



# RECENT ADVANCES IN BIODIESEL AND AFTERTREATMENT SYSTEMS FOR DIESEL ENGINES

The detrimental environmental effects of fossil fuels and rapid depletion of resources have fueled the search for clean and renewable sources of energy. Biodiesel is a growing force within the fuel industry, with research highlighting its superiority to diesel in the context of engine emissions. Research on engine technology itself has also yielded favorable outcomes. Variable valve actuation demonstrates potential to reduce high NOx emissions. Emissions control technology involves various techniques that have been shown to be beneficial toward energy efficiency and reducing emissions. This paper compares the advantages and disadvantages of each method and demonstrates their potential to bolster the effectiveness and mitigate the drawbacks of one another when implemented in combination. The current research reveals that the implementation of variable valve and emission control technology alongside biodiesel may prove a viable strategy for improving engine performance and reducing emissions.

## Introduction

For over a century, the widespread use of fossil fuels has had significant consequences on the ecosystem. Air and water pollution, land degradation, and climate change are among the many detrimental effects resulting from the burning of oil, coal, and natural gas [1]. The transportation sector, involving the use of heavy-duty diesel engines, accounted for approximately 15.8% of global emissions in 2023 [2]. However, the rising popularity of renewable energy, coupled with the rapid expansion of technological advancements, has enabled modernized approaches toward resolving this issue [1].

Renewable fuels like biodiesel, derived from vegetable oils and animal fats, are growing in popularity for their effectiveness at addressing specific pollutants. The drawbacks to many biodiesels include increased NOx emissions and poor engine efficiency, prompting the implementation of modified engine technology and aftertreatment systems. In particular, variable valve actuation and emission control technology have demonstrated potential to reduce NOx emissions and improve fuel efficiency, making them ideal counteractive measures to biodiesel's limitations. This paper demonstrates how the combination of biodiesel, variable valve technology, and selective catalytic reduction may be beneficial toward improving engine performance and reducing emissions.

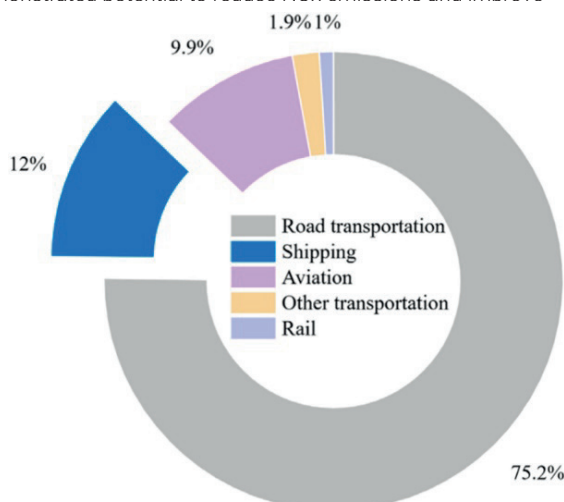


Fig. 1. Distribution of CO<sub>2</sub> emissions in the global transport sector by sub-sector in 2023

Adapted from [2]

## Biodiesel

Biodiesel refers to renewable fuel derived from biological sources such as plant oils and animal fats. It can be blended with pure diesel to achieve optimal results.

A 2025 study by Heeraman utilized the Kirloskar TV1 diesel engine to simulate the performance of various biodiesel blends. For the study, a mixture of oilseed radish, desert date, and Jatropha oils was combined with pure diesel through the transesterification process shown in Figure 2. A reduction was found in both CO and HC emissions across all biodiesel blends from pure diesel, indicating improved combustion with biodiesel. These results are consistent with the findings of Zheng and Cho (2023) and Kujamberdiev et al. (2023), who investigated castor and swine oil-derived biodiesels, respectively [4, 5]. Despite these promising results, the issue of fuel efficiency is prominent across all three studies. For instance, Figure 3 shows that BTE is typically lower across biodiesel blends. BSFC also tends to increase from pure diesel to biodiesel, indicating inefficiency. However, it is worth noting that out of all blend ratios, the lowest ratio of 20% biodiesel to 80% diesel had the least detrimental effect on the engine efficiency while still retaining improvements over pure diesel regarding emissions. Mu et al. (2023), using a tung oil-derived biofuel, further found that a 10% biodiesel blend consumed less fuel than 20% and 50% biodiesel blends [6]. From these results, it is evident that poor fuel efficiency can partially be resolved through using a low ratio of biodiesel, though it should be noted that the issue of high NOx emissions warrants the use of different strategies that will be discussed later.

