared by dissolving NaOH (1 wt% of the oil) in ethanol (one-third of the oil weight) under the same temperature and stirring conditions until complete dissolution was achieved, as illustrated in *Figs. 2* and *3*.

Fig. 2. Heating the oil.

Fig. 3. Mixing ethanol with NaOH.

3.1.3 | Transesterification reaction

The preheated oil and ethoxide solution were mixed and maintained at 60°C with continuous stirring (600 rpm) for 45 minutes. This reaction converted triglycerides into ethyl esters (biodiesel) and glycerin as a by-product, as shown in *Fig. 4*.

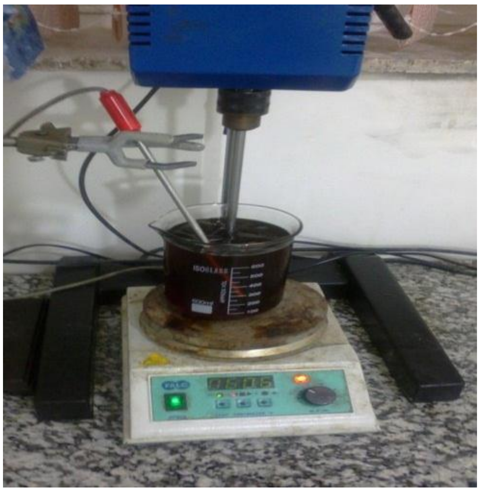

Fig. 4. Mixing the oil and the ethoxide.

3.1.4 | Neutralization and separation

After the reaction, the mixture was allowed to cool to room temperature (25°C). To neutralize residual alkali and separate salts, hydrochloric acid (46%) was added (1.2% v/v of initial oil). The solution separated into two phases: the upper phase containing crude ethyl ester and the lower containing sodium chloride precipitate, as depicted in *Fig. 5*. The upper phase was filtered to remove residual salts.

Fig. 5. Salt sedimentation.

3.1.5 | Washing and purification

Residual alcohol, glycerin, and other impurities were removed via water washing. Deionized water at 50°C (equal in volume to the ester phase) was gently added and allowed to settle for 12 hours. This process was repeated three times until the washing water appeared clear, indicating a purified biodiesel product.

3.1.6 | Biodiesel recovery

The upper layer, consisting of purified ethyl esters, was filtered through fine paper filters to obtain the final biodiesel fuel.

3.2 | Fuel Property Measurement

To ensure the produced biodiesel met international standards, its key physicochemical properties were measured following ASTM D6751 specifications, including density, kinematic viscosity, flash point, cloud point, and pour point. These parameters are critical for evaluating fuel performance and engine compatibility and are presented in *Table 1*.

Table 1. Standard numbers and allowable limits for biodiesel properties.

Property	Standard Test Method	Allowable Range	Unit
Density	ASTM D4052	0.86–0.90	g/cm³
Kinematic viscosity	ASTM D445	1.6–6	mm²/s
Flash point	ASTM D93	Minimum 130	°C
Cloud point	ASTM D5773	Minimum -7	°C
Pour point	ASTM D97	Minimum -10	°C

3.3 | Engine Testing Procedure

To evaluate engine performance and emissions, the produced biodiesel was blended with conventional diesel at volumetric ratios of 10%, 20%, 30%, 40%, and 50%, designated as B10, B20, B30, B40, and B50, respectively. Pure diesel (B0) was used as the reference fuel. Tests were performed on a six-cylinder OM-355 Euro II diesel engine under four load conditions (25%, 50%, 75%, and 100%) and two engine speeds (1500 and 2200 rpm), in accordance with the ECE R49 standard.

3.4 | Measurement and Instrumentation

Engine torque was measured using an eddy-current dynamometer (E400 model), while exhaust gas components (CO_2, NO_x, UHC, soot, and O_2) were analyzed using an AVL Ditest 4000 gas analyzer. Exhaust temperature was recorded using a PT-100 thermocouple. Vibration data were collected using a VMI Easy Viber vibration analyzer equipped with a piezoelectric sensor (AC102-1A) mounted magnetically on the engine body. Sampling frequency was set to 8 kHz, ensuring accurate capture of combustion-induced vibrations.

Fig. 6. Dynamometer, equipment control room and data acquisition.

