Converting Agricultural Engines to Run on Hydrogen: A Sustainable Solution to Climate Challenges

تحويل المحركات الزراعية للعمل بالهيدروجين كحل مستدام لمواجهة التحديات المناخية

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Abstract:

To meet the growing demand for low-emission agricultural machinery, researchers are exploring innovative and sustainable methods to reduce the environmental impact of internal combustion engines and lower greenhouse gas emissions. This study investigates the use of hydrogen as a supplementary fuel in diesel engines to maximize efficiency and minimize harmful emissions. The experiments were conducted at the Green Power H2O facility, where hydrogen was tested as a complete replacement for diesel fuel in a set of diesel engine pumps. Greenhouse gas emission levels were measured and compared between diesel and hydrogen operation, with strict adherence to safety standards for hydrogen usage. The tests were carried out under engine loads ranging from 30% to 70%. The results demonstrated a successful 100% replacement of diesel with hydrogen. No greenhouse gas emissions—carbon monoxide (CO), carbon dioxide (CO_2), or sulfur dioxide (SO_2)—were detected when using hydrogen. The exhaust gas velocity increased to 4 meters per second with the rise in hydrogen pressure. The water discharge rate reached 56 cubic meters per hour under the same engine load, surpassing that of diesel operation. This research highlights the potential of hydrogen as a clean and efficient alternative fuel, significantly reducing greenhouse gas emissions responsible for global warming while maintaining or enhancing engine performance.

Keywords: Carbon emissions, hydrogen, agricultural engines, sustainability, climate challenges

Introduction:

Achieving sustainability in the agricultural sector requires a multifaceted approach, including resource conservation, soil health management, efficient water use, and climate change mitigation. While agricultural machinery enhances productivity and expands farming operations, most machines still rely on diesel engines. Unfortunately, diesel engines contribute significantly to air pollution, emitting harmful substances such as carbon dioxide (CO_2), which accounts for 3% of global air pollution, along with nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM) (Nader, 2018). Additionally, about 25% of diesel engine energy is lost as waste heat.

These emissions have a direct impact on climate change, reinforcing the urgent need for cleaner, emission-free energy solutions (Mohamed. A,2019); (Peterson, 2022); (Sajan, 2021). The global shift toward sustainable fuel alternatives has gained momentum, with hydrogen emerging as a promising candidate (Priya et al., 2024). While some studies focus on reducing fossil fuel dependency—given their environmental and ecological risks (Jenni Bai et al., 2023; Aravindan et al., 2023)—others emphasize the transition to hydrogen as a long-term solution (Pravin,2015). Research has also explored hydrogen production methods to ensure sustainability (Ibrahim & Canan, 2015).

This study aligns with Egypt's 2030 vision for a cleaner, emission-free environment by investigating hydrogen as a replacement for diesel in agricultural engines. The experimental results demonstrate a complete elimination of carbon emissions when using hydrogen, marking a significant step toward sustainable farming practices. Replacing diesel fuel in agricultural engines with hydrogen demonstrates remarkable results in eliminating carbon emissions.

Research Significance

With global agriculture under increasing pressure to reduce its carbon footprint, switching from diesel to hydrogen engines is emerging as a radical solution. On the one hand, conventional diesel-powered agricultural machinery is a major contributor to greenhouse gas emissions, releasing harmful pollutants such as carbon dioxide and sulfur dioxide, which contribute significantly to climate change. Hydrogen, on the other hand, offers a zero-emission alternative, as its combustion produces only water vapor, completely eliminating carbon emissions. In addition to environmental benefits, hydrogen enhances operational efficiency. Some studies suggest that hydrogen engines can match or outperform diesel engines, but less attention has been given to the critical importance of reducing or eliminating emissions with improved water discharge rates, which is critical for irrigation and agriculture in harsh environmental conditions. Furthermore, the scalability of hydrogen aligns with global sustainability goals, offering a practical path to decarbonizing food production while maintaining productivity.

Hydrogen adoption in agriculture is not just an innovation; it is essential to mitigate challenges, achieve climate emissions targets, and secure the future of the agricultural sector. By investing in this clean energy transition, stakeholders can boost environmental resilience and agricultural sustainability.

Research Problem

While hydrogen holds significant promise as a clean fuel for the agricultural sector, the conversion of traditional diesel engines to hydrogen faces several critical challenges. First, there are technical obstacles related to developing safe and efficient infrastructure for hydrogen storage and distribution, particularly in rural and remote areas where agricultural activities are concentrated. Second, the high conversion costs for existing equipment may pose a barrier for farmers, especially in developing countries with limited resources.

Additionally, the lack of technical awareness among agricultural workers regarding the operation and maintenance of hydrogen-powered engines could slow the transition. Questions also arise regarding the source of hydrogen production itself. If it is generated using fossil fuels, the environmental benefits become limited.

However, this problem presents important research and practical opportunities. There is an urgent need for in-depth studies on improving hydrogen combustion efficiency, developing innovative financing solutions to facilitate the transition, and establishing supportive government policies. This promising field also requires international collaboration to share knowledge and develop unified safety and performance standards.

Thus, this research seeks to address these comprehensive challenges by assessing the technical and economic feasibility of equipment conversion, analyzing long-term environmental impacts, and proposing an integrated framework for real-world implementation.

Research Objectives

The primary objective of this research is to investigate the viability of hydrogen as a clean energy alternative for agricultural engines, with the overarching goal of reducing carbon emissions and mitigating climate change impacts. The study specifically aims to:

1. Evaluate the technical feasibility and assess the performance and efficiency of hydrogen-powered engines compared to conventional diesel engines under various operational conditions, including different load capacities (30% to 70%) and real-world farming scenarios.
2. Analyze the environmental benefits of reducing greenhouse gas emissions (CO, CO_2, and SO_2) achieved by replacing diesel with hydrogen, emphasizing the potential to meet global sustainability targets in the agricultural sector.
3. Identify implementation challenges and examine the infrastructural, economic, and safety barriers to widespread hydrogen adoption, including storage, distribution, and engine modification requirements.
4. Propose practical solutions and develop actionable strategies to overcome adoption hurdles, such as cost-effective conversion technologies, policy incentives, and training programs for farmers and technicians.
5. Promote sustainable practices and highlight hydrogen’s role in supporting climate-smart agriculture, ensuring food security while aligning with the global transition to net-zero emissions.

By addressing these objectives, this research seeks to provide a comprehensive framework for decarbonizing agricultural machinery, contributing to environmental conservation, reducing greenhouse gas emissions, and making agricultural systems more sustainable.

Research Methodology

1. Experimental Approach
   - Conduct laboratory tests on diesel engines modified to run on hydrogen.
   - Compare engine performance using conventional diesel fuel versus hydrogen.
   - Measure emissions (CO_2, CO, SO_2, NOx) under different operating conditions (30%-70% of load).
2. Quantitative Analysis
   - Collect technical data (combustion efficiency, fuel consumption, service life).
   - Use precise measurement tools (e.g., exhaust analyzers, flow meters).
   - Apply statistical analysis to compare results.
3. Case Study Approach

- Apply the model to a specific farm/area.
- Monitor practical challenges during actual implementation.
- Measure key performance indicators (KPIs).

