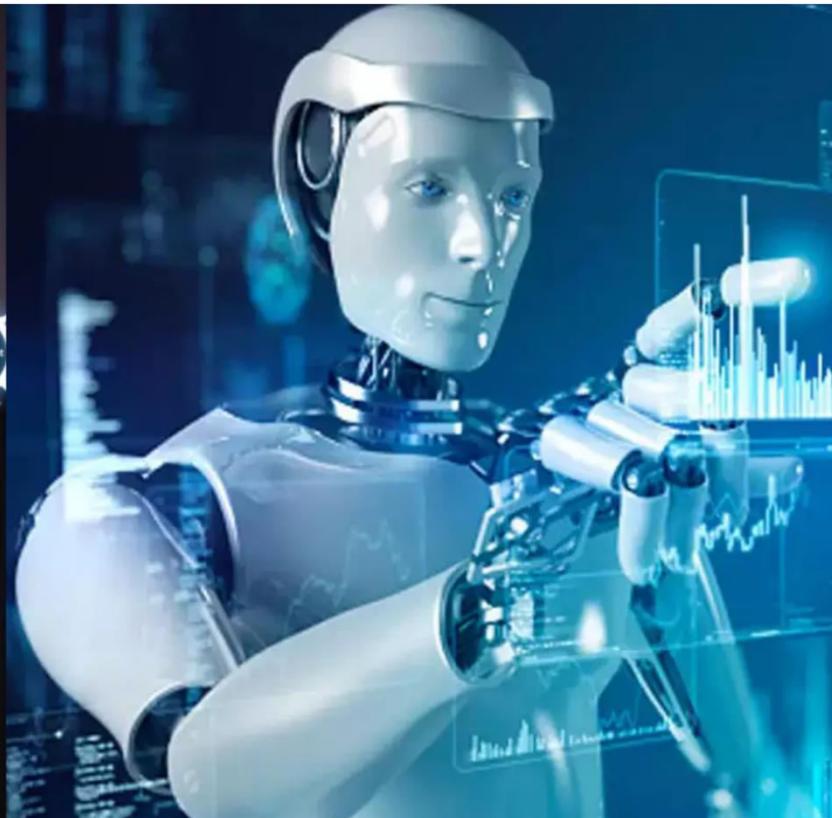




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Artificial Intelligence Enabled Mechanical Multi-Nozzle Wheel Sprayer for Precision Agriculture

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ABSTRACT: Precision agriculture demands efficient, intelligent and resource-optimized crop protection methods to address challenges such as labor scarcity, excessive pesticide usage, uneven spraying, and environmental impact. Traditional manual and mechanically operated sprayers lack adaptability to varying field conditions, leading to inefficiencies and health risks for farmers. This paper presents an Artificial Intelligence Enabled Mechanical Multi-Nozzle Wheel Sprayer for Precision Agriculture. The system integrates a mechanically driven multi-nozzle wheel sprayer with AI-based decision assistance to enhance spraying accuracy and efficiency. Experimental evaluation shows improved spray uniformity, reduced pesticide consumption, enhanced operator safety, and lower human effort. The proposed system offers a sustainable, low-cost, and intelligent solution suitable for small and medium-scale farmers.

KEYWORDS: AI-Enabled Agriculture, Precision Spraying, Mechanical Sprayer, Smart Farming Equipment

I. INTRODUCTION

Agriculture remains the backbone of many developing economies, yet it faces persistent challenges such as labor shortages, rising input costs, and environmental concerns associated with chemical pesticide usage. Conventional backpack and manually operated sprayers expose farmers to harmful chemicals, deliver non-uniform spray patterns, and often result in over-applications of pesticides.

Precision agriculture aims to optimize agricultural inputs by applying the right amount of resources at the right place and time. Mechanical wheel sprayers provide mobility and consistent motion; however, without intelligence, they cannot adapt to varying crop densities, field conditions, or spraying requirements. Recent advancements in artificial intelligence enable decision-based assistance even in low-cost agricultural equipment.

This research proposes an AI-enabled mechanical multi-nozzle wheel sprayer that combines simple mechanical actuation with intelligent decision support to improve spraying efficiency, reduce pesticide wastage, and enhance farmer safety.

II. LITERATURE REVIEW

Previous studies on agricultural spraying systems have primarily concentrated on manual and battery-operated knapsack sprayers, which are widely adopted due to their low initial cost and ease of use. However, these systems suffer from several limitations, including non-uniform spray distribution, high operator fatigue, excessive pesticide exposure, and inconsistent application rates that depend heavily on operator skill. Prolonged use of knapsack sprayers has also been associated with adverse health effects due to direct chemical contact and inhalation.