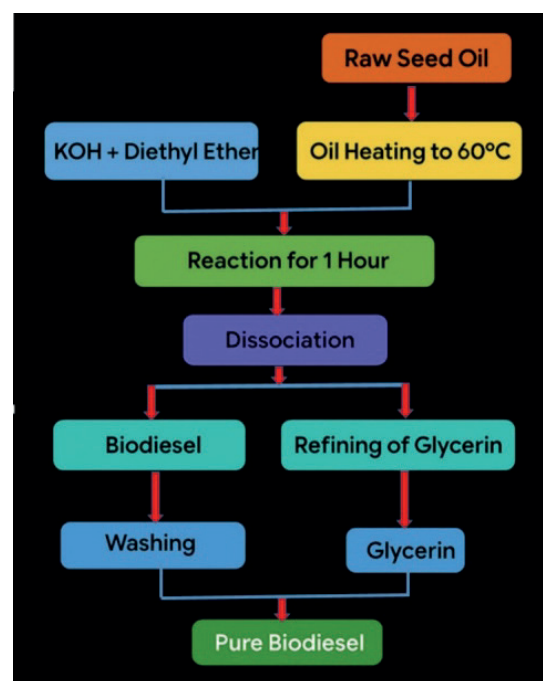


Fig. 2. Flow chart of the transesterification process followed to produce the biodiesels.

Adapted from [5]

Figure 4 depicts the cetane numbers of the various biodiesels. The blend with the lowest value, B20, is used for castor and lard. The studies suggest that the high cetane number of biodiesel results in the improved combustion that subsequently reduces CO and HC emissions. This idea is documented by a paper from Chukwuezie et al., who attribute an increased cetane number to decreased ignition delay, resulting in a subsequent increase in injection pressure and finer fuel particles [7]. These finer particles ultimately result in more complete combustion [8]. In the context of biodiesel, it may be beneficial to compare the derived cetane numbers from different feedstocks when considering combustion and overall performance.

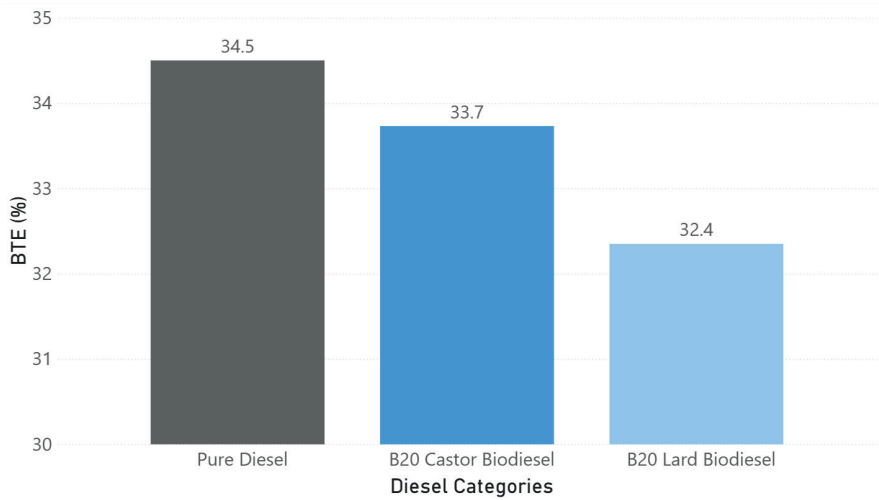


Fig. 3. BTE of biodiesel types at 75% load and 1200 RPM

Compiled from [3], [4]

**Variable Valve Actuation**

Variable valve actuation (VVA), which involves altering the timing of valve opening and closing cycles, demonstrates potential to lower NOx, the main pollutant from biodiesel. Kim et al. (2024) investigated the application of VVA in an off-road diesel engine using the equipment depicted in Figure 5. Notably, the modulation of intake valve closing (IVC) timing was found to generally increase exhaust emissions like HC, CO, and soot. On the other hand, NOx emissions were reduced, most significantly with extreme modulation of IVC [9]. A 2024 study by Lamani et al. similarly found that NOx reduced by approximately 400ppm with LIVC using pure diesel. When employing a renewable fuel blend with n-butanol and diesel, they found that NOx levels generally trended downward with EIVC [10].

