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Greenhouse gas reduction system for engines using electrolyte technology

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ABSTRACT

This research focuses on developing a system to reduce greenhouse gas emissions in internal combustion vehicle engines using electrolyte technology and embedded programming on an electronic board via the OBI protocol. The main objectives are to create a prototype, apply it in real-world scenarios, evaluate its efficiency, and facilitate technology transfer. The system, designed to reduce greenhouse gases from vehicles, consists of a Bluetooth on-board diagnostics (OBD) scanner connected to the electronic control unit (ECU). This scanner transmits data to an embedded microcontroller through a Bluetooth module. The microcontroller, which includes software for controlling oxygen measurement and production, operates to decrease greenhouse gas emissions. The results show that the electronic device, IC ELM327, decodes OBD into RS232, processes the oxygen output from the exhaust pipe using embedded programming on the Arduino Uno-R3 microprocessor, and controls the oxygen production unit with electrolyte technology. The system adds 9.82% oxygen to the exhaust and reduces carbon monoxide by 21.04% and carbon dioxide by 13.86%. Additionally, the technology transfer received high satisfaction with a mean score of 4.61, indicating efficient technology dissemination.

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1. INTRODUCTION

Vehicle emissions resulting from the combustion of various fuels lead to the release of carbon monoxide, particulate matter, hydrocarbons, sulfur dioxide, and other pollutants, which significantly contribute to the greenhouse effect [1]–[3]. These emissions are linked to global warming and climate change, impacting ecosystems and human health adversely [4], [5]. According to the Organization for Economic Co-operation and Development (OECD) 2010, personal vehicles are responsible for approximately 65% of carbon dioxide emissions in the transportation sector [6]. For instance, an average car emits around 271 grams of carbon dioxide per kilometer traveled, substantially contributing to overall emissions when multiplied by the number of vehicles in use [7], [8].

In light of increasing environmental awareness and stringent regulations, there is a pressing need for innovative technologies to reduce vehicle emissions [9], [10]. Various studies have explored the use of oxyhydrogen (HHO) gas produced by electrolysis as a supplementary fuel, which has shown promise in reducing harmful emissions [11]–[13]. For example, the use of HHO gas can lower the output of CO_2 and NOx during combustion, thereby improving fuel efficiency and reducing environmental impact [14]–[16].

This research aims to design and develop a greenhouse gas reduction system for internal combustion engine vehicles, utilizing electrolysis technology and embedded programming. The system will be evaluated for its efficiency and effectiveness in reducing greenhouse gases and facilitating technology transfer for practical application [17]–[19]. Further, the integration of advanced oxidation processes is considered to enhance the treatment of exhaust gases [20], [21]. Additionally, the role of smart grids and renewable energy sources in supporting such environmental technologies is becoming increasingly important [22], [23]. The application of electrostatic precipitators and advanced water treatment methods also provides a broader context to the environmental technologies being developed [24], [25].

2. METHOD

The development and deployment of a greenhouse gas reduction system for vehicles powered by internal combustion engines encompass a comprehensive integration of diverse technologies and several meticulous steps. This section elaborates on the systematic methodologies adopted for designing, developing, and evaluating the innovative system. Central to the system's functionality is the application of electrolysis technology, supplemented by sophisticated embedded programming and seamless integration with the vehicle's on-board diagnostics (OBD) protocol. This multifaceted approach ensures that the system not only meets the desired environmental goals but also aligns with contemporary technological standards for automotive emissions control. The overarching aim is to achieve a significant reduction in greenhouse gas emissions through a reliable, efficient, and scalable solution that can be adapted across various internal combustion engine platforms.

2.1. System design and development

The system is designed to reduce greenhouse gas emissions from internal combustion engines by integrating electrolysis technology with a microcontroller for efficient production of oxyhydrogen gas (HHO). The core component, the electrolytic cell, splits water molecules into hydrogen and oxygen, powered by the vehicle's electrical system. It includes an anode that releases oxygen and a cathode that releases hydrogen. The oxyhydrogen outlet directs HHO gas to the engine, reducing emissions, while the gas pressure-controlled reaction system regulates gas flow and pressure for safe and efficient operation, as shown in Figure 1. The embedded microcontroller (Arduino Uno-R3) manages the electrolysis process and interfaces with the vehicle's electronic control unit (ECU), adjusting electrolysis parameters dynamically based on data received via a Bluetooth OBD scanner connected to an OBD-II port. This scanner, an IC ELM327, interfaces with the ECU, decoding and transmitting critical engine parameters to the microcontroller. Custom software developed for the microcontroller processes this data, using AT-commands to optimize gas production and reduce emissions. Oxygen production control allows the microcontroller to control oxyhydrogen gas production in real-time, analyzing oxygen levels in the exhaust to effectively reduce greenhouse gases while maintaining engine performance. The system design ensures a balance between oxygen and hydrogen production, significantly reducing emissions such as CO_2 and NOx, with the entire process carefully monitored to adapt to varying vehicle operating conditions (refer to Figure 1 for a schematic of the electrolytic cell).