Boom sprayers have been extensively studied for large-scale agricultural operations, offering wider coverage and improved uniformity compared to manual methods. While effective for commercial farming, boom sprayers require tractors or powered vehicles, making them economically impractical and operationally unsuitable for small and marginal farmers with fragmented landholdings. Additionally, their high capital cost, maintenance requirements, and fuel dependency limit their adoption in resource-constrained agricultural environments. Recent advancements in sensor-based precision spraying systems have introduced technologies such as machine vision, ultrasonic sensors, and GPS-based control to enable site-specific pesticide application. These systems significantly improve spray accuracy and reduce chemical wastage by adapting spraying parameters in real time. However, such advanced autonomous or semi-autonomous sprayers involve complex electronic hardware, high computational requirements, and substantial financial investment. As a result, their practical deployment remains limited to technologically advanced and large-scale farming operations. Mechanical wheel-driven sprayers have emerged as a cost-effective alternative, utilizing ground wheel motion to regulate spray delivery in proportion to forward movement. These systems eliminate the need for external power sources and offer improved consistency compared to manual sprayers. Nevertheless, conventional mechanical sprayers lack adaptability to varying crop conditions, spray requirements, and field variability, leading to suboptimal pesticide usage.

Recent research highlights the growing potential of artificial intelligence-based decision systems in agriculture, particularly for optimizing operational parameters using limited sensor or user input data. AI techniques such as rule-based logic, fuzzy systems, and lightweight machine learning models have demonstrated effectiveness in enhancing decision-making without excessive computational complexity. Despite this progress, the integration of AI-assisted decision support with purely mechanical spraying systems remains largely unexplored. This research gap motivates the present work, which aims to combine mechanical simplicity with intelligent decision assistance to develop an affordable, efficient, and farmer-friendly precision spraying solution.

III. SYSTEM ARCHITECTURE AND METHODOLOGY

3.1 Overall System Architecture

The proposed system consists of:

- Mechanical wheel-driven transmission mechanism
- Multi-nozzle spray assembly
- Pesticide storage tank
- AI-enabled decision assistance module
- Manual control interface

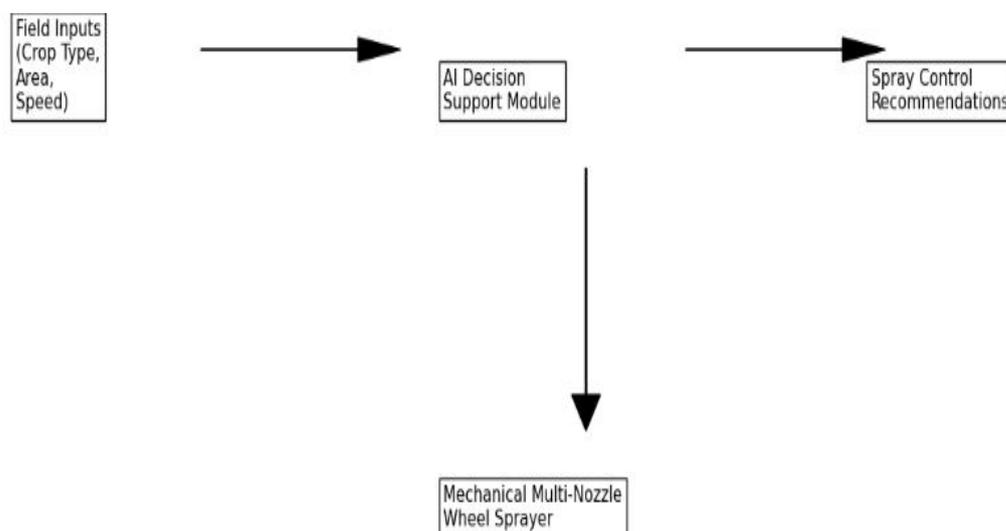


Figure 1: Block diagram of AI-enabled mechanical multi-nozzle wheel sprayer.

3.2 Mechanical Design

The sprayer uses a ground wheel connected to a mechanical linkage that actuates multiple spray nozzles as the wheel rotates. The arrangement ensures:

- Uniform spray distribution proportional to forward motion
- Reduced dependency on external power sources
- Consistent spray rate

3.3 AI-Enabled Decision Assistance

A lightweight AI logic module assists the operator by:

- Suggesting nozzle activation patterns
- Recommending spray duration and coverage
- Adjusting spraying strategy based on crop type and field conditions

Inputs may include operator-defined parameters, basic environmental data, and operational speed. The AI does not directly control actuation but provides decision support, ensuring simplicity and reliability.