Previous Studies

Brzeziński and Pyza (2021), in their study titled “Carbon Dioxide Emission from Diesel Engine Vehicles in Intermodal Transport,” stated that many logistics operators operate in both domestic and foreign markets using various forms of transport organization. Choosing a corresponding technology and appropriate form of transport has an influence not only on delivery time and costs but also on the environment as a whole. There is a plethora of public research available in global literature discussing various ways of tapping transport. Nonetheless, there is a lack of complex studies detailing carbon emissions coming from transport activity, specifically where a theory of organic fuel combustion in the form of a chemical reaction with oxygen is considered. To fill this gap, we offer an innovative Emission Model of Industrial Sources (EMIS) method. This method makes it possible to determine the amount of CO_2 emitted into the atmosphere via various transport methods. It also enables us to estimate, in terms of CO_2 output, a threshold where transport of containers via combined mode becomes more favorable for the environment than road transport. We ran a simulation of our algorithm to create boundary conditions. This lets us prepare a regression function of CO_2 emissions for intermodal and road transport as a function of various transport distances. The simulation results suggest that our approach may be used by supervisory institutions responsible for developing and utilizing combined transport.

According to Megía et al. (2021), in a study titled "Hydrogen Production Technologies: From

Fossil Fuels toward Renewable Sources," the global economic growth, the increase in the population, and advances in technology lead to an increase in the global primary energy demand. Considering that most of this energy is currently supplied by fossil fuels, a considerable amount of greenhouse gases is emitted, contributing to climate change, which is the reason why the next European Union binding agreement is focused on reducing carbon emissions using hydrogen. This study reviews different technologies for hydrogen production using renewable and non-renewable resources. Furthermore, a comparative analysis is performed on renewable-based technologies to evaluate which technologies are economically and energetically more promising. The results show how biomass-based technologies allow for a similar hydrogen yield compared to those obtained with water-based technologies, but with higher energy efficiencies and lower operational costs. More specifically, biomass gasification and steam reforming obtained a proper balance between the studied parameters, with gasification being the technique that allows for higher hydrogen yields, while steam reforming is more energy-efficient. Nevertheless, the application of hydrogen as the energy vector of the future requires both the use of renewable feedstocks and a sustainable energy source. This combination would potentially produce green hydrogen while reducing carbon dioxide emissions, limiting global climate change, and, thus, achieving the so-called hydrogen economy.

Furthermore, as stated by Lee et al. (2023) in "Probabilistic Assessment of Cereal Rye Cover Crop Impacts on Regional Crop Yield and Soil Carbon," field studies on the effects of winter cover crops (WCCs) in agricultural systems are often costly, demand substantial labor, and are restricted in their applicability to localized sites. To overcome these limitations and enable broader spatial and temporal assessments, this study employed the Agricultural Production Systems Simulator (APSIM) model to investigate alternative crop rotation systems. Specifically, two WCC-integrated rotations—corn–rye–corn–rye and corn–rye–soybean–rye—were compared against conventional rotations of continuous corn and corn–soybean. Simulations were conducted across the state of Illinois at a spatial resolution of 5 km × 5 km over a twenty-year period (2000–2020).

The primary objective of this analysis was to assess the extent to which the integration of winter cover crops (WCCs) influences both soil organic carbon (SOC) dynamics and crop productivity across diverse environmental and management contexts. To enhance robustness, the modeling framework incorporated multiple sources of uncertainty, including baseline soil conditions, interannual climatic variability, heterogeneity in soil properties, and variations in management practices. By employing this probabilistic approach, the study was able not only to estimate the likelihood of positive or negative outcomes but also to quantify the expected magnitude of changes in crop yields and SOC following WCC adoption. This framework, therefore, offers a more comprehensive and scalable understanding of the potential benefits and trade-offs associated with integrating winter cover crops into agricultural systems.

The findings indicate that integrating cereal rye into rotations enhanced corn yield stability statewide. Notably, regions with a low probability of immediate SOC increase ($p < 0.75$) still showed significant potential for long-term carbon sequestration with sustained WCC use. This study offers the most comprehensive uncertainty analysis of WCC benefits to date, providing valuable insights into their spatially and temporally variable advantages to support broader adoption.

Moreover, a study by Bahmanpour et al. (2024), titled "The Effect of Temperature and Drying Method on Drying Time and Color Quality of Mint", examined the combined effects of low-concentration hydrogen peroxide (H_2O_2) solutions and transient spark discharge plasma on Pectobacterium inactivation. The interaction between these two treatments is evaluated for potential synergistic antimicrobial activity. Furthermore, the chemical and physical properties of the plasma-treated H_2O_2 solution are analyzed to better understand the underlying mechanisms. Ultimately, this approach can be presented as an eco-friendly solution for rinsing citrus fruits on an industrial scale.

Barzanouni et al. (2024) investigated the synergistic effect of Atmospheric Pressure Cold Plasma (APCP) and hydrogen peroxide (H_2O_2) on the control of citrus postharvest green mold. The fungal isolate was cultured on Sabouraud Dextrose Agar (pH 5.6) at 27 °C for seven days. The researchers adjusted the spore concentration to approximately 10^6 spores/mL using UV spectrophotometry (absorbance 0.1 at 420 nm), following the procedure described by Palou et al. (2002).

The experimental setup employed a point-to-plane plasma reactor, in which a high-voltage needle electrode was positioned 15 mm above a Petri dish containing the spore suspension mixed with H_2O_2 at concentrations of 0.05%, 0.1%, or 0.5% (v/v). A grounded electrode was submerged in the solution. The reactor was operated with an 18 kV transient spark discharge (pulse duration <100 ns, current >1 A, frequency 0.5–10 kHz) and supplied with an airflow of 2 L/min. The authors conducted treatments for 2.5, 5, 10, and 15 minutes on 5 mL spore suspensions. Following the treatments, they measured the concentrations of H_2O_2, NO_2^-, and NO_3^-, in addition to pH and electrical conductivity. The collected data were statistically analyzed using SAS version 9.4.

Additionally, Mattalitti, Hos, et al. (2024), stated in a study titled "Sustainable Agriculture Development and Food Security: A Systematic Review, Indonesian Annual Conference Series," that sustainable agriculture is essential to ensure food security, especially in agriculturally rich regions like Southeast Sulawesi. This review consolidates current research on sustainable agricultural practices in the region, evaluating their role in enhancing food security. Key themes explored include the synergy between traditional farming techniques and modern sustainable approaches, the influence of local institutions in promoting sustainable agriculture, and socioeconomic challenges, such as limited financial resources and labor availability, which hinder widespread adoption.

