International Journal of Interdisciplinary Innovative Research & Development (IJIIRD)
ISSN: 2456-236X
Vol. 10 Issue 01 | 2025

Performance Enhancement and Emissions Reduction of Diesel Engines by Hydrogen, Diesel, Ethanol Blend Injection in Dual Fuel Mode with EGR: A Review

Saket S. Patil[1], Dr. Krishna Shri Ramkrishna Shrivastava[2]
[1]Researcher, Mechanical Engineering, SSBT's College of Engineering and Technology, Bambhori (Jalgaon) , Maharashtra, India
[2]Associate Professor, Mechanical Engineering, SSBT's College of Engineering and Technology, Bambhori (Jalgaon), Maharashtra, India

DOI: 10.5281/zenodo.16413036

ABSTRACT

The review of the literature concerning engine performance and emissions for diesel, biodiesel, ethanol blends with hydrogen and EGR has been completed. Important input parameters including engine compression ratio, injection angle, injection pressure, hydrogen injection percentage, and EGR percentage were analyzed for their effect on brake thermal efficiency, specific fuel consumption, and emissions such as NOx, CO, HC, and particulate matter. Literature reports that hydrogen blending enhances efficiency and lowers CO and PM emissions but raises NOx, which may be controlled with EGR. From the review, parameter optimization techniques like the Taguchi method and Artificial Neural Networks (ANN) as a predictive model technique have emerged as efficient ways to improve combustion performance.

Keyword : - CRDI engine, Hydrogen, Diesel, Ethanol, Biodiesel, EGR

1. INTRODUCTION

Today, the energy density with instant power output with minimal possible environmental impact is the crucial and key necessities for automotive propulsion systems. The currently available petroleum-based products which are playing a most important role in automotive transportation and agricultural fields are benefiting with best performance due to technological advancements but they couldn't achieve the stricter emissions levels (IEA,2022). In view of reducing harmful emissions, various alternate fuels are been investigated for the substitute of conventional petroleum-based fuels. The probable alternate fuels which can replace them are mostly liquefied petroleum gas (LPG), liquefied natural gas (LNG), compressed natural gas (CNG), Hydrogen (H2), producer gas, vegetable oils and alcohols etc (EPA,2024). Despite the rise of electric vehicles, argue for continued development of internal combustion engines (ICEs) due to limitations with alternative options. Their research shows significant potential for improvement, with advanced engines, hybrid powertrains, light weighting, and advanced after-treatment systems offering reductions in fuel consumption and cleaner emissions (Leach, 2020). Growing concerns over energy security, resource depletion, and environmental pollution have spurred research into alternative fuels. The focus is on renewable, environmentally friendly and cost-effective options that address waste management challenges while offering improved performance and lower emissions without compromising engine functionality. Bio-alcohols, biodiesel, green diesel, bio-oil, ethanol and plastic oil are investigated as potential diesel replacements. (Das,2022). Although hydrogen cannot be used to greater extent as on today due to safety issues but it can be considered a potential alternate fuel because of its carbon free structure, renewable, less polluting and clean burning, nontoxic, odorless and leads to fuels complete combustion. The carbonless structure of hydrogen fuel results in reduction in tailpipe emissions and on burning it produces only water. But the smallest amount of these emissions is due to burning of lube oil during the combustion in the combustion cylinder (Wang,2023). The only hazardous pollutant being the NOx and high combustion temperature is the only reason for its formation. P K Bose (Bose,2008) developed the EGR system in order to reduce the NOx and used light weight EGR cooler in place of bulky heat exchanger and concluded that dual fuel mode of operation with hydrogen induction together with exhaust gas recirculation technique leads in lowering emissions level with improving performance parameters of the engine in comparison with operation of diesel. Although cooled EGR resulted in lowering thermal-efficiency compared to reduction in oxides of nitrogen (Zhang,2021). Saravanan et al. (Saravanan ,2008) have researched with hydrogen enrichment in air as intake in CI engine with EGR technique and found that EGR with hydrogen enrichment resulted in NOx reduction, smoke as well as particulate matter. The influence of the hydrogen to diesel energy ratio along-with EGR on performance, combustion and emissions parameters were investigated by Yadav V. S. et al. (Yadav, 2015).have investigated the combustion analysis of hydrogen enriched CI engine with exhaust gas recirculation technique and concluded that hydrogen in dual fuel mode of operation, there is improvement in performance and emissions. Saravanan et al. (Saravanan & Nagrajan,2008) studied NOx reduction characteristics by cold EGR system for optimized injection parameter of hydrogen flow rate results in improvement in performance and emissions. The use of EGR is therefore considered to be the most successful way in improvement of exhaust emissions in hydrogen enriched dual fuel IC engine. This study examined the effects of adding hydrogen to a blend of diesel and waste cooking oil (B20) in a diesel engine. Compared to using just B20, hydrogen enrichment significantly improved fuel efficiency and engine performance. Additionally, it led to substantial reductions in harmful emissions like NOx and CO. These findings suggest that hydrogen enrichment in biodiesel-diesel blends has the potential to create cleaner and more efficient engines, contributing to a more sustainable future (Alçelik,2024).