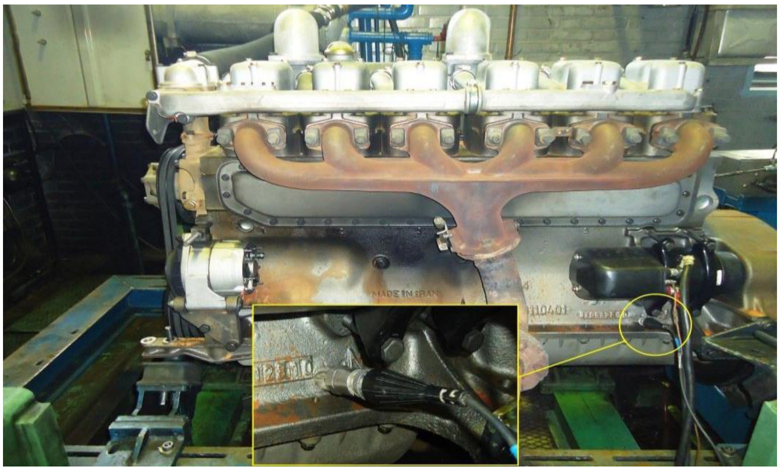

Fig. 7. Sensor mounting location on the engine and orientation for vibration measurement.

3.5 | Data Analysis

Recorded vibration data were analyzed in both the time and frequency domains. Frequency-domain analysis was conducted using the Fast Fourier Transform (FFT) in MATLAB, while statistical analyses, including factorial ANOVA and Duncan's multiple range test, were performed using SPSS and Excel. The vibration intensity was quantified using the Root Mean Square (RMS) method, calculated from the amplitude data over the selected sampling interval, providing a reliable measure of engine mechanical stability under different fuel blends.

4 | Results and Discussion

The experimental results obtained from the measurement of the thermophysical properties of fuel samples, as well as the performance parameters, emissions, and vibrations of the engine introduced previous, the effect of fuel type (pure diesel and blends containing 10%, 20%, 30%, 40%, and 50% volumetric biodiesel) on engine performance, emissions, and vibrations at two engine speeds (1500 and 2200 rpm) and four load levels (25%, 50%, 75%, and 100% of full load).

4.1 | Measured Properties of Fuel Blends

After biodiesel production, the quality of the produced biodiesel was verified by comparing its properties with ASTM standards, and the changes in the properties of biodiesel-diesel blends were also examined. *Table 2* presents the measured properties of these fuel blends. The results indicate that all properties of the biodiesel produced from waste cooking oil comply with ASTM standards. Therefore, this fuel can be safely used in diesel engines. In this chapter, fuel blends are denoted by the symbol BX, where B represents biodiesel and X indicates the volumetric percentage of biodiesel in the blend.

Table 2. Properties of biodiesel-diesel fuel blends.

Blend	Density (gr/cm³)	Viscosity (mm²/s)	Cloud Point (°C)	Pour Point (°C)	Flash Point (°C)
B0	0.808	2.45	-3.7	-24	78
B10	0.813	2.76	-1.3	-18.8	81
B20	0.818	3.01	1	-14.7	85
B30	0.824	3.14	3	-11	89
B40	0.830	3.28	5.3	-8	95
B50	0.837	3.44	8	-2.5	103
B60	0.845	3.71	10.7	-2.2	110
B70	0.852	3.95	12.5	0	117
B80	0.859	4.17	14.1	2.5	122
B90	0.867	4.41	15.8	4.3	134
B100	0.875	4.63	17	6	158

The analysis of fuel blend properties indicates that increasing the biodiesel fraction significantly influences several key thermophysical characteristics. The density of the fuel blends rises with higher biodiesel content, which can be attributed to the longer hydrocarbon chains present in biodiesel molecules.

Similarly, fuel viscosity increases as the biodiesel fraction grows. While diesel functions as a lubricant in components such as the injector pump, the elevated viscosity can be beneficial in reducing wear and tear; however, excessive viscosity may demand additional energy for injection and impair complete atomization, potentially affecting combustion efficiency. Cold flow properties, including cloud point and pour point, also increase with higher biodiesel ratios, primarily due to the high content of saturated fatty acids and waxes in biodiesel derived from waste cooking oil. These elevated cold flow temperatures may restrict the use of biodiesel blends in colder climates. However, techniques such as crystallization in normal hexane can be employed to lower the cloud and pour points. Finally, the flash point of the blends rises with increased biodiesel content, improving safety in storage and transportation. Nevertheless, an excessively high flash point may pose challenges during engine start-up and warm-up procedures. Overall, these results highlight the trade-offs involved in biodiesel blending, emphasizing the need to balance fuel properties for optimal engine performance and operational safety.