Fuel	Cetane Number
Pure Diesel	48.7
Castor Biodiesel	50
Lard Biodiesel	52
Mixed Biodiesel	53
Tung Oil Biodiesel	56

Fig. 4. Cetane numbers of biofuels

Compiled from [3], [4], [5], [6]

Zhao and Li (2024) implemented the Miller cycle in a marine diesel engine. Using CFD software, they simulated the dispersion of NOx across various IVC timings as shown in Figure 6a. In the context of NOx emissions, the optimal timing was found to be IVC165, which demonstrated the lowest level of NOx generation. It should be noted, however, that this timing resulted in less in-cylinder oxygen, leading to incomplete combustion and soot generation as shown in Figure 6b. When soot emission is considered, the optimal timing falls somewhere between IVC 165 and IVC 185 [11]. In any case, IVC as a general strategy proves to be an effective measure for managing high NOx emissions from diesel engines.

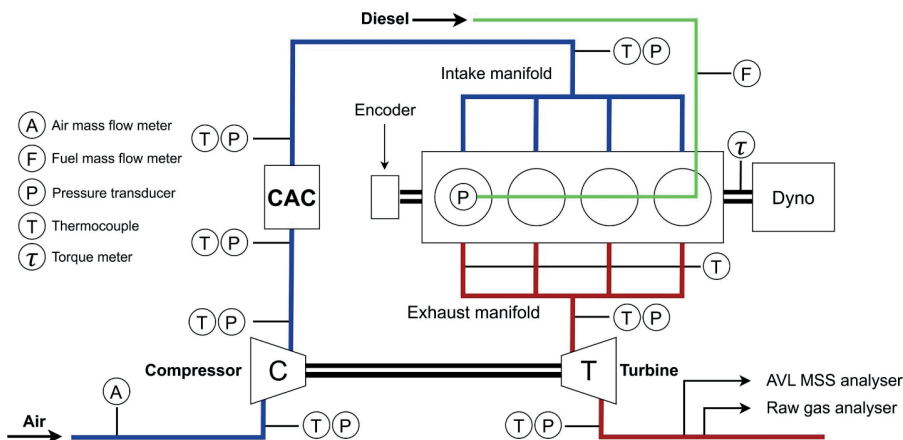


Fig. 5. Schematic diagram of engine test bench with instrumentation.

Adapted from [9]

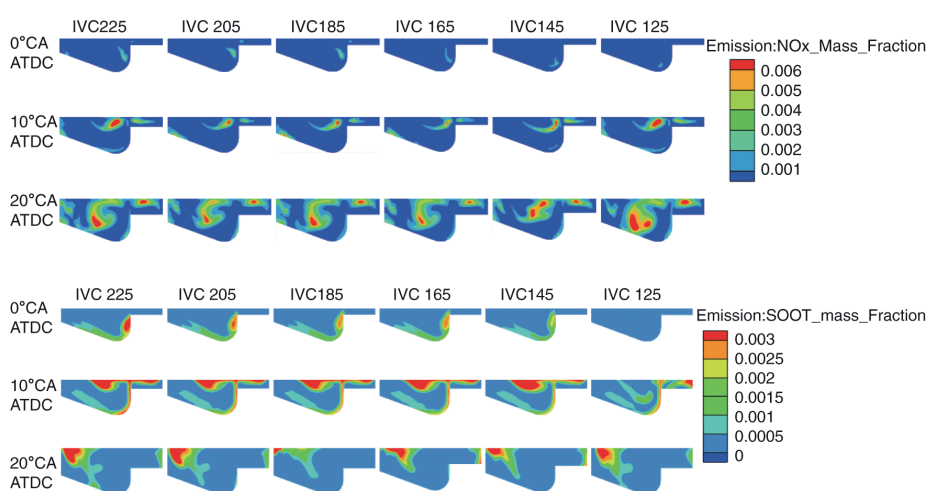


Fig. 6. The spatial NOx and soot dispersions within the cylinder miller cycle schemes