By analyzing existing methodologies, socioeconomic conditions, and institutional frameworks, this review offers a holistic perspective on how sustainable agriculture can strengthen food supply stability in Southeast Sulawesi. The findings provide actionable insights for policymakers and practitioners seeking to implement effective and scalable sustainable farming strategies (Felix Donkor &Kevin Mearns, 2021). In recent times, the environmental impacts of energy supply have progressively gained policy focus on the sustainable development agenda. The United Nations and other international organizations have encouraged governments to significantly expand the share of renewable energy, while greener technologies are being promoted, especially in resource-rich nations. However, countries are at diverse levels of development and thus confronted with unique energy challenges (San Miguel and Cerrato, 2020).

It is therefore necessary to introduce tailored measures to successfully transition to a low-carbon economy (Rana et al. 2020). The shift toward a low-carbon society represents a significant paradigm shift in the energy sphere toward sustainable development. Sustainable development denotes a development paradigm that seeks to enhance human development goals and concurrently safeguard the capacity of ecological systems to supply the natural resources and ecosystem services that support the social economy (Ozturk and Acaravci, 2011; Shaker, 2015). A more widespread definition traced to the Brundtland Report of the concept of sustainable development, first formally defined in 1987, emphasizes fulfilling current societal needs while safeguarding the capacity of future generations to meet theirs. Over time, this framework has evolved to integrate three key pillars: economic growth, social equity, and environmental protection, ensuring long-term planetary and societal well-being (Van Pelt et al. 2014).

Consequently, sustainability should be viewed as humanity's target of human-ecosystem equilibrium, while sustainable development refers to the holistic approach and temporal processes that lead us to the end point of sustainability (Shaker, 2015). There have been several policy innovations to address this agenda of sustainable development across the globe. The United Nations' Sustainable Development Goals (SDGs) are widely recognized as the global blueprint for facilitating the sustainable development agenda. In this regard, it is essential to use environmentally friendly approaches to meet the escalating global energy demands for clean energy solutions and sustainable development. In other words, sustainable development seeks to enhance the living standards of people, fulfill essential social needs, and minimize resource degradation during related processes, thereby ensuring a balance between economic growth, social welfare, and environmental protection (Ozturk and Acaravci, 2011). This study looks at a myriad of topics relating to clean energy use, environment, and sustainable development, highlighting the significance of clean energy usage for both developed and developing countries.

Furthermore, a study on hydrogen as an alternative fuel, by Vinoth Kanna (2018), states that as oil prices increase, the interest in alternative fuels increases. Growing concerns over global air pollution have intensified the urgency for cleaner energy solutions. Initiatives like India's demonstration programs highlight national commitments to addressing this challenge. Rising oil prices further accelerate the competitiveness of alternative fuels, though critical uncertainties remain—particularly regarding which fuels will dominate and to what extent they can displace gasoline as the primary petroleum derivative. The transition will likely involve a mix of alternatives, shaped by technical feasibility, policy support, and market dynamics.

However, widespread adoption faces barriers, including economic constraints, technological limitations, and infrastructural gaps. Historically, gasoline's affordability and abundance have overshadowed alternatives, but volatile oil markets could rapidly alter this landscape. Among the promising options, biomass-derived fuels and hydrogen stand out. Hydrogen, in particular, holds transformative potential: Fuel cells could replace batteries in portable electronics, power vehicles, and even residential electricity supply.

Lipei Fu et al. (2022) suggested in their study "Research Progress on CO_2 Capture and Utilization Technologies" that industrial expansion has led to escalating greenhouse gas emissions, thus exacerbating climate change impacts. As the primary driver of the greenhouse effect, CO_2 mitigation has become a critical global priority. While source reduction efforts have shown limited success, emerging perspectives recognize CO_2 not merely as a pollutant but as a valuable carbon resource. This dual nature has spurred significant research into advanced capture and utilization strategies. This review first comprehensively evaluates state-of-the-art CO_2 capture technologies, including chemical absorption processes, adsorption using solid-phase porous materials, membrane separation systems, cryogenic separation techniques, hydrate-based methods, and microbiological approaches. The paper then systematically analyzes CO_2 utilization pathways across four domains: physical applications, chemical conversion processes, biological utilization methods, and mineralization techniques. Notably, the work highlights several cutting-edge CO_2 resource utilization technologies. Through comparative analysis of various methods' advantages and limitations, this review provides critical insights and references for addressing CO_2-related challenges, offering valuable guidance for future research directions in carbon capture and utilization.

As suggested by Singh et al (2023), in their study titled "Carbon Capture, Sequestration and Utilization for Sustainable Environmental Solutions: Current Advancements and Future Prospects," carbon capture and sequestration (CCS) has emerged as a critical component of global energy strategies, offering significant potential for reducing CO_2 emissions from conventional fossil fuel power plants. This comprehensive review examines current CCS technologies, including capture methods, pre-combustion systems, post-combustion processes, oxyfuel combustion technology, and direct air capture (DAC) systems. The study provides a detailed analysis of the technical parameters influencing CCS efficiency and implementation. Our evaluation reveals that existing CO_2 sequestration technologies are already being deployed at commercial scales, yielding valuable derivatives such as specialty chemicals, advanced polymers, and sustainable construction materials. Among emerging technologies, DAC has demonstrated particularly promising results with increasing commercial adoption. The review identifies several potential future applications while addressing current implementation challenges. We propose policy frameworks to accelerate CCS deployment and support global decarbonization efforts. This work serves as both a technical reference and a strategic guide for researchers and policymakers working toward sustainable carbon management solutions.

Materials and Methods:

This study investigates the partial substitution and complete replacement of diesel fuel with hydrogen in a diesel engine pump set. The experimental setup utilizes a modified diesel engine configuration, with Table 1 detailing the technical specifications of the pump set unit (https://www.man.eu/engines/en/products/on-road/busses-and-special-vehicles/busses-and-special-vehicles.html).