4.2 | Carbon Dioxide Emissions

CO_2 is the final product of the combustion of any carbon-based fuel. Considering that CO_2 constitutes approximately 60% of greenhouse gases, it plays a major role in the greenhouse effect. This phenomenon has severe consequences, such as prolonged and frequent droughts, global temperature rise, polar ice melting, expansion of deserts, and other short- and long-term environmental impacts. The CO_2 emissions from the tested engine using different fuel samples under various load conditions at engine speeds of 1500 and 2200 rpm are presented in *Figs. 8* and *9*, respectively. The concentration of CO_2 is expressed as a volumetric percentage in dry exhaust gas.

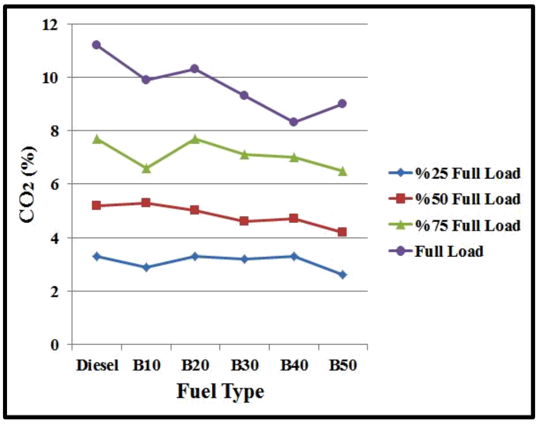

Fig. 8. CO_2 emission level at an engine speed of 1500 rpm.

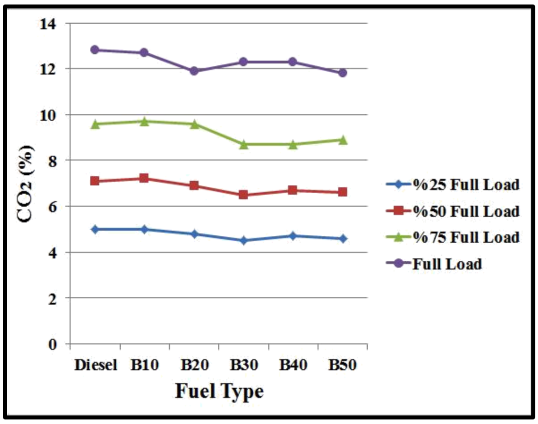

Fig. 9. CO_2 emission level at an engine speed of 2200 rpm.

The results indicate that the CO_2 emissions from the engine increase with rising engine speed when the load and fuel type are kept constant. This is due to higher fuel consumption and more complete combustion, as a greater amount of fuel enters the combustion chamber at higher speeds. Similarly, increasing the engine load leads to higher CO_2 emissions at constant speed and fuel type, as more fuel is injected into the combustion chamber to meet the increased power demand. The type of fuel also plays a significant role: biodiesel contains oxygen in its molecular structure and has a lower carbon-to-hydrogen (C/H) ratio compared to pure diesel. This characteristic results in a reduction of CO_2 emissions during the combustion of biodiesel-diesel blends. Consequently, increasing the biodiesel content in the fuel mixture effectively lowers the CO_2 output from the engine. These trends are clearly illustrated in *Figs. 8* and *9*.

4.3 | Experimental Results of Engine Performance and Engine Torque

The engine torque results for various fuel samples and loads at 1500 rpm and 2200 rpm are shown in *Figs. 10* and *11*. Increasing the engine speed from 1500 to 2200 rpm leads to a reduction in torque for a given load and fuel type. At higher speeds, cylinder filling becomes incomplete, reducing compression and combustion pressures. Additionally, the inertial forces from reciprocating components increase, further decreasing torque. In general, torque initially rises with increasing speed but later decreases due to the engine's limited power output. Factors such as reduced volumetric efficiency, excessive intake air heating, shortened intake duration, and increased friction losses at high speeds all contribute to the observed torque reduction.