Adapted from [11]

**Emissions Control Technology**

Aftertreatment systems are designed to reduce engine emissions, typically targeting NOx and PM emissions. Methods include exhaust gas recirculation (EGR), which involves recirculating exhaust gas back into the engine, and selective catalytic reduction (SCR), which utilizes a catalyst to reduce NOx emissions.

Deng et al. (2025) investigated the effects of EGR on a turbocharged diesel engine. They found a slight decrease in CO<sub>2</sub> emissions from 689 g/kWh to 682.7 g/kWh with a rise in CO emissions from 1.8 g/kWh to 5.5 g/kWh. This suggests that the lower combustion temperatures shown in Figure 7a result in weaker CO to CO<sub>2</sub> conversions with EGR. Along with this, HC emissions also rose, indicating incomplete combustion. A decrease in NOx emissions was observed, along with a decrease in PM emissions, contradicting the standard NOx-PM relationship. The authors attribute this to the excess oxygen content from the engine's lean air-fuel ratio [12]. Kim et al. (2024) additionally implemented internal EGR alongside VVA strategies and found increases in HC and CO, consistent with results of Deng et al. At the same time, the reduction in combustion temperatures also led to significantly decreased NOx emissions by up to 99% [9]. Although the reductions in NOx and PM emissions are promising, the increases in HC and CO may offset the benefits of using biodiesel, lowering the appeal of EGR as a strategy.

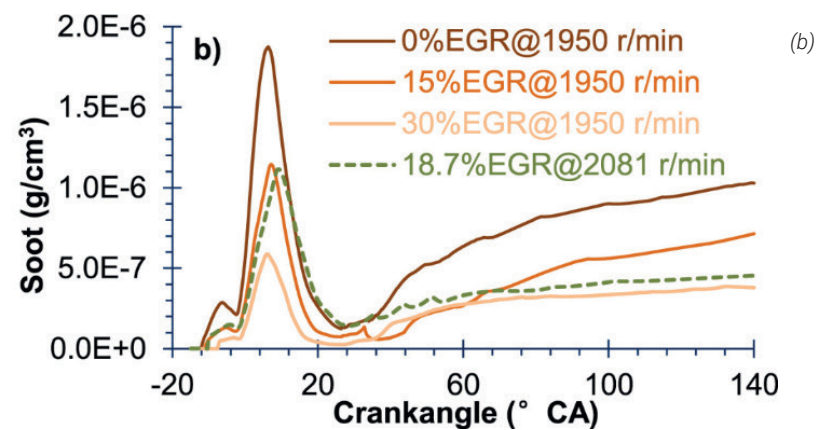
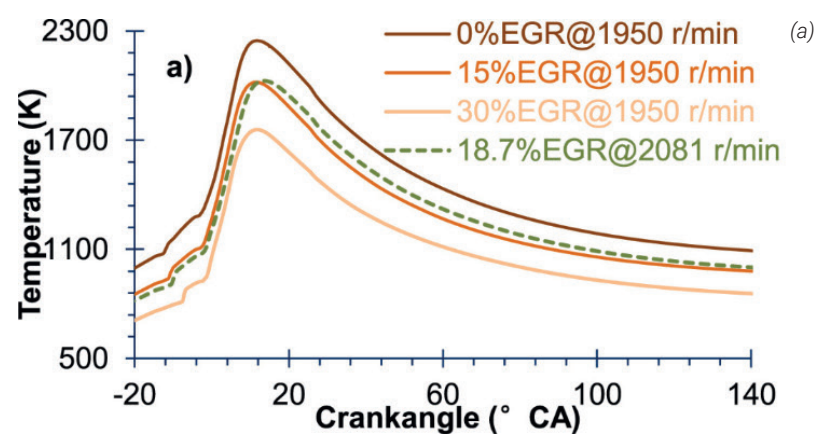


Fig. 7. The transient PN emission rate with and without EGR: (a) 0–200 s, (b) 1300–1500 s.

