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Sustainable Crop Performance Model through the iReMix Automated Nutrient Flow System

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Abstract. Global food security challenges require nutrient-delivery systems that can improve crop productivity while conserving water and fertiliser resources. This revised conceptual paper presents iReMix, an automated nutrient-flow and gravity-assisted mixing system for fertigation applications. In response to reviewer comments, the manuscript was strengthened by replacing non-agriculture references with recent agriculture-related sources and by clarifying that runoff and leaching reduction are treated as model-supported performance indicators rather than unsupported field claims. The proposed framework integrates nutrient tanks, gravity-based mixing, distribution pipelines, flow regulation, low-cost sensors, and a feedback-driven control unit. It also introduces measurable indicators for future validation, including nutrient use efficiency, water productivity, coefficient of variation for flow uniformity, runoff coefficient, leachate electrical conductivity, and nutrient loss load. Evidence from recent smart-fertigation and drip-fertigation literature shows that automated or sensor-supported fertigation can improve water and nutrient productivity and reduce nutrient losses when monitored appropriately. The expected contribution of iReMix is therefore positioned as a practical, modular, and low-cost pathway for improving fertigation consistency, reducing manual mixing time, and enabling evidence-based nutrient management among small and medium-scale growers. Future work will validate the model through pilot testing, drainage/runoff measurement, sensor calibration, and comparative analysis against conventional manual fertigation.

Keywords: Smart fertigation, iReMix system, nutrient flow modeling, precision agriculture, sustainable crop performance

1. INTRODUCTION

Global agriculture is under increasing pressure to raise productivity while reducing environmental impacts associated with excessive water and fertiliser use, a challenge repeatedly highlighted in global food and agriculture sustainability reports (Food and Agriculture Organization of the United Nations [FAO], 2017). Fertigation, which combines irrigation and fertiliser application, is widely recognised as an important strategy for delivering water and nutrients directly to the crop root zone. However, the effectiveness of fertigation depends on the consistency of nutrient mixing, flow distribution, and timing of application. When these factors are poorly controlled, nutrient concentrations may fluctuate, leading to uneven crop growth, wastage of inputs, and potential nutrient losses through runoff or leaching.

Conventional small-scale fertigation practices often depend on manual fertiliser preparation, fixed irrigation schedules, and limited monitoring. These practices are practical and inexpensive, but they may create variability in nutrient concentration, labour-intensive operations, and difficulty in verifying whether supplied nutrients are actually utilised by plants. Recent studies on drip fertigation and smart fertigation have shown that improved monitoring, sensor feedback, and precise application can improve nutrient use efficiency and reduce environmental nitrogen losses compared with traditional irrigation and fertiliser broadcasting approaches (Ahmad et al., 2022; Aziz et al., 2022; Bonelli et al., 2024; Kumari et al., 2025; Li et al., 2021; Savvas et al., 2024; Zheng et al., 2023).

The iReMix system is proposed as a low-cost automated nutrient-flow model that combines gravity-assisted mixing with controlled distribution and monitoring. Unlike high-end fertigation automation systems that depend heavily on complex dosing units, iReMix emphasises practical applicability through modular tanks, pipe networks, flow regulation, sensors, and simple control logic. This makes the system potentially suitable for small and medium-scale growers who require better consistency than manual mixing but may not be able to invest in expensive industrial fertigation platforms.

This paper aims to conceptualise and strengthen a sustainable crop performance model through the iReMix automated nutrient flow system. Specifically, the paper: (i) describes the system architecture and nutrient-flow cycle; (ii) proposes measurable performance indicators for agronomic, environmental, and operational assessment; and (iii) reframes runoff-related claims as testable indicators supported by literature and future empirical validation. This positioning addresses the need for stronger data support while maintaining the conceptual nature of the manuscript.

2. LITERATURE REVIEW

The iReMix system is conceptualized as a smart fertigation model that integrates hardware and software components into a closed-loop nutrient management cycle. Its design emphasizes precision, automation, and sustainability to ensure optimal crop performance while reducing resource inefficiencies.

2.1 Smart Fertigation and Nutrient Management

Smart fertigation integrates irrigation, nutrient application, sensing, and control to deliver nutrients according to crop demand. Solar and IoT-based fertigation systems demonstrate how soil, weather, and crop data can support real-time irrigation scheduling and more precise nutrient delivery (Ahmad et al., 2022). In controlled and field fertigation systems, soil moisture and electrical conductivity (EC) sensors are particularly important because they indicate water availability, soluble salt concentration, and possible nutrient movement in the root zone (Kumari et al., 2025).

Recent meta-analytical evidence also supports the importance of fertigation as an environmental management strategy. Zheng et al. (2023) reported that drip fertigation increased crop yield while reducing several nitrogen-loss pathways compared with traditional irrigation and fertilisation practices. Although the exact percentage of reduction depends on crop type, soil texture, climate, and management practice, the evidence supports the use of monitored fertigation as a pathway to reduce nutrient losses when compared with uncontrolled or over-applied systems.

For soilless and greenhouse production, closed-loop or sensor-supported fertigation has been shown to improve resource use by monitoring drainage solution, electrical conductivity, and nutrient balance (Bonelli et al., 2024; Savvas et al., 2024). These studies are relevant to iReMix because they show that claims related to nutrient loss reduction should be supported by measurable indicators such as drainage volume, leachate EC, nitrate concentration, and nutrient mass balance rather than by general statements alone.

2.2 iReMix System Components

Nutrient source and gravity-assisted mixing. The iReMix model uses nutrient tanks and gravity-assisted flow to improve the consistency of fertiliser mixing before distribution. This design reduces dependence on complex dosing machinery and supports practical deployment in small-scale fertigation systems.