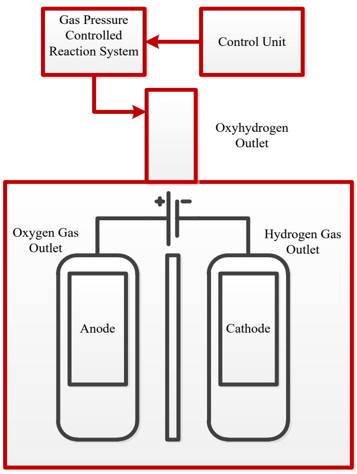

Figure 1. Schematic of the electrolytic cell for GHG reduction in combustion engines

The prototype of an oxyhydrogen gas production system utilizes a battery as the power source and operates on the principle of electrolysis. This involves immersing two sets of electrodes in a solution and connecting them to the positive and negative terminals to generate oxygen (O_2) at the positive electrode and hydrogen at the negative electrode. Production is controlled to utilize only oxygen gas, as depicted in Figure 2.

From Figure 2, the image shows a prototype of an electrolysis-based oxyhydrogen gas production system. On the left, a cylindrical electrolytic cell is visible, which is where water is electrolyzed to separate it into hydrogen and oxygen gases. The system's control unit, housed in a white box on the right, contains various electronic components including microcontrollers and wiring. This unit manages the electrolysis process, regulating voltage and current as necessary. The setup appears to be mounted on a metal frame for stability and includes various tubes and wires connecting the components, indicating the pathways for gas transport and electronic connections.

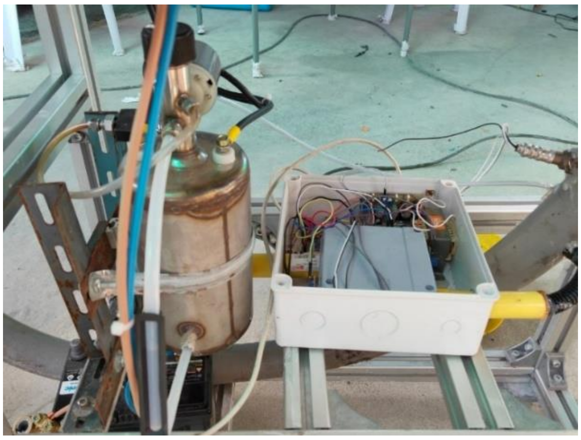

Figure 2. Battery-powered oxyhydrogen generator based on electrolysis

2.2. Embedded microcontroller and data communication

Designing and constructing a gas production control unit suitable for automobiles involves integrating a connection with the engine's OBD2 port via an OBD2 interface unit. This setup facilitates communication through Bluetooth technology, allowing data to be wirelessly transmitted and displayed on a computer. The computer processes this information to control the production of gas by the oxyhydrogen gas production system through relays using a microcontroller. Preliminary system testing and experimentation are depicted in Figure 3.

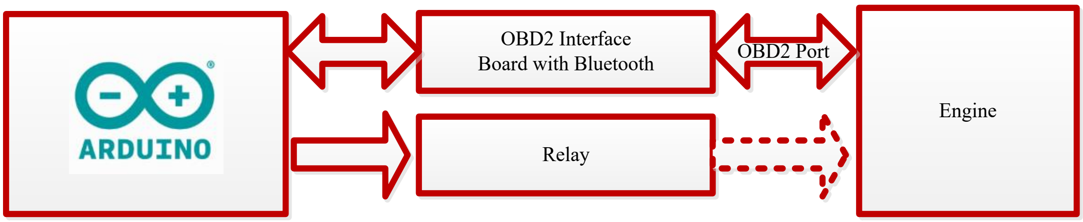

Figure 3. Data communication and control flow

Figure 3 illustrates the data communication and control flow in a vehicle’s gas production system. At the heart of the setup is an Arduino board that serves as the central processing unit. It interfaces with the vehicle’s ECU through an OBD-II port, facilitated by an OBD2 interface board equipped with Bluetooth technology. This setup enables the Arduino to receive critical engine data wirelessly. A relay component is also depicted, indicating its role in the operation, possibly to control the flow or activation of specific processes within the system based on the data received from the ECU.