Table 1: Engine specifications

Model	APAN diesel RTM
Bore	78 mm
Stroke	78.4 mm
Power	20 HP
Cooling	Air
Starting system	Manual
Cylinder NO.	1
Pump inlet	5 Inch
Pump outlet	5 Inch
Q	80 m^3/hr.
Pressure	10 Pa

The research began with preliminary tests using conventional diesel fuel. The engine was operated according to standard procedures, while one of the researchers, who holds a license for measuring carbon emissions and preparing carbon footprint reports from the National Quality Institute of the Egyptian Organization for Standardization and Quality (license number: NQI/CFP/05/25/239), measured the amount of greenhouse gas emissions from the diesel fuel using the E8500 gas analyzer, as shown in Figure 1 (https://site.jjstech.com/pdf/E-Instruments/E8500-Manual.pdf). Table 2 shows the specifications and measurement range of the device, and the combustion equation for diesel fuel is given below:

$$C_{13}H_{28} + 20\ O_2 \rightarrow 13\ CO_2 + 14\ H_2O$$

Figure 1: Gas analyzer E8500

Source: https://analyserservices.com/product/e8500-plus-portable-industrial-combustion-gas-emissions-analyzer/

Table 2: Gas analyzer specification

Model	E8500	
Physical	Material: ABS plastic case with internal aluminum shielding. Dimensions (analyzer): 11.42” x 10.24” x 4.88”/29.0 x 26.0 x 12.4 cm. Weight: (analyzer): 11 lbs./5 kg. Carrying case (analyzer & all accessories): Approx. 22 lbs. / 10 kg	
Power	7.2 Volt, 8 AH rechargeable battery pack. Operating time: 4 to 8 hours, 110/240 VAC input, 12 V/2.5A fast charger. Charging time: 6 hours minimum.	
Instrument pumps	Gas sample pump: high-quality diaphragm pump with long-life motor. CO dilution pump. Automatic condensate drain pump.	
Gas-range	Carbon monoxide (CO)	0% - 10% 10% - 15%
	Carbon dioxide (CO_2)	0% - 20% 20% - 50%
	Hydrocarbons (HC or CxHy)	0 - 0.40 % 0.40 – 1.00 % 1.00 – 3.00 %
	Oxygen (O_2)	0 – 25%
Temperature	0 – 2000 ºF (0 – 1100ºC)	
Velocity	10 – 300 ft/sec (3 – 100 m/sec)	

In the second phase, the engine was transitioned from diesel to hydrogen fuel by gradually introducing hydrogen at 3 PSI while proportionally decreasing diesel input until achieving pure hydrogen operation, with critical safety measures implemented to prevent backfiring, including the installation of a flashback arrestor between the hydrogen source and engine, as shown in Figure 2. The hydrogen was supplied directly from an electrolyzer cell (Figure 3 and Table 3), powered by a solar array, which continuously produced hydrogen through water electrolysis; the generated hydrogen then flowed through a regulator and buffer before entering the engine's combustion system, where it burned according to the stoichiometric hydrogen combustion equation, enabling carbon-free operation while maintaining performance comparable to diesel fuel. The hydrogen goes into the hydrogen poplar, then into the inlet to the engine for combustion according to the following equation:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$$

Figure 2: Flashback arrestor

Source: https://www.howoautopart.com/hirschmann-607495-sensor-davs-300-for-xcmg

Table 3: Electrolyzer aspects

Dimension	20*20*15 cm
Pressure	4 PSI
Rate	0.2 L/min
Solar cell	12 V & 30 A

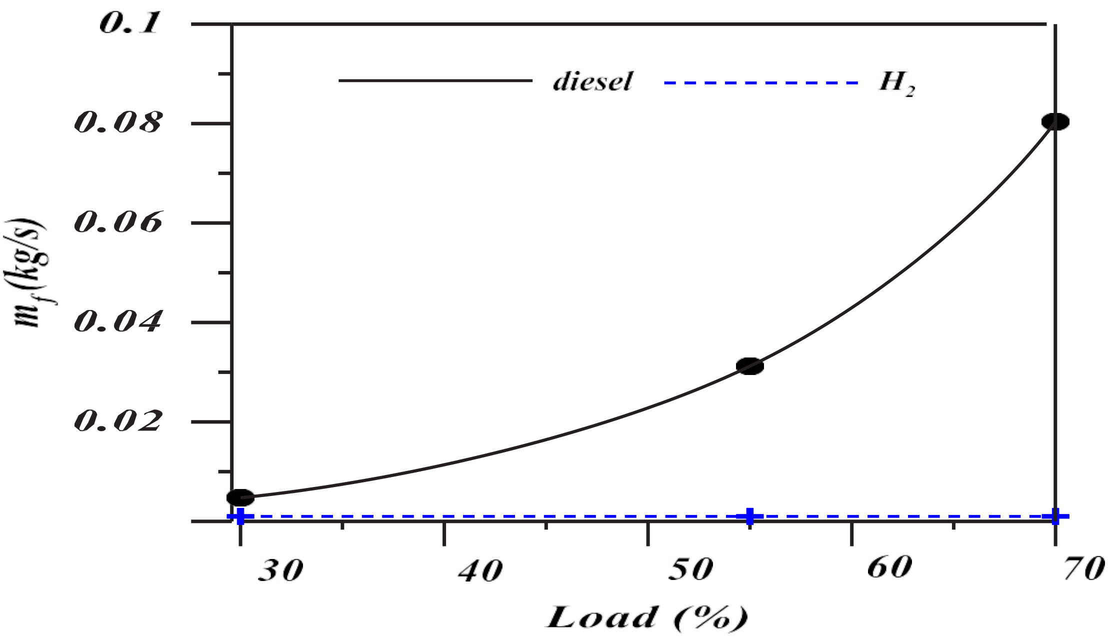
Figure 3: Hydrogen electrolyzer

Source: Manufactured by Green Power Company https://greenpowerh2o.website/

Results:

Experimental results demonstrated distinct performance characteristics between diesel and hydrogen across varying engine loads (30-70%). As shown in Figure 4, diesel fuel consumption increased linearly from 0.008 kg/s at 30% load to 0.08 kg/s at 70% load, while hydrogen maintained near-zero consumption under all load conditions. Comparative analysis revealed significant differences in exhaust temperatures, with hydrogen operation demonstrating near-elimination of carbon emissions (carbon monoxide, carbon dioxide, and sulfur oxides), with minimal secondary effects due to operational factors. Improved exhaust flow dynamics were observed, particularly at high pressures where hydrogen achieved superior speeds. Together, these results highlight the advantages of hydrogen in agricultural applications, offering comparable engine performance to diesel while significantly reducing fuel consumption and environmental impact through carbon-neutral combustion with minimal emissions that could be overcome in the future.