3.4 Working Principle

As the operator pushes the sprayer, wheel rotation drives the nozzle mechanism, spraying pesticide uniformly across the crop area. The AI assistance provides guidance before and during operation, enabling efficient and targeted spraying.

IV. MECHANICAL DESIGN

4.1 Experimental Setup and Testing

Field experiments were conducted to evaluate the performance of the proposed AI-enabled mechanical multi-nozzle wheel sprayer under real agricultural conditions. The experimental study focused on assessing spray uniformity, pesticide consumption, operator effort, and overall coverage efficiency. The tests were carried out on small agricultural plots representative of typical farming conditions encountered by small and marginal farmers.

4.2 Experimental Setup

The experimental setup consisted of the proposed mechanical multi-nozzle wheel sprayer equipped with AI-based decision assistance and a conventional manual knapsack sprayer used as a reference system. Both sprayers were operated on similar crop rows with uniform plant spacing and comparable crop height to ensure consistency. The same type of pesticide solution and nozzle specifications was used in both systems to maintain experimental fairness.

The field plots were divided into equal sections, and spraying operations were conducted under similar environmental conditions, including wind speed, temperature, and humidity, to minimize external influences on spray behaviour. The operator maintained a consistent walking speed during the experiments, while the AI module provided spray recommendations for the proposed system prior to operation.

4.3 Spray Uniformity Evaluation

Spray uniformity was evaluated by visually and quantitatively assessing the distribution of pesticide across the crop canopy. Collection papers were placed at predefined intervals along the crop rows to capture spray droplets. The distribution pattern obtained using the proposed sprayer was compared with that of the manual knapsack sprayer. Improved uniformity was observed in the wheel-driven system due to motion-proportional spraying and consistent nozzle activation.

4.4 Pesticide Consumption Measurement

Pesticide consumption was measured by recording the volume of pesticide solution used to cover a fixed area of land. For both sprayers, the initial and final levels of pesticide solution in the tank were measured to calculate total consumption. The proposed AI-enabled sprayer demonstrated reduced pesticide usage due to optimized spray recommendations and minimized over-application.

4.5 Operator Effort Assessment

Operator effort was evaluated based on physical workload and fatigue experienced during spraying operations. Parameters such as total spraying time, ease of maneuverability, and subjective fatigue levels reported by the operator were considered. The wheel-driven mechanical sprayer significantly reduced physical strain compared to the manual knapsack sprayer, as it eliminated the need to carry the pesticide load on the operator's back.

4.6 Coverage Efficiency Analysis

Coverage efficiency was assessed by measuring the effective area sprayed per unit time. The proposed system achieved higher coverage efficiency due to multi-nozzle operation and uniform spray distribution. The AI-based recommendations further improved coverage by guiding optimal spraying patterns based on field conditions.

4.7 Comparative Analysis

The performance of the proposed system was systematically compared with the conventional manual knapsack sprayer across all evaluated parameters. The results demonstrated that the AI-enabled mechanical multi-nozzle wheel sprayer outperformed the traditional system in terms of spray uniformity, pesticide savings, operator comfort, and coverage efficiency, validating its suitability for precision agriculture applications.

V. AI-ENABLED DECISION LOGIC

The AI-enabled decision logic serves as the intelligent assistance layer of the proposed mechanical multi-nozzle wheel sprayer. Unlike fully autonomous or electronically controlled spraying systems, the proposed approach focuses on lightweight intelligence that enhances decision-making without introducing complex or expensive electronic actuation. This design philosophy ensures affordability, reliability, and ease of adoption for small and medium-scale farmers.

The AI module processes key operational inputs such as crop type, field area, and operator walking speed. Crop type information is used to estimate the required spray density and coverage pattern, as different crops demand varying levels of pesticide application. Field area input allows the system to determine appropriate spraying duration and nozzle activation strategy, ensuring uniform chemical distribution over the entire plot. Operator speed is considered to maintain consistency between forward motion and spray output, thereby reducing over-spraying or under-spraying.

Based on these inputs, the AI logic employs rule-based decision mechanisms to generate optimized spray recommendations. These recommendations include suggested nozzle combinations, spray duration, and coverage strategy tailored to the specific field conditions. By correlating motion-related parameters with spray requirements, the AI module helps maintain proportional spray delivery, even when operator speed varies.

Importantly, the AI module functions as a decision-support system rather than a direct control unit. The mechanical actuation of the sprayer remains wheel-driven, preserving system simplicity and minimizing dependency on electronic components. This separation of intelligence and actuation ensures robust operation in rural environments where power availability and electronic reliability may be limited.