Adapted from [12]

An alternative to EGR is SCR, which involves the use of a catalyst to reduce NOx emissions. Chen et al. (2023) proposed a core-shell structured catalyst with a CeO<sub>2</sub> core wrapped in MnOx coating for the selective catalytic reduction of NOx by NH<sub>3</sub>. They took relevant measurements with the CeO<sub>2</sub>@MnOx core-shell catalysts and, for comparison, CeMn catalysts. The core-shell catalysts are denoted as Ce@Mn, with the @ symbol denoting the coating of cubic CeO<sub>2</sub> in MnOx. The main goal of SCR is to convert NOx, one of the main pollutants in diesel exhaust, into less harmful gases [13, 14]. As shown in Figure 8, the Ce@Mn catalysts converted, on average, a higher percentage of NOx over a significantly broader temperature range compared to the CeMn catalysts. For engines, NOx would ideally be converted into N<sub>2</sub>, which is harmless. The N<sub>2</sub> selectivity of Ce@Mn was lower than that of CeMn between 100 and 150 °C; however, Ce@Mn outperformed CeMn past 200 °C due to the generation of N<sub>2</sub>O from CeMn [13]. Heavy-duty diesel engines typically produce exhaust gas temperatures in the range of 250 to 350 °C, making the core-shell catalysts ideal due to their superior performance at high temperatures [15].

In diesel engines, water (H<sub>2</sub>O) and sulfur dioxide (SO<sub>2</sub>) are two prevalent gases that make up portions of the exhaust fumes [14, 16]. H<sub>2</sub>O and SO<sub>2</sub> diminish the effectiveness of SCR, making it ideal to examine the tolerance of catalysts to these substances. Figure 9 shows that after introducing the H<sub>2</sub>O and SO<sub>2</sub> into the system, the conversion of the Ce@Mn52 catalyst decreased by a smaller proportion than the CeMn52 catalyst. When H<sub>2</sub>O and SO<sub>2</sub> were removed from the system, the conversion rates of Ce@Mn52 recovered completely, whereas those of CeMn52 recovered only partially. This suggests that it is favorable to use the Ce@Mn52 catalysts in practical application [13].

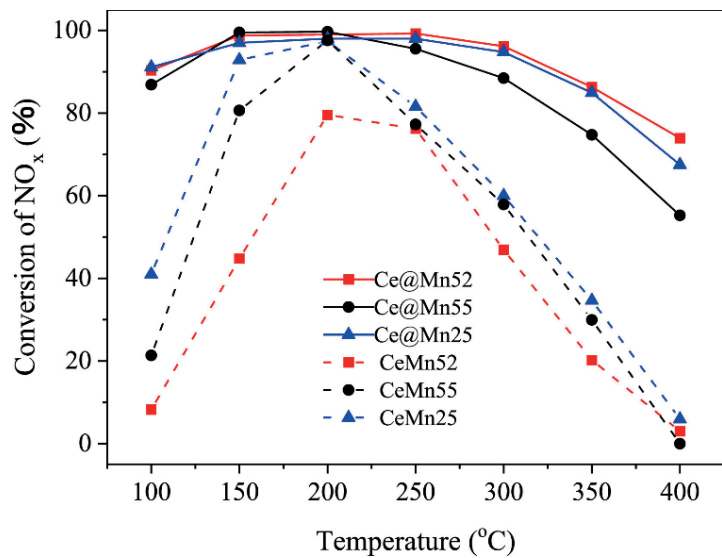


Fig. 8. NO<sub>x</sub> conversion as a function of temperature over Ce@Mn and CeMn catalysts. Reaction conditions: 500 ppm NO, 500 ppm NH<sub>3</sub>, 5% O<sub>2</sub>, N<sub>2</sub> as balance gas, GHSV= 176,000 h<sup>-1</sup>. Adapted from [13]