Conversely, increasing engine load at all speeds and for all fuel blends results in higher torque. This is due to a larger amount of fuel-air mixture entering the cylinder, which increases the combustion pressure and consequently the engine's output force. Therefore, both engine speed and load significantly influence torque, with higher loads enhancing torque and higher speeds eventually limiting it.

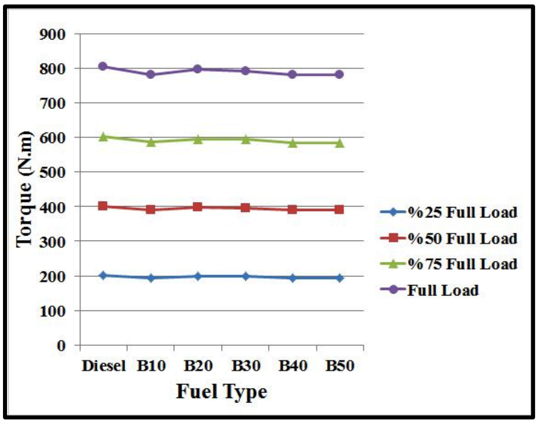

Fig. 10. Engine torque at 1500 revolutions per minute (rpm).

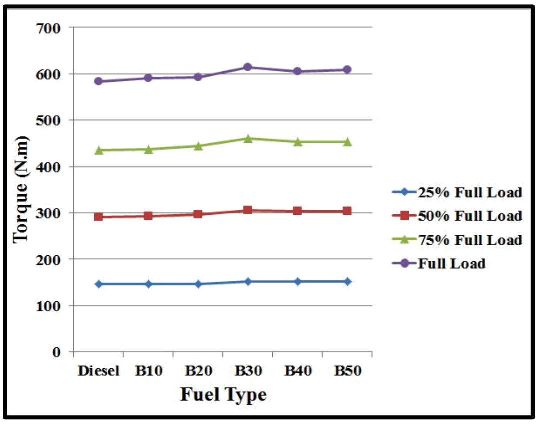

Fig. 11. Engine torque at 2200 revolutions per minute (rpm).

The analysis of engine torque under varying biodiesel–diesel blends and different engine speeds reveals distinct trends. At 1500 rpm, the torque slightly decreases with increasing biodiesel content, primarily due to biodiesel's higher viscosity and density and lower calorific value compared to pure diesel, which reduces combustion pressure. Additionally, the increased viscosity negatively affects injector spray quality, resulting in incomplete air–fuel mixing and lower combustion efficiency.

Conversely, at 2200 rpm, the torque shows a slight increase with higher biodiesel proportions. This is attributed to the oxygen content in biodiesel, which enhances combustion, as well as improved lubrication and reduced friction of moving parts. The difference between low- and high-speed behavior can be explained by cylinder filling: at low speeds, the cylinders are filled, and the excess air diminishes the effect of biodiesel oxygen, while at high speeds, incomplete cylinder filling limits oxygen availability, making the additional oxygen in biodiesel more impactful on combustion and torque. Overall, these findings indicate that biodiesel blends can maintain or slightly improve engine torque at higher speeds, while minor reductions at lower speeds are linked to physical fuel properties.

5 | Conclusion

The experimental results of this study reveal that the use of biodiesel–diesel blends has a minimal impact on the torque output of the tested diesel engine. At low engine speeds (1500 rpm), a slight reduction in torque was observed, which can be attributed to the higher viscosity and density of biodiesel, as well as its lower calorific value compared to conventional diesel. These factors lead to a modest decrease in combustion pressure and, consequently, torque. In contrast, at higher engine speeds (2200 rpm), torque exhibits a marginal increase with higher biodiesel content. This improvement is primarily due to the oxygen-rich molecular structure of biodiesel, which enhances combustion efficiency, and the improved lubrication properties that reduce friction losses in moving components. The results further indicate that the oxygen content in biodiesel becomes increasingly influential at higher speeds, where incomplete cylinder filling limits the availability of oxygen for combustion. Overall, the findings demonstrate that biodiesel blends can be effectively utilized in diesel engines without significantly compromising performance, while simultaneously offering environmental benefits such as reduced CO_2 emissions. These results support the potential of biodiesel as a sustainable alternative fuel for conventional diesel engines, providing both operational reliability and ecological advantages.

Conflict of Interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter discussed in this manuscript.

Data Availability

All data relevant to this study are contained within the manuscript. Additional information is available from the corresponding author upon reasonable request.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article. This work was completed without external funding.

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