This diagram illustrates the data communication and control setup within the oxyhydrogen gas production system for vehicle engines. At the heart of the system is an Arduino board that functions as the primary control unit. It communicates via Bluetooth with the OBD2 interface board, which is connected to the engine's OBD2 port. This setup enables real-time data transmission from the vehicle's engine to the Arduino, which processes the data and controls a relay. The relay manages the electrolysis process, crucial for the efficient and safe production of oxyhydrogen gas. This integrated system ensures precise control of gas production, enhancing vehicle efficiency and reducing emissions.

This image, shown in Figure 4, illustrates the data communication and control setup within the oxyhydrogen gas production system for vehicle engines. At the core of the system is an Arduino board that functions as the primary control unit. It communicates via Bluetooth with the OBD2 interface board, which connects directly to the engine's OBD2 port. This configuration enables real-time data transmission from the vehicle's engine to the Arduino, which then processes the data and controls a relay. The relay plays a critical role in managing the electrolysis process, essential for the efficient and safe production of oxyhydrogen gas. This integrated approach ensures precise control of gas production, enhancing vehicle efficiency and reducing emissions.

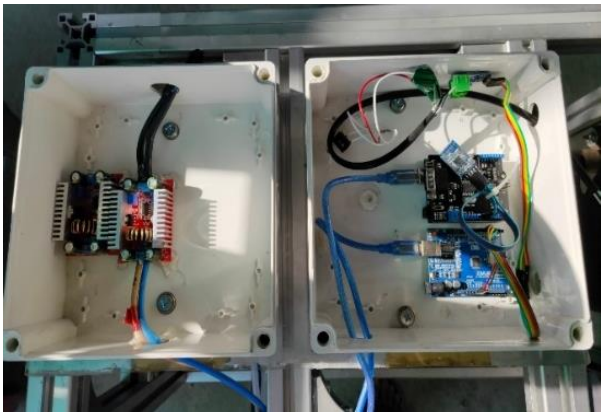

Figure 4. Experimental setup for oxyhydrogen gas production in vehicle engines

2.3. The design and construction of a data acquisition system for gas production monitoring in a greenhouse involves key components

The design and construction of a data acquisition system for monitoring gas production in a greenhouse involves various components. As depicted in Figure 5, the system incorporates oxygen (O_2) sensors and carbon dioxide (CO_2) sensors installed along the exhaust pipe. These sensors are crucial for measuring the O_2 left over from combustion and the CO_2 levels at the catalytic converter where the oxyhydrogen gas produced by the system is utilized to reduce emissions.

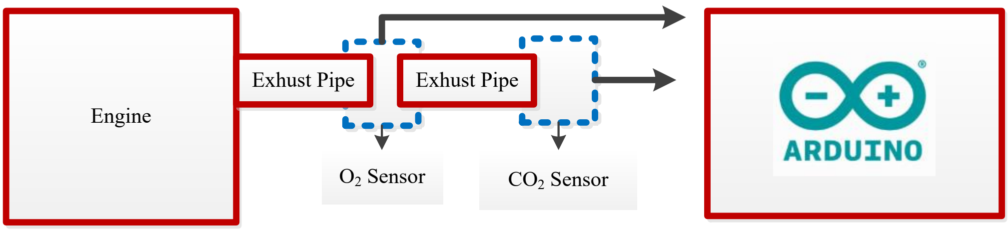

Figure 5. Data communication system diagram

In the real-world setup shown in Figure 6, the system comprises a laptop with programming software connected via Bluetooth to an OBD2 interface. This interface is connected to the engine's OBD2 port and relays information to a microcontroller. The microcontroller processes the data and controls the relay for the electrolysis unit, ensuring efficient gas production and emission control. This setup exemplifies a practical application of embedded systems in automotive applications for environmental enhancement.

