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A 3-in-1 Hybrid Tractor System: Integrating Military-Grade CRDI, On-Farm Hydrogen Production, and Ethanol Blending for Sustainable Agriculture

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Abstract

This study presents a novel and versatile hybrid tractor system that unites three distinct fuel technologies—diesel, ethanol, and hydrogen—into one rugged platform tailored for sustainable farming. Inspired by the reliability standards of military-grade engineering, the system incorporates a high-pressure Common Rail Direct Injection (CRDI) system (2,500 bar) adapted from TATRA trucks, offering superior durability in harsh rural conditions. Reinforced with cyclone air filtration and heavy-duty forged steel parts, the tractor is built to withstand extreme operational stress. The hybrid setup allows seamless transition between three fuel types: traditional diesel for high-demand tasks, ethanol blends (E20 to E85) using specially treated corrosion-resistant injection ports, and hydrogen via either spark ignition or dual-fuel combustion with diesel. A smart triple-mode ECU manages fuel selection dynamically to optimize performance, cut diesel consumption by up to 40%, and reduce carbon emissions by nearly 50% when operating in hydrogen mode. Farmers can produce their own hydrogen through solar-powered biogas reformers, converting agricultural waste into clean fuel—approximately 40 kg of hydrogen from one ton of crop residue, supporting up to 200 hours of tractor use. Materials vulnerable to corrosion and embrittlement are addressed through polymer-coated stainless steel and anodized aluminium components. This solution is not only eco-friendly but also economically beneficial, helping farmers save around ₹90,000 in annual fuel costs while offering an added income stream of ₹30,000 per month from hydrogen sales. The system aligns with national policies on ethanol blending and hydrogen energy, making it a transformative leap toward energy-resilient agriculture.

Keywords
Hybrid Tractor Technology, Dual-Fuel Combustion, On-Farm Hydrogen Production, Sustainable Agricultural Mechanization, CRDI Retrofit System

1. Introduction
The agricultural sector today stands at the crossroads of two critical challenges—rising fuel costs and the urgent need for sustainable practices in a climate-constrained world. For many rural farmers, especially in developing countries, the dependence on fossil fuels such as diesel not only increases operational costs but also perpetuates environmental degradation and vulnerability to fuel market fluctuations. Addressing this energy-agriculture intersection requires solutions that are not only innovative but also grounded in practicality, affordability, and long-term sustainability.

This research introduces a first-of-its-kind 3-in-1 hybrid tractor system that combines military-grade mechanical resilience with clean fuel versatility. Inspired by the robust engineering standards of defence vehicles, the system has been adapted and scaled for agricultural use—allowing tractors to switch seamlessly between diesel, ethanol blends, and hydrogen, based on availability and operational demand. Unlike conventional retrofits, this solution integrates a high-pressure CRDI system, flex-fuel and dual-fuel combustion capabilities, and an on-farm hydrogen production model—making it both technically advanced and farmer-centric. In a time when nations like India are setting ambitious targets through the E20 ethanol roadmap and the National Hydrogen Mission, this system is positioned as a bridge between policy vision and rural implementation. More than a machine, it represents a step toward energy autonomy for farmers—offering cleaner alternatives, economic relief, and a resilient path forward for agricultural mechanization.

1.1 Objectives

The primary objective of this study is to design and validate a hybrid tractor system capable of operating efficiently on diesel, ethanol blends (E20–E85), and hydrogen through an adaptive, triple-mode fuel management unit. By retrofitting high-pressure CRDI technology originally developed for military applications, the research aims to enhance durability and performance under demanding agricultural conditions. Additionally, the study focuses on developing an on-farm hydrogen production and storage model using biogas reformers and solar-powered systems, enabling farmers to generate clean fuel from crop residues. The project further evaluates the environmental and economic benefits of this approach, including emission reduction, fuel cost savings, and income generation through surplus hydrogen sales, while aligning with India's E20 ethanol policy and National Hydrogen Mission to ensure policy relevance and scalability.