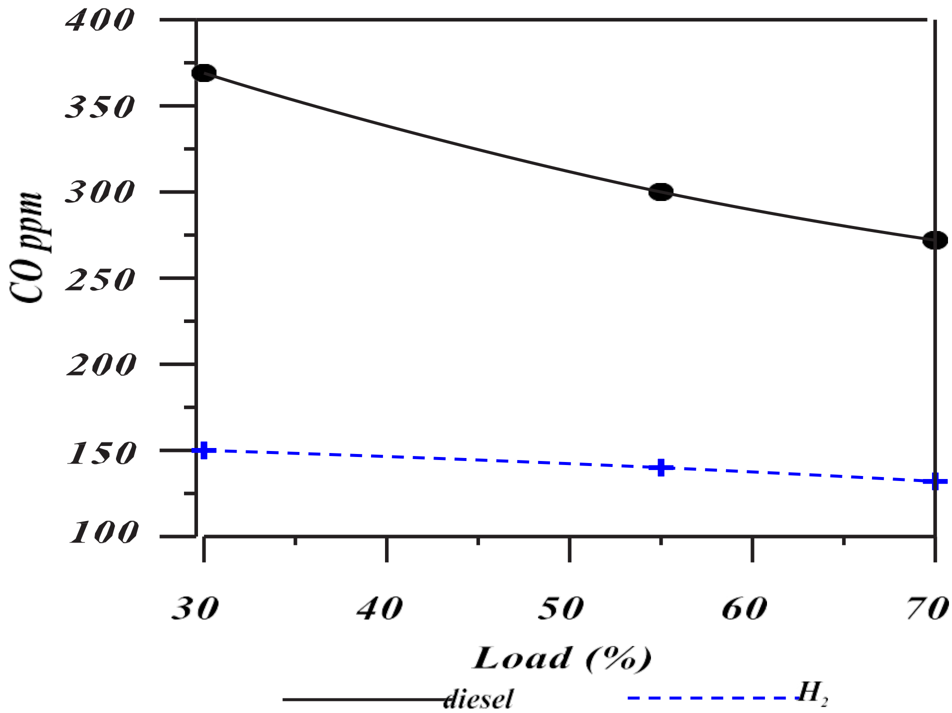
Figure 4: Engine load vs. fuel consumption



Source: Ahmed Mohamed Ibrahem; Ahmad Gomaa Mohamed; Moataz Ahmed Mahfouz, et al. *Journal of Agricultural & Environmental Sciences (Damanhour University)*. (2024). Volume 23, Issue 1. Pages 372-386

As illustrated in **Figure 5**, the comparative analysis of carbon monoxide (CO) emissions reveals significant improvements when using hydrogen fuel versus conventional diesel. While diesel operation showed CO levels decreasing from 340 ppm to 270 ppm as engine load increased from 30% to 70%, hydrogen fuel demonstrated substantially lower emissions, ranging from just 150 ppm to 130 ppm across the same load spectrum. These results clearly indicate hydrogen's superior environmental performance, with CO emissions reduced by approximately 55-60% compared to diesel operation, confirming its potential as a cleaner alternative fuel for agricultural machinery applications.

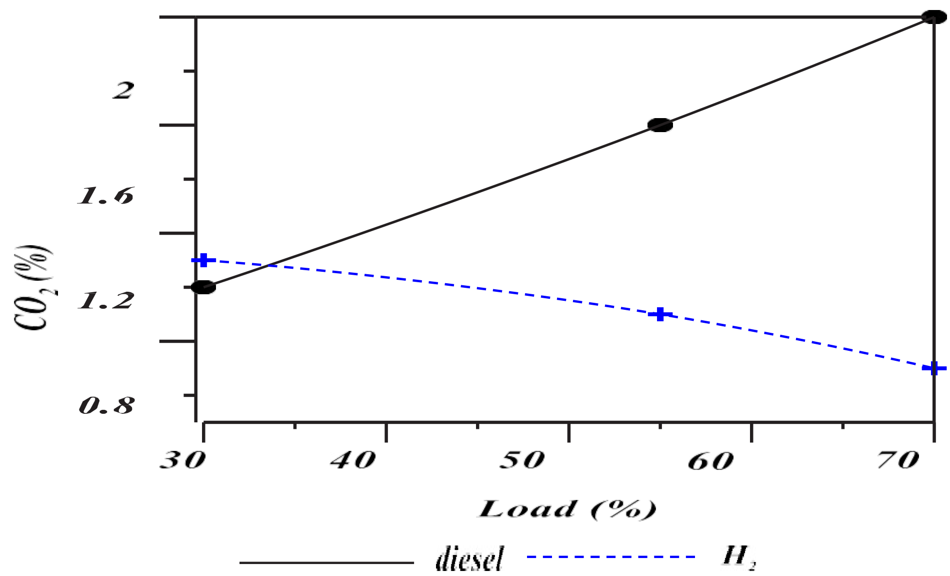
Figure 5: Engine load vs. carbon monoxide percentage



Source: Ahmed Mohamed Ibrahem; Ahmad Gomaa Mohamed; Moataz Ahmed Mahfouz, et al. *Journal of Agricultural & Environmental Sciences (Damanhour University)*. (2024). Volume 23, Issue 1. Pages 372-386.

Figure 6 shows the relationship between engine load and carbon dioxide (CO_2) percentage when using both fuel types. The carbon dioxide increases from 1 % to 2 % with increased engine load when using diesel fuel, but when using hydrogen fuel, carbon dioxide decreases from 0.9 % to 0.7 % with increased engine load. So, it is a significant improvement in the percentage of carbon monoxide when using hydrogen fuel than diesel fuel.

Figure 6: Engine load vs. carbon dioxide percentage



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As shown in Figure 7, the results reveal distinct behaviors of nitrogen monoxide (NO) emissions between diesel and hydrogen operation. In the case of diesel fuel, NO emissions increase moderately from 5 ppm to 12.5 ppm as engine load rises. This trend can be attributed to higher in-cylinder temperatures at greater loads, which promote thermal NO formation via the Zeldovich mechanism. However, overall NO levels remain comparatively low because diesel combustion is not perfectly clean; the presence of carbonaceous species and incomplete oxidation consumes part of the available oxygen, thereby limiting nitrogen–oxygen interactions.

By contrast, hydrogen combustion produces significantly higher NO concentrations, starting at 23 ppm under low load. This is primarily due to hydrogen's unique combustion properties: a very rapid flame speed, high diffusivity, and elevated flame temperatures compared to diesel. These conditions create favorable environments for NO formation in the early stages of combustion. Interestingly, as the load increases, NO emissions decrease slightly (from 23 ppm to 18.6 ppm). This counterintuitive decline can be explained by improved mixture homogeneity and higher in-cylinder densities at elevated loads, which reduce localized hot spots and consequently lower peak NO generation.

On the one hand, diesel fuel produces lower NO emissions than hydrogen, yet this comes at the expense of significant carbon dioxide and particulate matter emissions. Hydrogen, on the other hand, eliminates CO_2 and PM completely but poses challenges related to NOx formation due to its high-temperature combustion characteristics. These findings highlight that the key challenge in adopting hydrogen as a sustainable fuel lies not in carbon-related emissions—which are entirely avoided—but in controlling nitrogen oxides. Future mitigation strategies could involve exhaust gas recirculation (EGR), water or steam injection, or advanced catalytic after-treatment systems specifically designed for hydrogen engine emissions compared to hydrogen fuel.