Figure 6. Experimental setup for gas production monitoring

3. RESULTS AND DISCUSSION

3.1. Results of oxygen measurements before and after passing through the catalytic converter in engine exhaust

Following the design and development phases, the project advanced to experimental testing to validate theoretical models and practical implementations. This crucial phase assessed the system's performance in a controlled environment, focusing on measuring oxygen levels in the exhaust before and after passing through the Catalytic converter, see in Table 1. These tests verified the system's effectiveness in enhancing combustion and reducing emissions, bridging the gap between conceptual design and practical functionality. Figure 7 illustrates the oxygen measurements under controlled conditions: Figure 7(a) without supplemental oxygen and Figure 7(b) with controlled oxygen introduction. Researchers used an oxygen analyzer (Model JAY-120) to conduct ten trials, analyzing the data to calculate mean values for thorough statistical evaluation.

Table 1. Oxygen levels before and after catalytic conversion in engine exhaust

Test number	Oxygen level (%) before	Oxygen level (%) after
1	6.8	11.8
2	8.5	12.9
3	6.4	13.7
4	7.5	14.9
5	9.5	15.6
6	7.8	16.5
7	10.5	16.9
8	8.8	17.2
9	7.4	17.4
10	8.5	17.6

(a) (b)

Figure 7. Oxygen measurement in controlled conditions (a) without supplemental oxygen and (b) controlled oxygen

Table 1 details the oxygen levels measured before and after the catalytic conversion process in the engine exhaust. It is evident from the table that introducing controlled oxygen into the system consistently increases the oxygen levels in the exhaust, demonstrating the effectiveness of the catalytic converter in enhancing combustion efficiency. Figure 8 further provides a comparative analysis of the oxygen levels before and after treatment with the catalytic converter, graphically illustrating the increase in oxygen concentration post-treatment, which aligns with the data shown in Table 1. This increase indicates a more complete combustion process, potentially reducing harmful emissions.

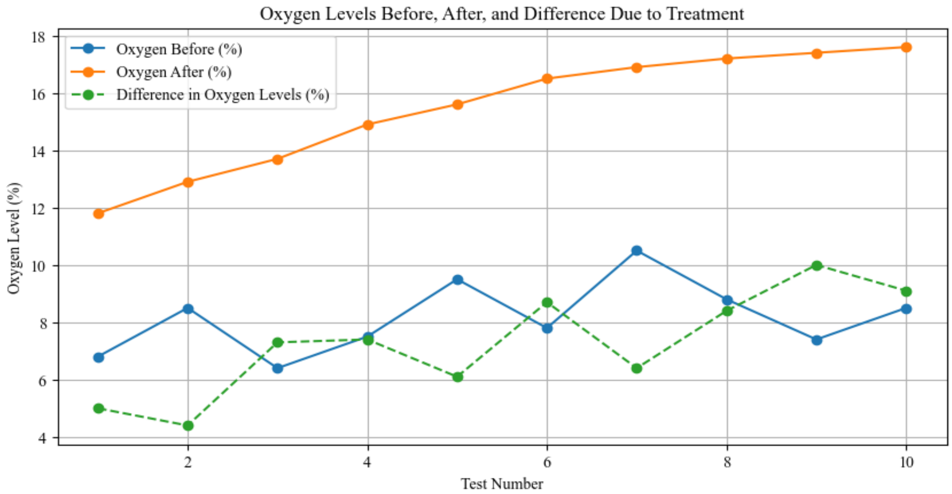

Figure 8. Comparative analysis of oxygen levels before and after treatment with catalytic converter

3.2. Measurement of exhaust gas emissions from diesel engines

Researchers employed an exhaust gas analyzer to assess the emission levels from diesel engines. This involved determining the gas concentrations resulting from the combustion process within the engine's exhaust. The analysis was carried out on a real vehicle, and measurements were taken ten times to ensure consistency and reliability. The collected data were then statistically analyzed, focusing on average values and standard deviations. The results are summarized in Table 2, which shows the concentrations of various gases at an engine speed of 1,200 RPM.

Table 2. Exhaust gas measurements from a diesel engine at 1,200 RPM

Gas Type	Average measured concentration (over 10 trials)
Oxygen (% volume)	17.50
Carbon Monoxide (ppm)	950.5
Carbon Dioxide (ppm)	532.0

3.3. Measurement of oxygen levels produced from the oxyhydrogen gas production system

Researchers utilized an oxygen analyzer (model JAY-120) to measure the oxygen levels generated by the oxyhydrogen gas production system. They conducted ten measurements and subsequently analyzed the data statistically to calculate mean values and standard deviation. The testing of the oxyhydrogen gas production system revealed that it can consistently produce oxygen at a concentration of 94.34%, making it viable for integration into relevant systems. From the results listed in Table 2, it is evident that the oxygen levels at the exhaust pipe were significantly lower than the normal atmospheric concentration of 20.9%. Additionally, high levels of carbon monoxide (CO) and carbon dioxide (CO_2) were recorded, indicating substantial emissions of these gases.

