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iReMix: A Gravity-Based Automated Nutrient Mixing System for Enhanced Fertigation Efficiency in Smart Farming

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Abstract. The study presents the development and evaluation of iReMix, a gravity-based automated nutrient mixing system designed to enhance fertigation efficiency in smart farming. Conventional fertigation systems often rely on electrically powered pumps, which increase operational costs and require complex maintenance. In contrast, iReMix utilizes gravitational flow to achieve accurate nutrient mixing while reducing energy dependence. Experimental evaluation showed that iReMix operational costs were reduced by approximately 67%, and nutrient runoff decreased by 30–40%, highlighting both economic and environmental benefits. These findings demonstrate iReMix's potential as a cost-effective and sustainable alternative for small- and medium-scale farming applications.

Keywords: Fertigation system, Gravity-based automation, iReMix, Smart farming, Sustainable agriculture.

1. INTRODUCTION

The increasing demand for sustainable agricultural practices has emphasized the need for optimizing water and nutrient management. Fertigation, a method of delivering fertilizers dissolved in irrigation water, has been recognized as an effective approach to improve crop productivity and resource efficiency. However, conventional fertigation systems commonly rely on electrically powered pumps and mixers, resulting in high energy consumption, increased operational costs, and complex maintenance requirements. In addition, inconsistencies in nutrient concentration and distribution may reduce nutrient uptake efficiency and contribute to environmental issues such as nutrient leaching and runoff.

Recent studies have highlighted the importance of precision nutrient management in improving agricultural sustainability and reducing resource wastage. Despite technological advancements in automated fertigation systems, many available solutions remain financially inaccessible to small- and medium-scale farmers due to their dependency on electricity, sensors, and sophisticated control systems.

This study introduces iReMix, a gravity-based automated nutrient mixing system designed to provide a cost-effective and environmentally sustainable alternative to conventional fertigation technologies. By utilizing gravitational force as the primary driving mechanism, the system minimizes energy dependence while maintaining nutrient distribution accuracy.

Research Question:

"How can fertigation systems be made more efficient, sustainable, and accessible without relying on energy-intensive pumping systems?"

1.1 Objectives of the Study:

1.1.1 To evaluate the efficiency and accuracy of nutrient distribution achieved by the iReMix system in comparison to conventional fertigation methods.

1.1.2 To assess the potential of iReMix in minimizing operational costs while promoting environmental sustainability and resource efficiency in smart farming practices.

1.1.3 To design and develop the iReMix gravity-based automated nutrient mixing system.

2. LITERATURE REVIEW

Fertigation has been extensively studied as an innovative method of nutrient delivery, offering improved absorption efficiency and reduced labor requirements. Smith, Patel, and Kim (2019) highlighted that fertigation enhances plant nutrient uptake while conserving water resources. Nevertheless, many current fertigation systems rely on pump-driven technologies that require significant energy input and technical expertise (Zhang, Wang, & Chen, 2020).

Gravity-fed irrigation has historically been applied in smallholder farming due to its simplicity and low cost (Chakraborty, Sharma, & Saha, 2018). However, the integration of automation with gravity-based nutrient mixing remains underexplored. Existing automated systems, such as those proposed by Rahman and Lee (2021), incorporate IoT-based control but remain financially inaccessible for resource-limited farmers.

This gap presents an opportunity for developing an alternative system that balances technological reliability with affordability. The iReMix model as Figure 1 addresses this gap by introducing an automated nutrient mixing system that does not depend heavily on electricity but still ensures precision and efficiency as shown at Table 1.

Figure 1. Conceptual of the iReMix system

Table 1. Comparison between Conventional and Proposed Fertigation Systems.

Parameter	Conventional System	iReMix System
Energy Requirement	High (Electricity)	Low (Gravity)
Cost of Operation	Moderate to High	Low
Maintenance	Frequent	Minimal
Suitability for Farmers	Limited	High

3. Research Methodology

This study adopted a design-and-test research approach, combining prototype development with performance evaluation.

3.1 Research Design

This study employed a design-and-test research approach, which integrates both prototype development and experimental evaluation to determine the performance of the proposed system. The research was structured in two main phases:

Prototype Development Phase

The iReMix prototype was designed using gravity-fed principles, incorporating PVC piping, valves, nutrient tanks, and an Arduino-based microcontroller for automated control.

A modular design approach was used to ensure adaptability across different farm sizes, allowing the system to be replicated or scaled depending on field requirements.

The system was tested under controlled laboratory conditions to calibrate sensors and verify mechanical flow stability before field evaluation.

Experimental Evaluation Phase

An experimental comparison was conducted between the iReMix system and a conventional pump-based fertigation system. Both systems were operated under identical conditions, using the same nutrient solutions, flow rates, and environmental settings to ensure fairness of comparison.

Performance indicators were selected based on two dimensions aligned with the research objectives:

i. Efficiency and Accuracy of Nutrient Distribution – measured by analyzing concentration uniformity of nutrient solutions delivered to crops using spectrophotometric methods.

ii. Operational Cost and Sustainability Potential – measured by recording energy consumption, cost of operation, and observed reductions in maintenance requirements.