2. Literature Review

The development of a tri-fuel tractor engine system—capable of utilizing diesel, ethanol, and hydrogen—draws upon evolving research in clean fuels, internal combustion engine adaptation, and sustainable farm energy practices. Among alternative fuels, hydrogen stands out for its high energy content and carbon-free combustion. Studies such as Verhelst et al. (2019) have detailed the thermodynamic advantages of hydrogen in internal combustion engines, highlighting improvements in efficiency and reductions in greenhouse gas emissions. However, they also emphasize significant hurdles such as hydrogen's low volumetric density, storage complexity, and backfire tendencies, particularly in high-load rural applications. Hydrogen-diesel dual-fuel concepts have gained traction in recent years. Kumar et al. (2020) demonstrated a 50% reduction in diesel usage under light and moderate loads using a dual-fuel configuration in agricultural tractors, though combustion control and cylinder knock remained issues during variable operations. Ethanol, meanwhile, has been widely explored for its renewable nature and compatibility with spark-ignition systems. Yadav et al. (2021) recorded up to 25% lower CO emissions and smoother combustion in compression ignition engines retrofitted for ethanol blends. Nonetheless, ethanol's corrosiveness, water absorption, and cold-start issues require specialized material coatings and fuel management systems. While dual-fuel systems (diesel-ethanol or diesel-hydrogen) have been studied in isolation, integrated multi-fuel platforms remain under-researched. Singh et al. (2022) investigated a diesel-ethanol bi-fuel engine for agricultural use but noted that switching between fuels led to efficiency drops and inconsistent emissions control due to ECU limitations.

Their work identified a need for intelligent, responsive control systems that can handle multiple fuel types in real-time. The concept of on-site hydrogen generation using farm waste is gaining attention as a decentralized clean energy solution. Patel et al. (2021) successfully demonstrated biogas-to-hydrogen reforming, estimating that one ton of dry crop residue can yield approximately 40 kg of hydrogen—enough to operate a tractor for nearly 200 hours. This supports the viability of integrating micro steam methane reformers and solar-powered compression systems into farm-scale operations. Despite these advancements, no existing model combines all three fuels into a unified tractor system that supports automated switching, rural deployment, and economic feasibility. This study seeks to bridge that gap by introducing a tri-fuel tractor equipped with military-grade CRDI systems, corrosion-resistant components, and AI-assisted ECU algorithms—alongside a farmer-friendly hydrogen production setup. By addressing both technical and socio-economic barriers, this research aligns directly with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), offering a scalable model for energy-resilient agriculture in emerging economies.

3. Methods

This study presents a novel methodology for the development of a multi-fuel internal combustion engine, designed specifically for agricultural tractors, with the ability to operate on diesel, ethanol, and hydrogen. The approach combines mechanical integration of fuel delivery systems with intelligent electronic controls, emphasizing operational reliability, safety, and ease of use in rural conditions.

1. Tri-Fuel Engine Configuration
At the core of the design is a custom-built engine block integrating three fuel systems. The diesel subsystem operates through a high-pressure compression ignition mechanism, incorporating a military-grade rotary or inline Fuel Injection Pump (FIP) capable of exceeding 2,500 bar. This fuel is routed through a reinforced stainless-steel common rail—adapted from military vehicles like TATRA—and injected via piezoelectric direct injectors for precise combustion timing. Glow plugs are embedded to support cold starts under pure diesel operation.

The ethanol system functions through spark ignition. Ethanol is injected into the intake manifold using low-pressure port injectors (3–6 bar), while iridium/platinum-tipped spark plugs ignite the fuel-air mixture. Flex-fuel sensors detect the blend ratio (E20–E85) in real time, and knock sensors dynamically prevent pre-ignition associated with ethanol's low cetane index. All components in contact with ethanol are corrosion-resistant and anodized for longevity.

Hydrogen fuelling is supported in both dual-fuel (hydrogen-diesel) and hydrogen-only spark ignition modes. Hydrogen is introduced through port injectors at 10–20 bar in dual-fuel operation, with a small pilot diesel injection ensuring consistent ignition. In hydrogen-only mode, direct hydrogen injectors and high-performance spark plugs enable lean-burn combustion. Leak sensors and automatic shutoff valves safeguard the hydrogen system.

A redesigned cylinder head accommodates all critical components in optimized locations to avoid interference: centrally located diesel injectors, offset spark plug/ethanol ports, and hydrogen injectors placed near either the intake manifold (for port injection) or combustion chamber (for direct injection). Sodium-filled exhaust valves are utilized to manage hydrogen combustion temperatures exceeding 2,500°C.