Figure 7: Engine load vs. nitrogen monoxide percentage

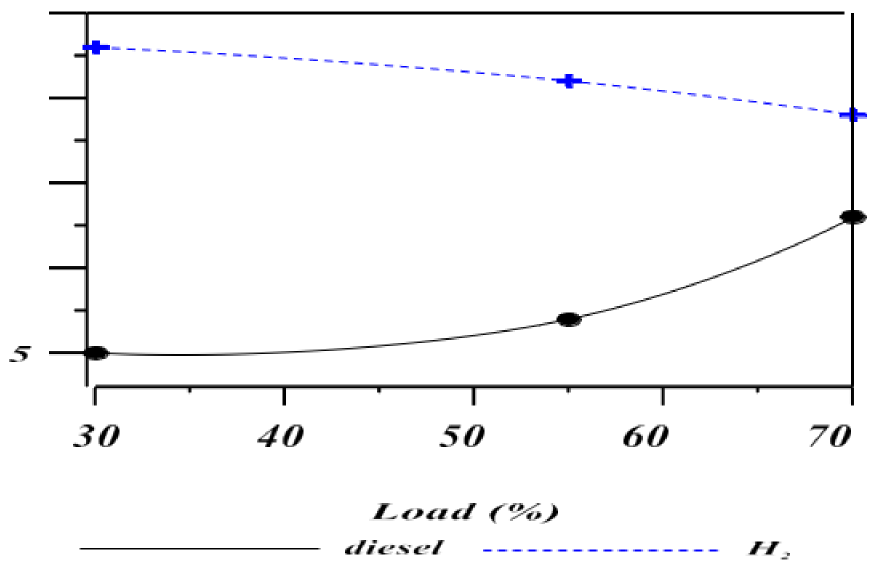

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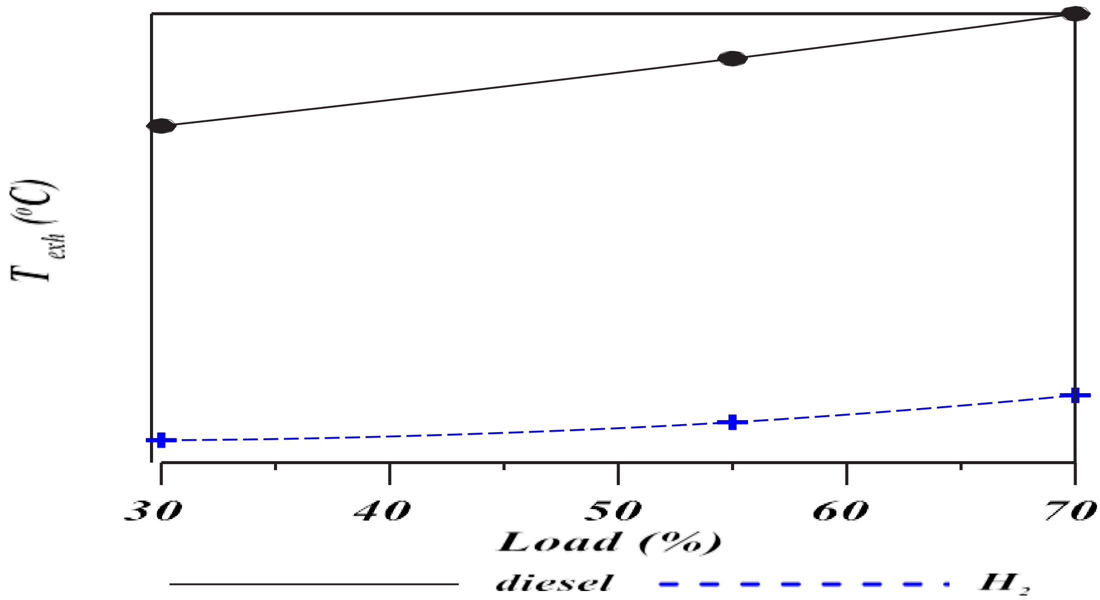
Figure 8 shows the relationship between engine load and exhaust temperature, which increases from 145 °C to 150 °C when using diesel fuel and increases from approximately 131 °C to 133 °C when using hydrogen fuel under the same operating conditions. This comparison highlights the lower exhaust gas temperatures associated with hydrogen combustion, reflecting its cleaner burning characteristics and reduced heat release relative to diesel.

Figure 8: Engine load vs. exhaust temperature



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Compared to conventional diesel fuel, the use of hydrogen results in lower exhaust gas temperatures, ranging between 131 °C and 133 °C under increasing engine load. This difference arises from the distinct combustion characteristics of hydrogen, which include higher flame propagation speed, the absence of carbon-based compounds, and more complete combustion with reduced formation of soot and unburned hydrocarbons. In contrast, diesel combustion involves slower flame development and partial oxidation of carbon-containing molecules, leading to higher heat release and consequently higher exhaust temperatures.

Figure 9 presents the relationship between engine load and exhaust velocity for both diesel and hydrogen fuel. The exhaust velocity increases from 0.001 m/s to 0.2 m/s with engine load when using diesel fuel, and the exhaust velocity increases from 3.95 m/s to 4.15 m/s with engine load when using hydrogen fuel, but when using hydrogen fuel, the velocity is higher than when using diesel fuel.