3.4. The utilization of oxygen produced by the developed oxyhydrogen gas production system in diesel engines

Researchers will introduce oxygen produced by the developed oxyhydrogen gas production system into the catalytic converter of a diesel engine's exhaust system. Subsequently, an exhaust gas analyzer will be used to measure the gas content in the diesel engine's exhaust to determine the amount of gas combusted from the exhaust. This testing will be conducted ten times, with the data recorded and analyzed statistically using mean values and standard deviation (S.D.), as shown in Table 3. From Table 3, it is evident that the oxygen content at the exhaust end has increased significantly, and the levels of CO have greatly decreased, while CO_2 levels have slightly decreased compared to the results without the system installed in Table 2. These results are presented as percentage reductions, illustrated in Figure 9.

Table 3. Test results of gas quantities in diesel engine exhaust after implementing the oxyhydrogen gas production system

Gas type	Average gas quantity measured over 10 Tests (ppm)
Oxygen (% volume)	18.9
Carbon Monoxide (ppm)	770.0
Carbon Dioxide (ppm)	434.0

3.5. Testing of the oxyhydrogen gas control system for vehicles

The research focused on the design and development of a system integrated with engine control through the OBD protocol. This phase involved creating compact, energy-efficient hardware and software suitable for vehicle exhaust systems, ensuring minimal modifications to the existing vehicle structure. The developed system seamlessly connects with the electronic engine control unit using an OBD module that communicates via Bluetooth, allowing easy pairing with a microprocessor for efficient oxygen measurements post-catalytic conversion. These capabilities were crucial for regulating the electrolysis process to reduce carbon monoxide and dioxide emissions, as depicted in Figures 9(a) and 9(b).

Subsequently, the system was installed on an ISUZU DMAX 2500 CC diesel vehicle with a common rail system, owned by the project leader. Before commencing real-world testing, the system was equipped with an exhaust reduction unit at the tailpipe. This setup facilitated the collection of operational data during testing, illustrated in Figures 9 (a) and 9(b), which underscored the system's efficacy in enhancing oxygen levels and reducing harmful emissions under controlled conditions.

Preliminary testing of the system at idle speeds of 1,000-1,200 RPM revealed significant improvements in exhaust gas composition. The results showed an increase in oxygen concentration at the exhaust, while carbon monoxide levels decreased substantially, and carbon dioxide levels slightly declined. These findings are detailed in Table 4 and Figure 10, which compares gas volumes before and after the system installation on a real vehicle.

(a) (b)

Figure 9. Vehicle system testing with installation: (a) system installation on an ISUZU DMAX 2500 CC diesel's exhaust pipe and (b) setup displaying the exhaust gas analyzer in use during testing

Table 4. The comparison of measured gas quantities before and after system installation

Type of Gas	Gas volume Before	Gas volume After	Percentage (- decrease / + increase)
Oxygen (% volume)	17.35	19.24	+9.82
Carbon Monoxide (ppm)	855.5	675.5	-21.04
Carbon Dioxide (ppm)	560.4	482.7	-13.86

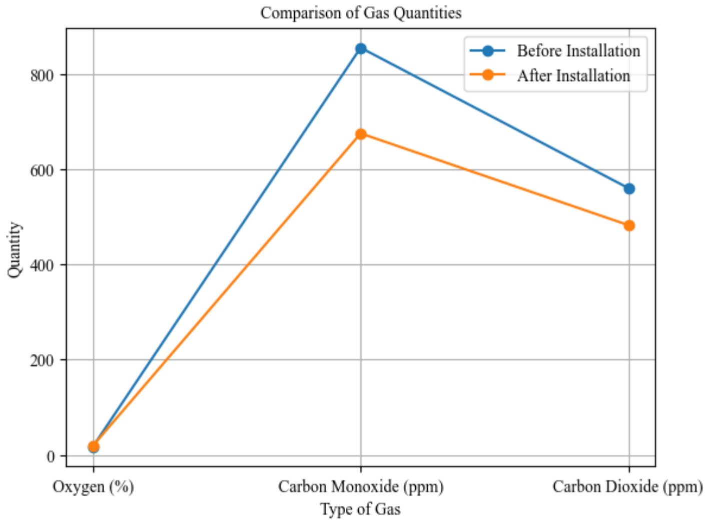

Figure 10. Comparative analysis of gas quantities before and after system installation