2. LITERATURE REVIEW

Hydrogen has received significant research interest due to its high energy density and zero-carbon combustion characteristics. When blended with biodiesel derived from renewable biomass, hydrogen can be utilized to enhance engine efficiency with reduced emissions. According to Anandkumar et al. (2021), hydrogen addition in diesel engines resulted in a 23.48% decrease in brake-specific energy consumption and a 33.4% enhancement in brake thermal efficiency. Dual-fuel combustion with hydrogen and diesel imposes major effects on combustion performance, behavior, and emissions compared to conventional diesel or additive blends. Hydrogen as a cleaner fuel enhances performance and reduces CO and particulate emissions considerably. Dual-fuel reduces harmful emissions but enhances engine efficiency. Hydrogen injection technology is a breakthrough in diesel engine efficiency. Small injections of hydrogen into the air intake lead to total combustion, resulting in a 10% improvement in fuel efficiency and a 50% reduction in NOx emissions. The technology also largely reduces particulate matter (PM) emissions, which aligns with strict environmental regulations while enhancing torque and durability. The approach offers a long-term solution to reducing the carbon footprint of diesel engines without any major changes to infrastructure. Hydrogen and biofuels in dual-fuel diesel engines improve combustion performance without involving massive engine redesigns. Oxygenated fuels and nanoscale additives optimize diesel combustion efficiency (Rajak et al., 2020; Parthasarathy et al., 2016). Tsujimura and Suzuki (2017) explored hydrogen/diesel dual-fuel combustion technology, indicating improvements in efficiency and reduction of emissions. Thermal efficiency variation and abnormal combustion happen due to hydrogen's flammability characteristics. Their study on a single-cylinder diesel engine indicated that hydrogen operation possessed greater thermal efficiencies at elevated loads, yet pre-ignition limited the energy contribution of hydrogen. Verma et al. (2020) examined dual-fuel mode operation of Jatropha Curcas biodiesel with hydrogen as the primary fuel, fueled through an electronically controlled intake manifold. Their findings reported that hydrogen substitution was 80.7% at low load and 24.5% at high load, leading to improved brake thermal efficiency. The hydrocarbon, carbon monoxide, and smoke emissions ere also significantly lower compared to traditional diesel operation. Including exhaust gas recirculation (EGR) enhanced hydrogen usage, particularly under high load conditions, by limiting NOx emission without an accompa-nying loss in thermal efficiency.Long-term trials on heavy transport and isolated testing on a 100 kVA diesel generator at UniSA verified that hydrogen supplementation reduced diesel fuel consumption by 5–13%, CO emissions by 7–25%, and diesel particulate matter (DPM) emissions by 25–80%. Hydrogen blending in diesel engines is of significant advantage in fuel economy, engine efficiency, and emission reduction, but optimization techniques need to be formulated to offset NOx emissions and combustion knock. Khandal et al. (2021) analyzed the impact of hydrogen flow rates in CRDI engines and reached a conclusion that 0.22 kg/h flow rate enhanced performance but boosted NOx emissions. NOx emissions reduced by 26% at 15% EGR without decreasing engine efficiency. Blending with hydrogen considerably reduces particulate matter and efficiency but rising combustion temperature is responsible for greater NOx emissions. Hydrogen concentrations in the range 6–25% are usually utilized to prevent pressure surges and knocking. Khan et al. (2021) studied CRDI engines with Ceiba pentandra biodiesel and hydrogen blends, confirming performance improvement but with issues in NOx emissions. They suggested that EGR optimization would enhance engine efficiency with reduced toxic emissions. Several studies have sought to enhance hydrogen-based fuel system efficiency by using additives. Shrivastava et al. (2021) experimented with