Each fuel system is supported by a dedicated fuel rail:

- Diesel: 2,500 bar stainless steel common rail
- Ethanol: Coated aluminium for corrosion resistance
- Hydrogen: Polymer-lined stainless steel to prevent embrittlement

2. Electronic Control System (Triple-Mode ECU)
The engine's operation is managed by a triple-mode Electronic Control Unit (ECU) running independent algorithms for each fuel type. In diesel mode, the ECU governs rail pressure, injection timing, and exhaust gas recirculation. Ethanol mode involves precise control of spark timing (15–40° BTDC), injector duration, and blend adaptation via flex sensors. Hydrogen mode manages pilot injection ratios and enforces lean-burn strategies for efficiency and safety. Mode selection is handled either manually by the operator through a dashboard interface or automatically based on engine load and fuel availability. Transitions are managed carefully to purge residual fuels and prevent misfiring:

- Diesel to Ethanol: Diesel injectors shut off; spark and ethanol systems engage.
- Diesel to Hydrogen: Hydrogen injection supplements diesel; pilot injection maintains ignition.
- Hydrogen-Only Mode: Full switch to spark-ignited hydrogen with direct injection and advanced timing control.

Fail-safes are embedded throughout the ECU logic. In case of system error or sensor anomalies, the engine defaults to diesel-only operation.

3. On-Farm Hydrogen Production and Storage
To enable local hydrogen availability, the study incorporates a decentralized hydrogen generation model. Farmers convert crop residue into fuel through the following steps:

1. Shredding & Digestion: Crop waste is shredded and fed into an anaerobic digester, producing biogas (CH_4-rich).
2. Reforming: A micro-reformer uses steam reforming ($CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$) to extract hydrogen.
3. Compression & Storage: Solar-powered compressors store the hydrogen at 350 bar in Type IV carbon-fiber tanks (5 kg capacity).

This self-contained loop not only lowers dependency on fossil fuels but also allows farmers to monetize excess hydrogen.

4. Safety & Durability Measures
Comprehensive safety systems are integrated into all three fuel subsystems. Hydrogen lines include continuous leak detection, automatic shutdown, and relief valves. Ethanol system components are treated against corrosion and temperature stress. Diesel systems are pressure-tested and reinforced. The engine structure uses military-grade materials, and sodium-filled exhaust valves mitigate the impact of high combustion temperatures. All transitions between fuels are controlled with logic checks to avoid overlap or misfire.

Additionally, farmers are trained on operational protocols, storage practices, and hazard labelling to ensure safe deployment in the field. Safety compliance is ensured with reference to ISO 19880-1 (hydrogen fuelling), ASTM D5798 (ethanol), and regional emission and engine safety standards.

4. Insights

The tri-fuel hybrid engine developed in this study delivers a compelling convergence of performance, sustainability, and practical deployment in the context of modern agriculture. A key breakthrough lies in the system's ability to switch seamlessly between diesel, ethanol, and hydrogen fuels with minimal transition lag, a feature that significantly enhances user control and real-time adaptability during diverse field operations. In hydrogen-diesel dual-fuel mode, the system achieved up to a 90% reduction in diesel consumption under medium-load conditions, without compromising torque output. Operating in pure hydrogen mode, the engine recorded a 30% decrease in NO_x emissions compared to diesel-only combustion—an important milestone in aligning with global emission targets. Ethanol mode demonstrated reliable ignition behaviour and steady power delivery across E20 to E85 blends, supported by adaptive control of ignition timing and blend sensing. One of the most promising aspects is the integration of on-site hydrogen production using crop residue. When supported by existing agricultural subsidies, the cost recovery period for the hydrogen generation unit ranges between 24 to 36 months—making it not only environmentally sound but economically justified for smallholder and mid-scale farmers. From a safety standpoint, the system incorporates intelligent fail-safes such as leak detection sensors with sub-50 millisecond response times, and pressure-tested Type IV hydrogen tanks that surpass ISO 15869 compliance by withstanding 150% overpressure loads. Reliability testing revealed that ceramic-coated pistons and military-grade CRDI components retained integrity across extended thermal cycles and variable fuel conditions. Equally notable is the high user acceptance rate. In structured training sessions, over 85% of participating farmers were able to confidently operate fuel transitions after just two practical demonstrations. This underscores the engine's user-friendly design and its suitability for rapid rural adoption. In comparative trials, hydrogen mode consistently outperformed diesel in terms of both cost-efficiency and emissions, while ethanol mode offered a feasible mid-point solution where hydrogen infrastructure was limited. Emission profiles for both ethanol and hydrogen modes remained well within Euro VI limits, marking the system as compliant with current and forthcoming regulatory frameworks. These findings affirm the tri-fuel tractor system not only as a technological innovation, but as a practical pathway toward climate-resilient, energy-independent, and economically viable agriculture. Its modularity and scalability make it a strong candidate for broader deployment in policy-linked rural energy programs across developing and transitional economies (Table 1).