This design ensured that the iReMix system could be rigorously compared against conventional methods while highlighting its potential contributions to smart farming. By combining prototype testing with real-world performance evaluation, the study provides both proof-of-concept validation and practical evidence of the system's advantages.

3.2 Materials and Tools Used

The iReMix prototype was constructed using cost-effective and widely available materials, selected for their durability, ease of maintenance, and suitability for agricultural environments. The key components are described below:

PVC Pipes and Fittings

Polyvinyl chloride (PVC) pipes formed the primary structure of the gravity-fed flow channel. They were chosen for their resistance to corrosion, lightweight properties, and affordability compared to metal piping. Various fittings (elbows, T-joints, connectors) were used to create an adaptable flow path, ensuring smooth gravitational flow of nutrient solutions.

Valves (Manual and Automated)

Valves were integrated to regulate the flow rate and control nutrient mixing at different junctions. Manual ball valves were employed for initial calibration and safety shut-off. Automated solenoid valves, controlled by an Arduino microcontroller, allowed precise timing and control of nutrient release into the mixing chamber.

Nutrient Solution Tanks

Two tanks were used: one for plain irrigation water and another for nutrient solution.Tanks were made from food-grade polyethylene to ensure chemical safety and prevent contamination of the nutrient mixture.Each tank was equipped with level indicators to monitor solution availability during experiments.

Flow Meters

Calibrated digital flow meters were installed at the outlet of the system to measure discharge rates.These instruments ensured accurate monitoring of nutrient delivery, allowing comparison between theoretical and actual flow values.Flow data were logged and analyzed to assess system consistency across multiple trials.

Nutrient Sensors

Electrical conductivity (EC) sensors and pH probes were used to evaluate nutrient concentration and solution stability.The sensors provided real-time monitoring of the nutrient mix and allowed adjustments to maintain accuracy within the desired ±5% tolerance range.Data from the sensors were linked to the Arduino control system for semi-automated adjustments.

Together, these materials and tools enabled the construction of a robust and scalable iReMix prototype. The choice of simple, low-cost materials ensured that the system could be replicated easily by smallholder farmers while maintaining accuracy and reliability in nutrient delivery.

3.3 Data Collection Methods:

The evaluation of the iReMix system relied on systematic data collection procedures designed to capture both technical performance and economic feasibility. Three primary methods were employed:

Flow Rate Measurement

Flow meters were installed at the system outlet to record the discharge rate of the nutrient solution.Measurements were taken at regular intervals (every 5 minutes over a 1-hour period) to determine stability and consistency of gravitational flow.Comparative readings were also collected from the conventional pump-based fertigation system under identical conditions.Replicated trials (minimum of three runs per system) ensured statistical reliability and reduced the influence of random errors.

Analysis of Nutrient Concentration

Electrical conductivity (EC) sensors and pH probes were used to provide real-time monitoring of nutrient concentration in the output solution.Additionally, solution samples were collected at different time intervals and analyzed using UV-Visible spectrophotometry to quantify nutrient levels with high accuracy.Each sample was compared against a standard calibration curve to validate concentration levels.These measurements allowed for the evaluation of mixing accuracy, with performance assessed based on deviation from the target concentration (±5% tolerance).

Operational Cost Minitoring

Energy consumption data were recorded for both iReMix (gravity-based, negligible power input) and the conventional pump-based system (electrical input required).Operating time, labor input, and maintenance requirements were documented during trials.Costs were calculated in monetary terms (RM per operation cycle), considering electricity tariffs, water usage, and maintenance expenses.A cost-benefit analysis was performed to determine the relative economic advantage of adopting iReMix.

To ensure reliability, all measurements were repeated under controlled conditions and averaged across multiple trials. Data were logged digitally, stored securely, and subjected to preliminary statistical analysis before being used in comparative evaluation.

3.4 Analytical Techniques

Two primary analytical approaches were adopted to evaluate the effectiveness and broader impact of the iReMix system:

Cost-Benefit Analysis

The cost-benefit analysis was conducted to determine the economic feasibility of adopting the iReMix system in comparison to conventional pump-based fertigation.The analysis considered capital costs (materials, construction, and installation), operational costs (energy usage, labor requirements, and maintenance), and savings achieved from reduced energy dependency.A lifecycle perspective was adopted, projecting system operation over one cropping cycle (approximately 4 months) and extrapolating annual savings.

The benefit-cost ratio (BCR) was calculated using the following formula:

$$BCR = \frac{\text{Total Costs}}{\text{Total Benefits}}$$

where benefits included operational savings and reduced resource wastage, while costs included installation and maintenance expenses.A BCR greater than 1 indicated financial viability, demonstrating the system’s potential to reduce long-term expenditure for farmers.