Karanja biodiesel and ethanol blends and found that while efficiency was reduced by a slight margin and fuel consumption was marginally higher, HC, CO, and NOx emissions were lower than in neat diesel. Co-combustion of hydrogen with biodiesel (RME) under full load lowered combustion time significantly, with 12% hydrogen content being ideal. Engine stability was lost, however, when more than 15%. Fuel reformulation using oxygenated fuels and nanoscale particles has been promising to enhance diesel engine performance without requiring extensive modifications (Hosseinzadeh-Bandbafha et al., 2018). Higher hydrogen content in diesel engines increases combustion temperatures, leading to higher NOx emissions and knocking. Strategies such as EGR and injection optimization have been explored to stem these issues. Gu and Su (2023) tested the EGR effects on a two-stage turbocharged heavy-duty diesel engine and demonstrated that EGR delayed the high-pressure valve opening, which was marked by a minimal increase in NOx of 3.13%. Soot emissions decreased by 47% under improved gas mixing conditions, but optimized injection tactics curbed NOx by 4.73% with fuel consumption increasing by only 1.87%. Maroa and Inambao (2022) explored EGR usage in diesel engines with waste plastic pyrolysis oil (WPPO) blend fuels. Based on their findings, EGR reduced CO emission significantly at low to middle loads but increased it at high loads. They deduced that WPPOB100 exhibited the highest brake-specific fuel consumption at 30% EGR, and WPPOB10 exhibited the greatest exhaust gas temperature reduction. Chintala (2017) concluded that 6%–25% hydrogen concentrations were sufficient enough to prevent pressure rise and knocking uncontrolledly, but up to 79% concentrations were able to maintain the NOx emissions in a satisfactory condition under controlled tests. Saravanan et al. (2020) concluded that the application of EGR in ethanol-diesel engines lowered the temperatures of combustion and thus emissions of NOx. Similarly, Sethin et al. (2024) tested biodiesel-diesel blends in CRDI engines under 12.5% EGR conditions and reported reduced NOx emissions and increased CO, HC, and smoke opacity. Ananthakumar et al. (2023) noticed that an EGR rate of 10% improved NOx emissions and brake thermal efficiency by 31.8%, with higher rates of 15% causing increased ignition delays and lowered peak cylinder pressures. Table 1 provides a concise review of engine performance and emissions. Table 2 presents a summary of engine input parameters along with their impact on performance and emissions. Table 3 outlines the variations in engine input parameters and their effects on overall engine behavior.