The experimental results demonstrate that the newly developed system effectively reduces harmful emissions from vehicles with internal combustion engines. By introducing oxyhydrogen gas (HHO) generated through electrolysis, the system enhances combustion efficiency by augmenting the oxygen supply in the combustion chamber, leading to more complete fuel combustion and decreased emissions of pollutants like CO and NOx. The resultant increase in exhaust oxygen levels further substantiates this efficiency improvement. Integration of a Bluetooth OBD scanner with an embedded microcontroller facilitates real-time electrolysis monitoring and control, critical for dynamically adjusting electrolysis parameters based on data from the vehicle's ECU. This technological synergy ensures robust data transmission and precise control via AT-commands between the ELM327 device and the Bluetooth module.

The system's impact on reducing greenhouse gas emissions carries substantial environmental and economic benefits, notably improving air quality and potentially reducing health risks associated with air pollution while saving fuel costs for vehicle owners. Despite these promising outcomes, challenges remain, particularly regarding the technical complexity of installing and maintaining the electrolytic cell and microcontroller, which may hinder widespread adoption. Future initiatives should aim at simplifying the system's design for better accessibility and conducting long-term durability and performance evaluations to ensure reliable operation over time.

The comprehensive satisfaction assessment conducted as part of this research aimed to gauge the response from exhaust system manufacturers and automotive professionals to the newly developed greenhouse gas reduction system. This evaluation was meticulously designed to encompass various critical aspects of the system's application in real-world automotive settings, using a structured satisfaction survey. Participants rated their satisfaction on a scale from 1 to 5, where scores ranged from minimal satisfaction to maximum satisfaction. The assessment covered the system's structural design and compatibility, where the overall design and individual components were evaluated for their suitability with automotive exhaust systems. This aspect included assessments of the design's appropriateness for practical use, the adaptability of the components used, and the ease of operational procedures. The high average score of 4.65 indicated robust approval of the system's structural integration. Furthermore, the system's control mechanisms and usability in operational settings received a commendable average score of 4.69. This score reflects that both the control interfaces and the operational procedures of the system are well-suited and user-friendly for their intended automotive applications. The practicality of maintaining and cleaning the prototype system was also highly rated, affirming the system's performance and maintenance ease in actual automotive environments, with an average satisfaction score of 4.50.

Overall, the feedback garnered from training participants was overwhelmingly positive, with high satisfaction scores across all evaluated categories, particularly in design and control mechanisms, culminating in an average overall satisfaction score of 4.61. This substantial approval, as highlighted during the training sessions and workshops (refer to Figure 11), is pivotal in driving forward the technology transfer process, ensuring that the system's benefits are effectively communicated and appreciated by the professional community. This enthusiastic reception is instrumental in further refining the system and promoting its widespread adoption to achieve significant reductions in vehicular emissions.

3.6. Future implications

The integration of embedded control systems with real-time exhaust monitoring introduces a promising direction for intermediate emission-reduction technologies. This system offers a practical retrofit solution for existing vehicles, especially in regions where full transition to electric vehicles is not yet viable. Experimental results demonstrated significant environmental impact, with a 21.04% reduction in carbon monoxide emissions, a 13.86% decrease in carbon dioxide levels, and a 9.82% increase in exhaust oxygen concentration. These improvements confirm the system's capability to enhance combustion efficiency and reduce harmful emissions effectively.

With further refinement, the system could be adapted into commercial after-market solutions or embedded in future automotive designs to comply with evolving global emission regulations. However, to ensure practical adoption, challenges such as system complexity, installation costs, and long-term durability must be addressed. Future research should focus on simplifying the system design, conducting extended field tests, and enhancing system reliability for large-scale implementation.

To promote technology transfer and evaluate user acceptance, workshops were organized with automotive professionals. Figure 11 illustrates key activities during these workshops. Figure 11(a) shows the presentation session, where researchers explained the system's design, functionality, and benefits. Figure 11(b) captures the system demonstration, highlighting real-time exhaust gas monitoring and control capabilities. Figure 11(c) depicts a discussion panel, where experts and participants provided feedback, discussed potential improvements, and explored practical implementation opportunities. These activities are essential to ensuring that the system's advantages are communicated effectively to stakeholders, facilitating widespread adoption in the automotive sector.