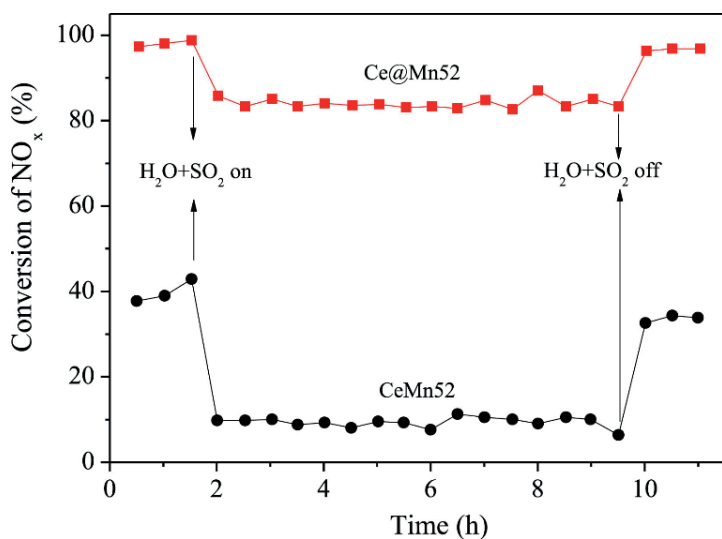


Fig. 9. The effects of H<sub>2</sub>O and SO<sub>2</sub> on the activities of Ce@Mn52 and CeMn52 catalysts at 150 °C. Reaction conditions: 500 ppm NO, 500 ppm NH<sub>3</sub>, 5% O<sub>2</sub>, 5% H<sub>2</sub>O, 50 ppm SO<sub>2</sub>, N<sub>2</sub> as balance gas, GHSV= 176,000 h<sup>-1</sup>. Adapted from [13]

**Conclusion**

Biodiesel generally produces less CO and HC emissions than pure diesel with trade-offs regarding NO<sub>x</sub> emissions and fuel efficiency. To maximize emissions reduction, feedstocks with high cetane numbers should be selected as they promote better combustion. Counteracting the setbacks of biodiesel involves optimizing blend ratios, modifying engine valve technology, and introducing aftertreatment systems. Based on the research, a low blend ratio of biodiesel to diesel mitigates poor BTE and high BSFC. Additionally, the application of IVC demonstrates potential to offset the high NO<sub>x</sub> emissions from biodiesel. To further reduce NO<sub>x</sub> levels, the implementation of SCR with core-shell structured CeO<sub>2</sub>-MnO<sub>x</sub> catalysts would be beneficial due to their high N<sub>2</sub> selectivity at high temperatures. With this three-pronged approach, the optimal balance between engine performance and emissions reduction can be achieved. Future research should investigate the effects of valve technology and SCR together with varying feedstocks and blend ratios of biodiesel.