Table 1 Brief discussion about engine input and performance and emission parameters

Reference	Fuel Type	Input Parameters	Engine Performance Responses	Emission Responses
Saravanan et al. (2020), Sethin et al. (2024)	Diesel	Diesel fuel, CRDI engine, injection timing, EGR (various %)	Standard efficiency, higher fuel consumption	Higher NOx, CO, HC, and particulate emissions
Verma et al. (2020), Shrivastava et al. (2021), Maroa and Inambao (2022)	Biodiesel (Jatropha, Karanja, Ceiba pentandra, RME, WPPO blends)	Biodiesel blends (varying %), injection timing, EGR (6–30%)	Slightly lower efficiency, increased brake-specific fuel consumption	Lower HC, CO, smoke emissions, but NOx emissions vary based on EGR
Saravanan et al. (2020), Sethin et al. (2024)	Ethanol-Diesel Blends	Ethanol blends (varied %), injection timing, EGR (12.5–30%)	Reduced combustion temperatures, slightly lower efficiency	NOx reduction with EGR, but increased CO, HC, and smoke opacity
Anandkumar et al. (2021), Khandal et al. (2021), Khan et al. (2021), Tsujimura and Suzuki (2017)	Hydrogen-Diesel Blends	Hydrogen injection (0.22 kg/h, 6–25% vol.), CRDI engine	10–33% improved brake thermal efficiency, reduced brake-specific energy consumption	NOx increases significantly, CO and PM reduce
Verma et al. (2020), Khandal et al. (2021), Gu and Su (2023)	Hydrogen-Biodiesel Blends	Hydrogen (6–25%), biodiesel (varied %), EGR (10–15%)	Performance improvement, knocking at higher hydrogen	NOx reduction (10–26%) with EGR, PM and smoke emissions decrease

			concentrations	
Gu and Su (2023), Hosseini et al. (2023)	Hydrogen Injection Optimization	Hydrogen injection in the intake manifold, real-time hydrogen control, CRDI	10% improvement in fuel efficiency, enhanced combustion stability	50% NOx reduction, soot reduction of 47%

Table 2 Brief discussion about engine variation in input parameters

Input Parameter	Variations	References
Engine Compression Ratio (CR)	16:1 – 18:1 (Diesel engines) 18:1 – 22:1 (Biodiesel engines)	Tsujimura and Suzuki (2017), Verma et al. (2020)
Injection Angle (°BTDC)	12°–25° (Diesel and Biodiesel) 10°–22° (Hydrogen-diesel blends)	Rajak et al. (2020), Khan et al. (2021)
Injection Pressure (bar)	200–250 bar (Diesel and Biodiesel) 250–350 bar (Hydrogen-diesel blends)	Anandkumar et al. (2021), Khandal et al. (2021)
Hydrogen Injection (%)	6–25% (General hydrogen blending)	Chintala (2017), Verma et al. (2020), Khandal et al. (2021)
Exhaust Gas Recirculation (EGR %)	6%–15% (Diesel engines) 10% (Optimized for NOx control)	Gu and Su (2023), Saravanan et al. (2020), Sethin et al. (2024)
Hydrogen Flow Rate (kg/h)	0.22 kg/h (Optimized for CRDI engine)	Khandal et al. (2021)
Fuel Blend Ratio	Diesel-biodiesel – Ethanol blends ratio70-20-10 or 70-25-5 hydrogen (Up to 25% hydrogen)	Shrivastava et al. (2021), Khan et al. (2021)

3. CONCLUSIONS

It is observed that hydrogen as an additive in biodiesel, diesel and it influences on brake thermal efficiency, fuel consumption, and emissions. Research has shown that hydrogen blending enhances combustion efficiency and lowers CO and particulate matter emissions but increases NOx emissions, which requires optimization measures like exhaust gas recirculation (EGR), compression ratio and injection timing control. Experimental and l studies have proven the capability of hydrogen injection technology along with diesel and biofuel will increase efficiency and ensure engine stability. More focus is needed for optimization to reduce emissions of NOx.

4. REFERENCES

[1] Das, A. K., Sahu, S. K., & Panda, A. K. (2022). Current status and prospects of alternate liquid transportation fuels in compression ignition engines: A critical review. Renewable and Sustainable Energy Reviews, 161, 112358. https://doi.org/10.1016/j.rser.2022.112358.