The AI-enabled decision logic significantly reduces chemical wastage by preventing excessive pesticide application and improving spray uniformity. It also assists less-experienced operators by standardizing spraying practices, leading to more consistent crop protection outcomes. Overall, the integration of AI-based decision support with a mechanically actuated spraying system provides an effective balance between intelligence, cost, and operational simplicity.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental evaluation of the proposed AI-enabled mechanical multi-nozzle wheel sprayer demonstrates significant improvements in spraying efficiency, resource utilization, and operator safety when compared with a conventional manual knapsack sprayer. The performance assessment was based on key parameters including pesticide consumption, spray uniformity, operator effort, and coverage efficiency.

6.1 Pesticide Consumption Analysis

Field test results indicate a reduction in pesticide usage ranging from approximately 20% to 30% for the proposed system. This improvement is primarily attributed to the AI-based decision logic, which provides optimized spray recommendations based on field conditions and operational parameters. In contrast, the conventional knapsack sprayer relies heavily on operator judgment, often resulting in over-application of chemicals. The reduced pesticide consumption not only lowers operational costs but also minimizes environmental contamination and chemical residue on crops.

6.2 Spray Uniformity Performance

Spray uniformity was observed to be significantly higher in the proposed system. The wheel-driven mechanical actuation ensures that spray output remains proportional to the forward motion of the sprayer, leading to consistent distribution across crop rows. Additionally, the multi-nozzle configuration enables wider and more uniform coverage compared to single-nozzle manual sprayers. The AI-enabled recommendations further enhance uniformity by guiding appropriate nozzle selection and spray duration, reducing localized over-spraying or under-spraying.

6.3 Operator Effort and Fatigue Reduction

One of the major advantages of the proposed system is the reduction in physical strain experienced by the operator. Unlike the knapsack sprayer, which requires the operator to carry the pesticide tank on the back, the wheel-mounted system transfers the load to the ground. This design significantly reduces fatigue, especially during prolonged spraying operations. Field observations revealed improved maneuverability and reduced spraying time, contributing to enhanced operator comfort.

6.4 Safety and Environmental Impact

Operator safety is enhanced through reduced direct exposure to pesticides. The consistent and controlled spraying mechanism minimizes chemical drift and accidental spills, thereby lowering health risks associated with inhalation and skin contact. Furthermore, reduced pesticide usage contributes to improved environmental sustainability by decreasing soil and water contamination.

6.5 Overall Performance Comparison

A comparative analysis of both systems clearly indicates that the AI-enabled mechanical multi-nozzle wheel sprayer outperforms the conventional manual knapsack sprayer across all evaluated parameters. The integration of intelligent decision support with a simple mechanical design provides an effective balance between performance enhancement and cost efficiency. These results validate the suitability of the proposed system for precision agriculture applications, particularly for small and medium-scale farming operations.

VII. LIMITATIONS AND FUTURE SCOPE

Despite the promising performance of the proposed AI-enabled mechanical multi-nozzle wheel sprayer, certain limitations remain that provide opportunities for future improvement. The current system relies primarily on predefined input parameters and rule-based AI decision logic, which limits its ability to adapt dynamically to rapidly changing field conditions such as sudden variations in crop density, pest infestation severity, or environmental factors like wind speed and humidity.

At present, the system does not incorporate real-time sensing capabilities. The absence of sensors for parameters such as soil moisture, crop canopy density, and real-time spray deposition restricts the system's adaptability and learning potential. Integrating low-cost sensors and feedback mechanisms in future designs could enable real-time spray adjustment, further improving precision and chemical utilization efficiency.

The proposed system is mechanically actuated and does not include onboard power generation or energy harvesting. Future enhancements may involve the integration of solar power modules to support AI computation, sensing, and data storage, thereby improving energy independence and operational sustainability in remote farming regions.

Additionally, the current design does not provide data logging or performance tracking capabilities. Future versions may incorporate data acquisition systems to record operational parameters, pesticide usage, and field coverage. Such data can support long-term performance analysis, enable learning-based optimization, and assist farmers in decision-making across multiple crop cycles.

While the present system functions as a decision-support tool, future developments may explore semi-autonomous operation, where AI-generated recommendations are directly linked to controlled actuation mechanisms. This advancement could further reduce operator dependency while preserving affordability and system reliability. Overall, these enhancements offer a clear pathway toward evolving the proposed system into a more intelligent, adaptive, and sustainable precision agriculture solution.

VIII. CONCLUSION

The AI-enabled mechanical multi-nozzle wheel sprayer successfully combines simplicity and intelligence to improve agricultural spraying efficiency. It offers a sustainable solution for precision agriculture, particularly for small and medium-scale farmers.

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