**References**

- Denchak, M. (2022, June 1). Fossil Fuels: The Dirty Facts. Natural Resources Defense Council. <https://www.nrdc.org/stories/fossil-fuels-dirty-facts>
- Wong, S. J., Tan, H., Othman, M. H. D., Hatif, I. H., Woon, K. S., Said, M. F. M., Nie, F., Ho, W. S., Kek, H. Y., Fong, W. C. W., Chiong, M. C., Li, Y., & Wong, K. Y. (2026). Diesel vs. hydrogen-diesel dual-fuel engines for a sustainable future: A review of combustion, fuel properties, emissions, and performance. *Energy*, 356, 141315. <https://doi.org/10.1016/j.energy.2026.141315>
- Heeraman, J. (2025). Artificial neural network analysis of performance and emissions for mixed biodiesel blends in a DI diesel engine. *Thermal Science and Engineering Progress*, 67, 104218. <https://doi.org/10.1016/j.tsep.2025.104218>
- Zheng, F., & Cho, H. M. (2023). Investigation of the Impact of Castor Biofuel on the Performance and Emissions of Diesel Engines. *Energies*, 16(22), 7665. <https://doi.org/10.3390/en16227665>
- Khujamberdiev, R., Cho, H. M., & Mahmud, M. I. (2023). Experimental Investigation of Single-Cylinder Engine Performance Using Biodiesel Made from Waste Swine Oil. *Energies*, 16(23), 7891. <https://doi.org/10.3390/en16237891>
- Mu, Z., Fu, J., Zhou, F., Yuan, K., Yu, J., Huang, D., Cui, Z., Duan, X., & Liu, J. (2023). A Comparatively Experimental Study on the Performance and Emission Characteristics of a Diesel Engine Fueled with Tung Oil-Based Biodiesel Blends (B10, B20, B50). *Energies*, 16(14), 5577. <https://doi.org/10.3390/en16145577>
- Chukwuezie, O. C., Nwakuba, N. R., Asoegwu, S. N., & Nwaigwe, K. N. (2017). Cetane number effect on engine performance and gas emission: A review. *American Journal of Engineering Research*, 6(1), 56–67.
- Chen, Y., Wang, S., Wang, J., Guan, J., Wang, G., & Song, L. (2026). Effects of particle size and primary air staging on combustion characteristics and emissions of biomass fuels. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 48(1). <https://doi.org/10.1080/15567036.2026.2676764>
- Kim, J., Vallinmaki, M., Tuominen, T., & Mikulski, M. (2024). Variable valve actuation for efficient exhaust thermal management in an off-road diesel engine. *Applied Thermal Engineering*, 246, 122940. <https://doi.org/10.1016/j.applthermaleng.2024.122940>
- Lamani, V. T., Shivaprasad, K. V., Roy, D., Yadav, A. K., & Kumar, G. N. (2024). Computational fluid dynamic analysis of the effect of inlet valve closing timing on common rail diesel engines fueled with butanol–diesel blends. *Frontiers in Energy Research*, 12, 1447307. <https://doi.org/10.3389/fenrg.2024.1447307>
- Zhao, L., & Li, C. (2024). A study of the effect of the Miller cycle on the combustion of a supercharged marine diesel engine. *Energy Engineering*, 121(5), 1363–1380. <https://doi.org/10.32604/ee.2024.046918>
- Deng, B., Cai, W., Zhang, W., Bian, L., Che, X., Xiang, Y., & Wu, D. (2025). A comprehensive investigation of EGR (exhaust gas recirculation) effects on energy distribution and emissions of a turbo-charging diesel engine under World Harmonized transient cycle. *Energy*, 316, 134506. <https://doi.org/10.1016/j.energy.2025.134506>
- Chen, R., Peng, S., & Liu, Z. (2023). A novel core-shell Ce@Mn catalyst for the selective catalytic reduction of NO<sub>x</sub> with NH<sub>3</sub>. *Chemical Physics Impact*, 6, 100164. <https://doi.org/10.1016/j.chphi.2023.100164>
- Li, X., Huhe, T., Zeng, T., Ling, X., Wang, Z., Huang, H., & Chen, Y. (2022). Preparation and SO<sub>2</sub> capture kinetics of a DeSO<sub>x</sub> coating for the desulfurization of exhaust emission. *Heliyon*, 8(11), e11463. <https://doi.org/10.1016/j.heliyon.2022.e11463>
- Boriboonsomsin, K., Durbin, T., Scora, G., Johnson, K., Sandez, D., Vu, A., Jiang, Y., Burnette, A., Yoon, S., Collins, J., Dai, Z., Fulper, C., Kishan, S., Sabisch, M., & Jackson, D. (2018). Real-world exhaust temperature profiles of on-road heavy-duty diesel vehicles equipped with selective catalytic reduction. *The Science of the total environment*, 634, 909–921. <https://doi.org/10.1016/j.scitotenv.2018.03.362>
- Steiner, S., Bisig, C., Petri-Fink, A., & Rothen-Rutishauser, B. (2016). Diesel exhaust: current knowledge of adverse effects and underlying cellular mechanisms. *Archives of toxicology*, 90(7), 1541–1553. <https://doi.org/10.1007/s00204-016-1736-5>

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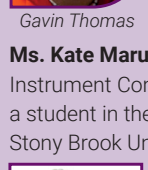
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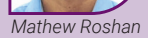
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