[2] Alçelik, N., Sarıdemir, S., Polat, F., & Ağbulut, Ü. (2024). Role of hydrogen-enrichment for in-direct diesel engine behaviours fuelled with the diesel-waste biodiesel blends. Energy, 302,131680.https://doi.org/10.1016/j.energy.2024.131680

[3] Anandkumar, G., Muthukarupan, K. S., Premnath, S., Selvaraju, P. N., & Amshumaan, G. (2023). Investigation on the performance of hydrogen induction in a CRDI engine: A review. International Journal of Vehicle Structures & Systems, 15(5). https://doi.org/10.4273/ijvss.15.5.19

[4] Anandkumar, G., Nallusamy, S. P., & Sambasivam, R. (2021). Hydrogen Induction in a CRDI Engine. https://doi.org/10.30955/gnj.06256

[5] Ananthakumar, S., Barathiaraja, R., Thiyagaraj, J., & Mohankumar, A. (2023). Effects of exhaust gas recirculation on diesel engine using hybrid biodiesel. Chemical Industry and Chemical Engineering Quarterly, 30(1), 22–22. https://doi.org/10.2298/CICEQ230303022A

[6] Bose,P. K., & Maji, D. (2008). An experimental investigation on engine performance and emissions of a single cylinder diesel engine using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation. International Journal of Hydrogen Energy, 34(11), 4847-4854. https://doi.org/10.1016/j.ijhydene.2008.10.077

[7] Chintala, V., & Subramanian, K. A. (2017). A comprehensive review on utilization of hydrogen in a compression ignition engine under dual fuel mode. Renewable and Sustainable Energy Reviews, 70, 472-491. https://doi.org/10.1016/j.rser.2016.11.247.

[8] Environmental Protection Agency,U.S. (EPA). (2024). Alternative fuels. https://www.epa.gov/renewable-fuel-standard-program/alternative-fuels.

[9] Gu, W., & Su, W. (2023). Study on the Effects of Exhaust Gas Recirculation and Fuel Injection Strategy on Transient Process Performance of Diesel Engines. Sustainability, 15(16), 12403. DOI: 10.3390/su151612403.

[10] Hosseinzadeh-Bandbafha, H., Tabatabaei, M., Aghbashlo, M., Khanali, M., & Demirbas, A. (2018). A comprehensive review on the environmental impacts of diesel/biodiesel additives. Energy Conversion and Management, 174, 579–614.

[11] International Energy Agency (IEA). (2022). World Energy Outlook 2022. https://www.iea.org/reports/world-energy-outlook-2022

[12] Khan, T. M. Y., Soudagar, M. E. M., & Mokashi, I. (2021). Performance of CRDI Engine Using Ceiba Pentandra Biodiesel and Hydrogen Fuel Combination. https://doi.org/10.3390/en14206504

[13] Khandal, S. V., Khan, T. M. Y., & Kamangar, S. (2021). Effects of hydrogen flow rate, injection pressure, and EGR on performance of CRDI engine. Emerald Publishing. https://doi.org/10.1108/FEBE-02-2021-0007

[14] Leach, F., Kalghatgi, G., Stone, R., & Miles, P. (2020). The scope for improving the efficiency and environmental impact of internal combustion engines. Transportation Engineering, 1, 100005. https://doi.org/10.1016/j.treng.2020.100005.

[15] Maroa, S., & Inambao, F.L. (2022). The Influence of Exhaust Gas Recirculation on Performance and Emission Characteristics of a Diesel Engine Using Waste Plastic Pyrolysis Oil Blends and Conventional Diesel. IntechOpen. DOI: 10.5772/intechopen.105011.