4. RESULTS

4.1 Nutrient Distribution Efficiency and Accuracy

The iReMix system demonstrated consistent and accurate nutrient mixing across multiple trials. The concentration of nutrients delivered to the crops was maintained within a ±5% deviation from the target values, meeting the accuracy threshold defined in the study. By comparison, the conventional pump-based system showed greater variability due to fluctuations in motor speed and uneven mixing during initial operation.

Table 2. Comparison of Nutrient Concentration Consistency

Trial	Target Concentration (ppm)	iReMix Measured (ppm)	Error (%)	Conventional System (ppm)	Error (%)
1	150	147	-2.0	141	-6.0
2	150	152	+1.3	156	+4.0
3	150	149	-0.7	160	+6.7

Interpretation: The results confirm that iReMix consistently maintains nutrient concentrations closer to the target, outperforming the conventional system in terms of accuracy.

4.2 Operational Cost Savings

Operational costs were significantly reduced when using the iReMix system. Since the system relies on gravitational flow, energy consumption was negligible compared to the pump-based fertigation system, which required continuous electricity. Maintenance costs were also lower due to fewer moving parts.

Table 3. Cost Comparison between iReMix and Conventional System (per cropping cycle)

Parameter	Conventional System (RM).	iReMix System (RM)	Savings (%)
Energy Consumption	120.00	5.00	95.8
Maintenance	60.00	20.00	66.7
Labor	80.00	60.00	25.0
Total Cost	**260.00**	**85.00**	**67.3**

Interpretation: iReMix reduced overall operational costs by approximately 67% per cropping cycle, demonstrating strong economic feasibility.

5. DISCUSSION

The findings of this study highlight the potential of iReMix as a sustainable alternative to conventional fertigation systems in smart farming. The system successfully met both objectives: ensuring accurate nutrient distribution and reducing operational costs while promoting environmental sustainability.

5.1 Nutrient Distribution Accuracy

The results demonstrated that iReMix consistently maintained nutrient concentrations within a ±5% deviation from target values. This performance surpasses that of conventional pump-based systems, which exhibited higher variability. The improved accuracy can be attributed to the gravitational mixing principle, which reduces turbulence and ensures uniform nutrient blending. These findings are consistent with Smith, Patel, and Kim (2019), who emphasized the importance of precision in fertigation to maximize nutrient uptake and minimize wastage. Unlike IoT-driven fertigation solutions (Zhang, Wang, & Chen, 2020), which often require complex sensor networks and computational inputs, iReMix achieves comparable accuracy with minimal technological demands, making it accessible to resource-limited farmers.

5.2 Cost Efficiency and Economic Viability

Operational cost analysis revealed that iReMix reduced overall expenses by approximately 67% per cropping cycle compared to conventional systems. The savings were primarily due to negligible energy consumption, reduced maintenance needs, and lower labor requirements. This aligns with Rahman and Lee (2021), who identified high energy costs and maintenance demands as barriers to adoption of automated fertigation systems among smallholders. By eliminating dependence on electricity, iReMix directly addresses this barrier, making fertigation more economically viable for small- and medium-scale farms.

5.3 Limitations and Future Directions

Despite its promising results, the iReMix system has limitations. Its performance is dependent on gravitational head height, which may restrict application in flat terrains or areas without elevation differences. Additionally, while the system was tested under controlled conditions, broader field trials across diverse crop types and climatic conditions are needed to validate scalability.

6. Conclusion

This study successfully designed, developed, and evaluated iReMix, a gravity-based automated nutrient mixing system intended to improve fertigation efficiency in smart farming applications. The findings demonstrated that iReMix could maintain nutrient concentration within a ±5% deviation from target values while significantly reducing operational costs by approximately 67% per cropping cycle.

The results support previous findings by Smith, Patel, and Kim (2019), who emphasized the importance of precise nutrient delivery in improving crop nutrient uptake and reducing fertilizer wastage. Furthermore, the present study extends the work of Chakraborty, Sharma, and Saha (2018) by demonstrating that gravity-fed agricultural systems can be integrated with automated nutrient control mechanisms to improve efficiency and practicality in modern farming environments.

Unlike highly automated IoT-based fertigation systems proposed by Rahman and Lee (2021), the iReMix system offers a simpler and more affordable alternative that minimizes dependence on electricity and advanced infrastructure. This makes the system particularly suitable for small- and medium-scale farmers with limited financial and technical resources.

Overall, the study demonstrates that iReMix has strong potential as a sustainable, energy-efficient, and economically viable fertigation solution capable of supporting smart farming and environmentally responsible agricultural practices.

Importance of the Study:

The findings demonstrate that iReMix offers a practical, low-cost, and environmentally responsible solution to the limitations of conventional fertigation. Its simplicity, affordability, and reliability make it particularly suitable for small- and medium-scale farmers who face financial and technical barriers in adopting advanced smart farming technologies.

Recommendations for Future Research:

- Conduct large-scale field trials across diverse crops, soil types, and climates to validate scalability and adaptability.
- Explore integration with renewable energy or low-cost IoT monitoring tools to further enhance automation and precision.
- Investigate long-term system durability and farmer adoption patterns to evaluate real-world impact on productivity and sustainability.

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