(a) (b) (c)

Figure 11. Workshop on new greenhouse gas reduction system for automotive professionals

4. CONCLUSION

The developed greenhouse gas reduction system for internal combustion engine vehicles has demonstrated significant potential in reducing harmful emissions and improving fuel efficiency. The integration of electrolysis technology with embedded microcontroller programming and real-time data processing offers an effective solution to the environmental challenges posed by vehicular emissions. Future research and development efforts should focus on optimizing the system design, enhancing user accessibility, and ensuring long-term reliability to facilitate widespread adoption and maximize environmental benefits.

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AUTHOR CONTRIBUTIONS STATEMENT

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Piyamas Chainok			✓	✓			✓			✓	✓		✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, PC, upon reasonable request.

REFERENCES

[1] V. Verma, M. Al-Dossari, J. Singh, M. Rawat, M. G. M. Kordy, and M. Shaban, "A review on green synthesis of TiO2 NPs: photocatalysis and antimicrobial applications," *Polymers*, vol. 14, no. 7, p. 1444, Apr. 2022, doi: 10.3390/polym14071444.

[2] A. Gougui, A. Djafour, M. B. Danoune, and N. Khelfaoui, "Field experience study and evaluation for hydrogen production through a photovoltaic system in Ouargla region, Algeria," *International Journal of Hydrogen Energy*, vol. 45, no. 4, pp. 2593–2606, Jan. 2020, doi: 10.1016/j.ijhydene.2019.11.188.

[3] L. Robles-Lorite, R. Dorado-Vicente, E. Torres-Jiménez, G. Bombek, and L. Lešnik, "Recent advances in the development of automotive catalytic converters: a systematic review," *Energies*, vol. 16, no. 18, p. 6425, Sep. 2023, doi: 10.3390/en16186425.

[4] O. Vermesan *et al.*, "Automotive intelligence embedded in electric connected autonomous and shared vehicles technology for sustainable green mobility," *Frontiers in Future Transportation*, vol. 2, p. 688482, Aug. 2021, doi: 10.3389/ffutr.2021.688482.

[5] E. Sokolovskij, A. Kilikevičius, A. Chlebnikovas, J. Matijošius, and D. Vainorius, "Innovative Electrostatic Precipitator Solutions for Efficient Removal of Fine Particulate Matter: Enhancing Performance and Energy Efficiency," *Machines*, vol. 12, no. 11, p. 761, Oct. 2024, doi: 10.3390/machines12110761.

[6] A. Ghafoor, J. Aldahmashi, J. Apsley, S. Djurović, X. Ma, and M. Benbouzid, "Intelligent integration of renewable energy resources review: generation and grid level opportunities and challenges," *Energies*, vol. 17, no. 17, p. 4399, Sep. 2024, doi: 10.3390/en17174399.

[7] A. Gupta *et al.*, "A comparative study of the impact on combustion and emission characteristics of nanoparticle-based fuel additives in the internal combustion engine," *Energy Science & Engineering*, vol. 12, no. 1, pp. 284–303, Jan. 2024, doi: 10.1002/ese3.1614.

[8] F. R. Malik, H.-B. Yuan, J. C. Moran, and N. Tippayawong, "Overview of hydrogen production technologies for fuel cell utilization," *Engineering Science and Technology, an International Journal*, vol. 43, p. 101452, Jul. 2023, doi: 10.1016/j.jestch.2023.101452.

[9] A. A. H. Faisal, S. F. A. Al-Wakel, H. A. Assi, L. A. Naji, and M. Naushad, "Waterworks sludge-filter sand permeable reactive barrier for removal of toxic lead ions from contaminated groundwater," *Journal of Water Process Engineering*, vol. 33, p. 101112, Feb. 2020, doi: 10.1016/j.jwpe.2019.101112.

[10] B. Nagappan, C. Chaudhary, D. K. Doda, and S. Kumar, "Review on smart grids and renewable integration: An artificial intelligence-powered perspective," *Multidisciplinary Reviews*, vol. 6, p. 2023ss070, Apr. 2024, doi: 10.31893/multirev.2023ss070.

[11] J. Huang, M. Chen, X. Zhang, W. Liu, and Y. Liu, "P-doped 3D graphene network supporting uniformly vertical MoS2 nanosheets for enhanced hydrogen evolution reaction," *International Journal of Hydrogen Energy*, vol. 45, no. 7, pp. 4043–4053, Feb. 2020, doi: 10.1016/j.ijhydene.2019.12.014.