Figure 9: Engine load vs. exhaust velocity

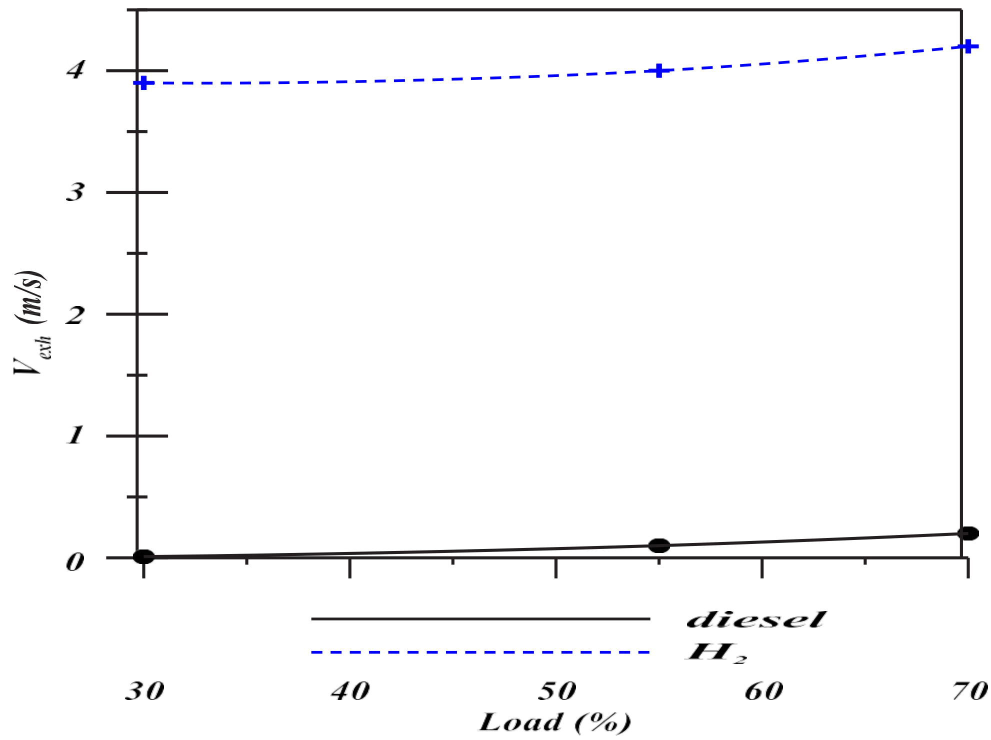

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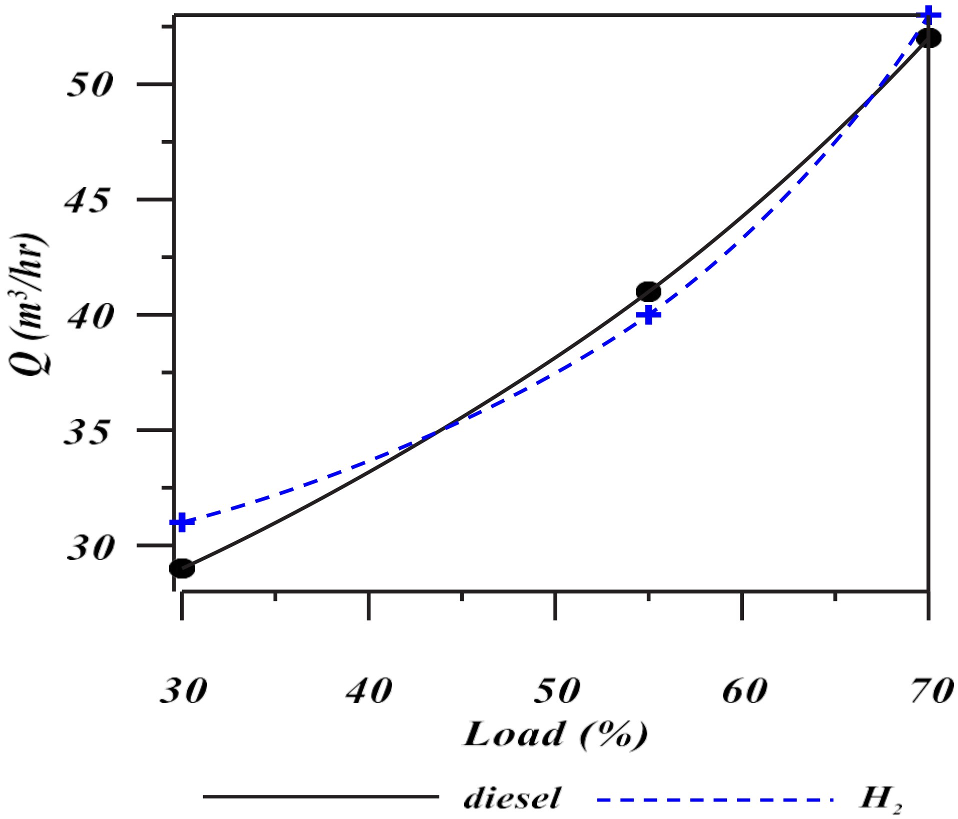
Figure 10 shows the relationship between engine load and pump discharge rate for both diesel and hydrogen fuels. For the diesel engine, the discharge rate increases from 28 m³/hr. to 54.6 m³/hr. as engine load rises. Similarly, with hydrogen fuel, the discharge rate increases from 32 m³/hr. to 56 m³/hr. Overall, the pump discharge rate is higher when using hydrogen fuel compared to diesel, indicating improved performance at the same engine load levels.

Figure 10: Engine load vs. pump discharge rate



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The Safety of Hydrogen Use in Agricultural Environments

The integration of hydrogen as a clean energy carrier in agricultural environments—powering machinery, irrigation pumps, and greenhouse operations—offers a promising path toward decarbonization. However, its safe deployment necessitates a rigorous understanding and implementation of specific safety protocols due to its unique physicochemical properties: a wide flammability range (4-75% in air), low ignition energy, and high propensity to leak.

- **Storage Safety:** On-farm hydrogen storage requires carefully designed safety systems, most commonly in the form of high-pressure gaseous storage or cryogenic liquid storage. For gaseous hydrogen, storage tanks must comply with international pressure vessel standards (e.g., ASME or ISO). They should be fitted with thermally activated pressure relief devices (TPRDs) to prevent over-pressurization and placed in secure, well-ventilated outdoor areas. These precautions reduce the risk of tank rupture and help avoid the buildup of leaked hydrogen, which could create a flammable atmosphere. In the case of liquid hydrogen (LH_2), storage dewars need to be equipped with vacuum insulation and pressure-build circuits to control boil-off gas. They should also be located away from ignition sources and protected from direct sunlight to minimize safety hazards.

- **Transportation Safety**: The movement of hydrogen within the farm premises, whether via pipelines or mobile trailers, demands robust integrity. Pipelines should be constructed from hydrogen-compatible materials (e.g., specific grades of stainless steel) to avoid embrittlement and leakage. They must be clearly marked, buried, or shielded and feature automated shut-off valves. Mobile transport requires securing tanks to prevent damage during transit, following designated routes away from high-traffic areas, and ensuring all connections are leak-free before operation.
- **Maintenance and Operational Safety:** A comprehensive safety culture is paramount. This includes the mandatory use of hydrogen-specific leak detection sensors in storage, maintenance, and operational areas to provide early warnings. Strict ignition control protocols must be enforced, such as prohibiting open flames and using intrinsically safe electrical equipment. Crucially, personnel require specialized training in hazard awareness, emergency procedures (e.g., emergency shutdowns), and proper maintenance practices for hydrogen systems. All equipment must be grounded to prevent static electricity buildup, and regular maintenance schedules must be adhered to inspect for material fatigue and potential leaks (Ibrahim & Kannan, 2015; Sajjan, 2021).

Economic Feasibility of the Research

The transition from conventional diesel fuel to hydrogen represents a paradigm shift, not only environmentally but also economically. A comparative cost analysis reveals a complex interplay between direct expenses, capital investment, and externalities.

1. Fuel Cost (Based on Energy Content):

Diesel Fuel: Currently holds a significant price advantage. Its cost is relatively low and stable due to mature infrastructure and established global supply chains. It is typically priced per liter or gallon.

Hydrogen: The cost of hydrogen is currently substantially higher than that of diesel. Its price is highly dependent on the production pathway:

Grey/Brown Hydrogen (produced from fossil fuels via steam methane reforming): The cost is lower than green hydrogen but still exceeds diesel, while still generating carbon emissions.

Green Hydrogen (produced via electrolysis powered by renewable energy): It is the most expensive option currently, due to the high capital costs of electrolyzers and the price of renewable electricity. However, its cost is projected to decrease significantly with technological advancements and economies of scale (Aravindan & Praveen, 2023; Asim et al., 2023).

2. Efficiency and Energy Consumption:

Diesel Engines: They exhibit a typical thermal efficiency ranging from 35% to 40% in modern applications, meaning a substantial portion of the fuel's energy is lost as waste heat.