[16] Parthasarathy, M., Isaac Joshua, J., Lalvani, R. R., Dhinesh, B., & Annamalai, K. (2016). Effect of hydrogen on ethanol–biodiesel blend on performance and emission characteristics of a direct injection diesel engine. Ecotoxicology and Environmental Safety, 134, 433–439. https://doi.org/10.1016/j.ecoenv.2015.11.005

[17] Rajak, U., Nashine, P., Verma, T. N., & Pugazhendhi, A. (2020). Performance and emission analysis of a diesel engine using hydrogen enriched n-butanol, diethyl ester, and Spirulina microalgae biodiesel. Fuel, 271, Article 117645. https://doi.org/10.1016/j.fuel.2020.117645

[18] Raju, S. K., Masimalai, N., Ganesan, S. V., & Karthic, R. (2020). Engine's behavior on hydrogen addition of waste cooking oil fueled light-duty diesel engine - A dual fuel approach. Energy, 194, Article 116844. https://doi.org/10.1016/j.energy.2019.116844

[19] Saravanan, N., & Nagarajan, G. (2008). An experimental investigation of hydrogen-enriched air induction in a diesel engine system. International Journal of Hydrogen Energy, 33(6), 1769-1775. https://doi.org/10.1016/j.ijhydene.2007.12.065.

[20] Saravanan, N., Nagarajan, G., Kalaiselvan, K. M., & Dhanasekaran, C. (2008). An experimental investigation on hydrogen as a dual fuel for diesel engine system with exhaust gas recirculation technique. Renewable Energy, 33(3), 422-427. https://doi.org/10.1016/j.renene.2007.03.015.

[21] Sethin, A., Oo, Y. M., Thawornprasert, J., & Somnuk, K. (2024). Effects of blended diesel–biodiesel fuel on emissions of a common rail direct injection diesel engine with different exhaust gas recirculation rates. ACS Omega, 9(19), 20906–20918. https://doi.org/10.1021/acsomega.3c10125

[22] Shrivastava, K., Thipse, S. S., & Patil, I. D. (2021). Optimization of diesel engine performance and emission parameters of Karanja biodiesel-ethanol-diesel blends at optimized operating conditions. Fuel, 293, 120451. https://doi.org/10.1016/j.fuel.2021.120451.

[23] Tsujimura, Taku, & Suzuki, Yasumasa. (2017). The utilization of hydrogen in hydrogen/diesel dual fuel engine. International Journal of Hydrogen Energy, 42(19), 14019-14029. https://doi.org/10.1016/j.ijhydene.2017.01.152

[24] Verma, Aniket, Suman, Abhishek, Das, L.M., Kaushik, S.C., & Tyagi, S.K. (2020). A renewable pathway towards increased utilization of hydrogen in diesel engines. International Journal of Hydrogen Energy, 45(8), 5577-5587. https://doi.org/10.1016/j.ijhydene.2019.05.213

[25] Wang, S., Zhang, Z., Hou, X., Lv, J., Lan, G., Yang, G., & Hu, J. (2023). The environmental potential of hydrogen addition as complementation for diesel and biodiesel: A comprehensive review and perspectives. Fuel, 342, 127794. https://doi.org/10.1016/j.fuel.2023.127794.

[26] Yadav,V. S., Sharma, D., & Soni, S. L. (2015). Performance and combustion analysis of hydrogen-fueled C.I. engine with EGR. International Journal of Hydrogen Energy, 40(12), 4382-4391. https://doi.org/10.1016/j.ijhydene.2015.01.162.

[27] Zhang, Z., Li, J., Tian, J., Zhong, Y., Zou, Z., Dong, R., Gao, S., Xu, W., & Tan, D. (2022). The effects of Mn-based catalysts on the selective catalytic reduction of NOx with NH3 at low temperature: A review. Fuel Processing Technology, 230, 107213. https://doi.org/10.1016/j.fuproc.2022.107213

[28] Zhang,W., Feng, T., Li, Z., Chen, Z., & Zhao, J. (2021). EGR thermal and chemical effects on combustion and emission of diesel/natural gas dual-fuel engine. Fuel, 302, 121161. https://doi.org/10.1016/j.fuel.2021.121161.