[12] R. J. Farrauto, M. Deeba, and S. Alerasool, "Gasoline automobile catalysis and its historical journey to cleaner air," *Nature Catalysis*, vol. 2, no. 7, pp. 603–613, Jul. 2019, doi: 10.1038/s41929-019-0312-9.

[13] L. Masello, G. Castignani, B. Sheehan, F. Murphy, and K. McDonnell, "On the road safety benefits of advanced driver assistance systems in different driving contexts," *Transportation Research Interdisciplinary Perspectives*, vol. 15, p. 100670, Sep. 2022, doi: 10.1016/j.trip.2022.100670.

[14] N. Kim, S. Cha, and H. Peng, "Optimal control of hybrid electric vehicles Based on Pontryagin's minimum principle," *IEEE Transactions on Control Systems Technology*, vol. 19, no. 5, pp. 1279–1287, Sep. 2011, doi: 10.1109/TCST.2010.2061232.

[15] A. Buttler and H. Spliethoff, "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2440–2454, Feb. 2018, doi: 10.1016/j.rser.2017.09.003.

[16] Z. Bao *et al.*, "Overview of technological development challenges of diesel particulate filters adapting to future emission regulations," *Chemical Engineering Journal*, vol. 506, p. 159982, Jan. 2025, doi: 10.1016/j.cej.2025.159982.

[17] M. A. Judge, V. Franzitta, D. Curto, A. Guercio, G. Cirrincione, and H. A. Khattak, "A comprehensive review of artificial intelligence approaches for smart grid integration and optimization," *Energy Conversion and Management: X*, vol. 24, p. 100724, Oct. 2024, doi: 10.1016/j.ecmx.2024.100724.

[18] L. Ning, N. Wang, J. Fu, Y. Ma, S. Gu, and M. Cheng, "Effect of high-voltage electrostatic precipitator dust collection plate structure on collection efficiency," *ACS Omega*, vol. 9, no. 35, pp. 37396–37407, Sep. 2024, doi: 10.1021/acsomega.4c06500.

[19] M. A. Alreshidi *et al.*, "Hydrogen in transport: a review of opportunities, challenges, and sustainability concerns," *RSC Advances*, vol. 15, no. 29, pp. 23874–23909, 2025, doi: 10.1039/D5RA02918J.

[20] J. Mukherjee *et al.*, "Advanced oxidation process for the treatment of industrial wastewater: A review on strategies, mechanisms, bottlenecks and prospects," *Chemosphere*, vol. 345, p. 140473, Dec. 2023, doi: 10.1016/j.chemosphere.2023.140473.

[21] A. de Souza, J. F. de Oliveira-Júnior, K. R. A. Cardoso, and S. Gautam, "Impact of vehicular emissions on ozone levels: A comprehensive study of nitric oxide and ozone interactions in urban areas," *Geosystems and Geoenvironment*, vol. 4, no. 1, p. 100348, Feb. 2025, doi: 10.1016/j.geogeo.2024.100348.

[22] T. Qoria, H. Wu, X. Wang, and I. Colak, "Variable virtual impedance-based overcurrent protection for grid-forming inverters: small-signal, large-signal analysis and improvement," *IEEE Transactions on Smart Grid*, vol. 14, no. 5, pp. 3324–3336, Sep. 2023, doi: 10.1109/TSG.2022.3232987.

[23] A. Jaworek, A. Marchewicz, A. T. Sobczyk, A. Krupa, and T. Czech, "Recent advances in electrostatic precipitation of particles from flue gases generated by domestic heating appliances. A brief outlook." 2024. doi: 10.2139/ssrn.4690646.

[24] K. Hussain, N. A. Khan, V. Vambol, S. Vambol, S. Yeremenko, and V. Sydorenko, "Advancement in Ozone base wastewater treatment technologies: Brief review," *Ecological Questions*, vol. 33, no. 2, pp. 1–23, Feb. 2022, doi: 10.12775/EQ.2022.010.

[25] S. Sebastian, S. Wijewardane, and S. Srinivasan, "Recent advances in hydrogen production, storage, and fuel cell Technologies with an emphasis on inventions, innovations, and commercialization," *Solar Compass*, vol. 8, p. 100065, Dec. 2023, doi: 10.1016/j.solcom.2023.100065.

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