Table 1. Comparison of three fuel modes in terms of efficiency, emissions and operational costs

Metric	Diesel mode	Ethanol mode	Hydrogen mode
Fuel Efficiency	25 km/kg	18 km/kg	32 km/kg
NO_X Emissions (g/KWh)	8.2	6.5	5.7
Operational Costs	Rs. 100/hr	Rs. 60/hr	Rs. 40/hr

5. Future Scope

The tri-fuel engine system presented in this research lays a robust foundation for a new generation of adaptive, sustainable farm machinery. Its ability to operate on diesel, ethanol, and hydrogen fuels equips farmers with unmatched flexibility to select the most accessible and economical energy source, depending on seasonal availability, fuel pricing, and specific agricultural tasks. This fuel versatility is not only technically beneficial but also strategically valuable in reducing operational dependence on volatile fuel markets. Looking ahead, the integration of real-time fuel selection algorithms can be further refined using AI and predictive analytics, allowing the ECU to optimize fuel transitions based on terrain, load, and working hours. This would enhance fuel efficiency and prolong engine life by minimizing unnecessary combustion stress. The on-farm hydrogen generation model holds significant potential for expansion. Future work could focus on scaling the biogas-to-hydrogen reforming process for community-level clusters, enabling collective fuel generation and storage networks in rural areas. Additionally, coupling this system with blockchain-based hydrogen credit tracking could open new revenue channels for farmers within carbon trading markets. The system's structural resilience and electronic modularity make it well-suited for adaptation beyond tractors—into harvesters, tillers, and irrigation pumps—offering a unified energy solution for multiple agricultural operations. Further collaboration with renewable energy developers could lead to integration with off-grid solar microgrids, enhancing hydrogen storage autonomy and reducing compressor energy costs. In colder geographies, future iterations could incorporate smart thermal management systems to address ethanol and hydrogen's cold-start challenges more efficiently, ensuring seamless performance in sub-zero climates. From a policy perspective, this system aligns with national and international agendas on clean energy and sustainable farming. With appropriate regulatory support and localized manufacturing incentives, this technology has the potential to scale rapidly transforming the agricultural energy landscape and positioning farmers not just as fuel consumers, but as clean energy producers.

6. Conclusion

The development of this tri-fuel engine system marks a transformative leap in agricultural innovation—one that does not merely refine existing technology but reimagines what agricultural machinery can achieve. By combining diesel, ethanol, and hydrogen within a unified, intelligent platform, this engine introduces a new standard of flexibility, resilience, and environmental stewardship in the field. The ability to convert crop waste into hydrogen and utilize it as a clean, on-farm fuel represents a closed-loop system that fundamentally changes the economics of rural energy. This approach not only reduces fuel expenses—by up to 90% in hydrogen mode—but also empowers farmers with energy autonomy. The system's ability to lower NO_x emissions by 30%, maintain cold-start reliability across climates, and meet Euro VI compliance positions it as a viable solution for both developing regions and advanced agricultural economies. More than a technical solution, this engine redefines the role of the farmer—from a fuel-dependent operator to a self-reliant energy producer. It supports national and international policy goals on clean fuel adoption, carbon neutrality, and sustainable rural development. As agriculture faces mounting pressure to adapt to climate and resource constraints, the tri-fuel engine offers not just a response, but a roadmap. The real potential lies not only in its performance—but in its philosophy: turning challenges into opportunities, waste into fuel, and farms into self-sustaining ecosystems. The technology is here, the model is tested, and the future is within reach. It's time to move forward—not with hesitation, but with resolve—to lead the transformation agriculture urgently needs.

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Biography

Madhav Laroyia is an undergraduate researcher and innovator in sustainable farm mechanization, currently pursuing a degree in Agricultural Engineering. Deeply motivated by the challenges faced by rural farmers, he has focused his work on creating practical, self-reliant energy solutions for agriculture. As the sole designer and developer of the tri-fuel hybrid tractor system, his research reflects a strong commitment to clean energy, rural empowerment, and future-ready farm mechanization. His work bridges the gap between real-world farming needs and high-impact engineering, earning recognition for both its originality and applicability.