Hydrogen fuel cells exhibit substantially higher energy conversion efficiency, with the ability to transform approximately 50–60% of the chemical energy stored in hydrogen into usable electrical power. In contrast, hydrogen internal combustion engines (H_2-ICEs) achieve efficiencies that are generally comparable to, or marginally greater than, those of conventional diesel engines. The superior efficiency of fuel cells directly contributes to a reduction in fuel consumption per unit of mechanical or electrical work output, thereby enhancing overall energy utilization and offering significant potential for improving the sustainability and cost-effectiveness of hydrogen-based energy systems.

3. Capital Expenditure (Initial Investment):

Diesel Systems: They entail relatively low capital outlay. Engines, fuel tanks, and refueling infrastructure are well-understood and manufactured cheaply at scale.

Hydrogen Systems: They require a substantially higher initial investment. These costs include storage systems, as high-pressure or cryogenic storage tanks are required, which are technologically complex and expensive to manufacture. Further, the conversion or new technology, as the cost of fuel cell stacks or modifying internal combustion engines to run on hydrogen, is significantly higher than that of conventional diesel engines. Finally, refueling infrastructure, as establishing a network for green hydrogen production, storage, and distribution, requires massive capital investment compared to the existing diesel infrastructure.

4. Maintenance Costs and Lifespan:

Diesel Engines: They are renowned for their durability and long operational lifespan. Maintenance costs are moderate and predictable (e.g., oil changes, filter replacements).

Hydrogen Fuel Cells: Long-term durability data is still emerging. While they have fewer moving parts, potentially reducing routine maintenance, the cost of replacing the fuel cell stack itself can be a significant future expense.

5. Externalities (Indirect Societal Costs):

Diesel Fuel: It carries high external costs not reflected in its market price, including: public health costs associated with air pollution (e.g., respiratory illnesses), environmental remediation costs from soil and water contamination, and the profound social and economic costs of climate change driven by carbon emissions.

Green Hydrogen: It has very low external costs. When produced from renewable sources, its lifecycle carbon emissions and local air pollutants are nearly negligible, thereby avoiding significant public health and environmental damage costs. The internalization of these externalities, through mechanisms like carbon pricing (Benzoni & Ru, 2023), drastically alters the economic calculus.

Recommendations

- Optimize hydrogen storage systems to enhance safety and efficiency for agricultural use.
- Conduct extensive testing under diverse operating conditions (e.g., high loads, hot and arid climates).
- Develop dual-fuel (diesel-hydrogen) hybrid engines as a transitional solution toward full

hydrogen adoption.

- Collaborate with agricultural machinery manufacturers to develop hydrogen-compatible models.
- Conduct on-the-ground feasibility studies on farms of varying scales.
- Promote green hydrogen production using renewable energy (solar, wind) to ensure sustainability.
- Integrate carbon capture technologies when using blue hydrogen as an interim solution.
- Monitor long-term emissions to identify any unexpected environmental impacts.
- Design awareness programs to educate farmers on hydrogen's environmental and economic benefits.
- Transition agricultural engines to hydrogen, which requires an integrated approach to ensure success as a sustainable solution. Future research should focus on bridging the gap between theory and practice.

Conclusion:

In conclusion, this study underscores the transformative potential of integrating hydrogen technology into Egypt's agricultural sector as a strategic pathway toward achieving Egypt's Vision 2030 and the aligned Sustainable Development Goals (SDGs). The findings demonstrate that hydrogen, as a clean energy carrier, can significantly decarbonize agricultural operations, enhance energy security, and promote environmental sustainability. By enabling the use of green hydrogen produced from renewable sources, this research directly supports SDG 7 (Affordable and Clean Energy) by providing a viable alternative to fossil fuels, reducing greenhouse gas emissions, and fostering the adoption of renewable energy in rural areas.

Furthermore, the adoption of hydrogen technology contributes to SDG 13 (Climate Action) by mitigating carbon emissions and reducing the agricultural sector's carbon footprint, thus supporting Egypt's commitments to global climate agreements. Additionally, by powering agricultural machinery and irrigation systems efficiently and sustainably, this technology enhances productivity and resilience, thereby supporting SDG 2 (Zero Hunger) through the promotion of sustainable agricultural practices and improved food security.

However, the successful implementation of hydrogen technology requires overcoming technical, economic, and regulatory challenges. Strategic investments in infrastructure, coupled with supportive policies and international cooperation, will be essential to unlock the full potential of hydrogen in agriculture. This research provides a foundational framework for policymakers, stakeholders, and researchers to leverage hydrogen technology as a catalyst for sustainable development, ensuring that Egypt's agricultural sector becomes a model of innovation and sustainability in line with Egypt's Vision 2030.

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المستخلص

لتلبية الطلب المتزايد على الآلات الزراعية منخفضة الانبعاثات، يبحث العلماء عن أساليب مبتكرة ومستدامة لتقليل الأثر البيئي لمحركات الاحتراق الداخلي وخفض انبعاثات الغازات الدفيئة. تبحث هذه الدراسة في استخدام الهيدروجين كوقود تكميلي في محركات الديزل؛ بهدف تعزيز الكفاءة وتقليل الانبعاثات الضارة. وقد أجريت التجارب في منشأة "جرين باور إتش تو"، حيث تم اختبار الهيدروجين كبديل كامل لوقود الديزل في مجموعة من مضخات محركات الديزل، وتم قياس مستويات انبعاثات الغازات الدفيئة ومقارنتها بين تشغيل الديزل والهيدروجين، مع الالتزام الصارم بمعايير السلامة لاستخدام الهيدروجين. أجريت الاختبارات تحت أحمال محرك تتراوح بين ٣٠٪ إلى ٧٠٪، وأظهرت تفوقًا بنسبة ١٠٠٪ في استبدال الديزل بالهيدروجين، ولم يتم رصد أي انبعاثات للغازات الدفيئة – أول أكسيد الكربون(CO) ، أو ثاني أكسيد الكربون(CO_2) ، أو ثاني أكسيد الكبريت – (SO_2) عند استخدام الهيدروجين. وقد زادت سرعة غاز العادم إلى ٤ أمتار في الثانية مع ارتفاع ضغط الهيدروجين. وقد بلغ معدل تفريغ المياه ٥٦ مترًا مكعبًا في الساعة تحت نفس حمل المحرك، متجاوزًا أداء تشغيل الديزل.

يسلط هذا البحث الضوء على إمكانات الهيدروجين كوقود بديل نظيف وفعال؛ مما يقلل بشكل كبير من انبعاثات الغازات الدفيئة المسببة للاحتباس الحراري مع الحفاظ على أداء المحرك أو حتى تعزيزه.

الكلمات المفتاحية: الكربون، الانبعاثات، الهيدروجين، المحركات الزراعية، الاستدامة، التحديات المناخية.

END OF

Second: English Researches