Distribution network. PVC pipelines, control valves, and emitters distribute the nutrient solution to crop rows. Flow-regulating valves are used to reduce under-application and over-application across different outlets.

Sensor layer. Low-cost sensors such as EC, pH, flow, and moisture sensors provide measurable indicators for system monitoring. EC data are used as a proxy for nutrient concentration, while flow data support uniformity and delivery-volume assessment.

Control mechanism. A basic controller or microcontroller can trigger pumps, valves, or timers according to selected thresholds. In the simplest configuration, iReMix can operate as a semi-automated system; in a more advanced configuration, it can be integrated with IoT monitoring for remote data logging.

Data and modelling layer. The modelling layer stores nutrient concentration, flow rate, delivery volume, crop growth, and drainage/runoff readings. These data are used to calculate performance indicators and compare iReMix with manual fertigation.

2.3 Sustainability Principles

Resource conservation is achieved when the amount of water and fertiliser supplied is aligned with plant requirements. For iReMix, this principle is measured through water productivity, fertiliser productivity, and nutrient use efficiency rather than through qualitative observation alone.

Environmental protection is addressed by measuring runoff and leaching indicators. In this revised manuscript, runoff reduction is not presented as a confirmed empirical result. Instead, it is proposed as a testable outcome to be evaluated using runoff coefficient, leachate EC, and nutrient loss load. This revision directly responds to the reviewer comment that runoff claims require stronger data support.

Operational sustainability is addressed through time-efficiency analysis. Because manual fertiliser mixing is labour-intensive, iReMix is expected to reduce mixing and distribution time. The time-saving percentage is calculated by comparing average manual operation time with average iReMix operation time across repeated cycles.

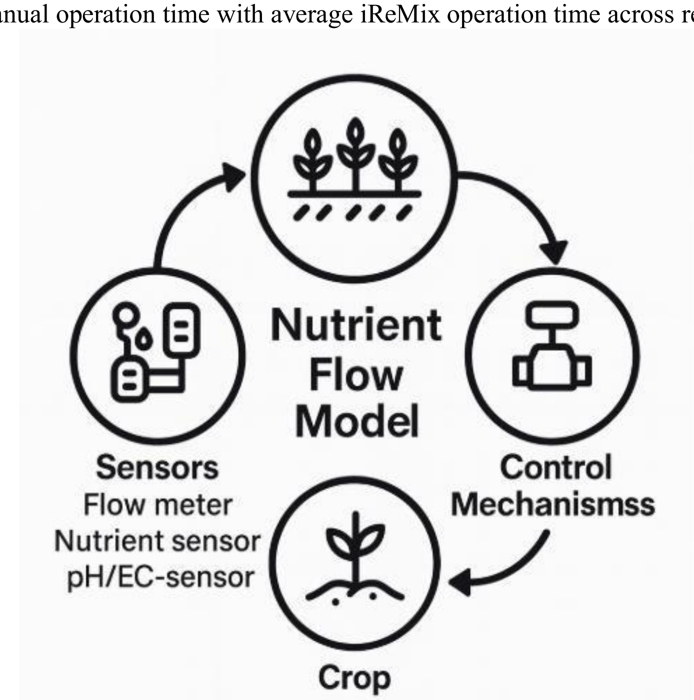

Figure 1. Nutrient Flow Cycle Model for iReMix

3. Research Methodology

This study adopts a conceptual design-and-test framework. The conceptual component describes the iReMix architecture and performance model. The test component proposes a validation protocol to compare iReMix with conventional manual fertigation. The methodology was revised to include measurable runoff and leaching indicators so that environmental claims can be verified during future pilot testing.

The proposed pilot validation uses two comparison groups: a conventional manual fertigation group and an iReMix fertigation group. Both groups should use the same crop type, number of plants, growth medium, planting duration, and environmental conditions as far as practicable. Data should be collected over repeated fertigation cycles to reduce the effect of random variation.

3.1 Experimental and Monitoring Parameters

Table 1. Monitoring Parameters

Parameter	Definition	Measurement / Formula	Purpose
Nutrient concentration	Strength of fertiliser solution	EC meter, pH meter, and/or laboratory nutrient analysis	Verifies consistency of nutrient preparation
Flow uniformity	Variation of output among emitters	Coefficient of variation (CV) = standard deviation of emitter flow / mean emitter flow × 100	Assesses distribution consistency
Fertiliser solution supplied	Total solution delivered to plants	Measured in litres per cycle	Determines input quantity
Drainage/runoff volume	Solution leaving the root zone or collection tray	Collected in container or drainage tray and measured in litres	Provides direct runoff/leaching support
Runoff coefficient	Proportion of supplied solution not retained	RC = drainage/runoff volume / supplied volume × 100	Supports environmental claim with data
Nutrient loss load	Estimated nutrient mass lost in runoff/leachate	NLL = drainage volume × nutrient concentration in drainage	Quantifies nutrient-loss risk
Nutrient use efficiency	Ratio of nutrient taken up or retained to nutrient supplied	NUE = nutrient retained or absorbed / nutrient supplied × 100	Assesses fertiliser efficiency
Water productivity	Crop output per unit water supplied	Yield or biomass / water supplied	Assesses water-use performance
Plant growth	Crop development indicator	Height, leaf number, canopy width, or biomass recorded weekly	Assesses crop response
Operation time	Time required for mixing and distribution	Stopwatch; manual vs iReMix cycles	Calculates time saving

Table 1 describes the monitoring parameters used to evaluate the effectiveness of the iReMix system in a measurable way. Parameters such as nutrient concentration, flow uniformity, fertiliser solution supplied, drainage/runoff volume, runoff coefficient, nutrient loss load, nutrient use efficiency, water productivity, plant growth and operation time are included to support the study findings. Each parameter is linked to a specific measurement method or formula, allowing the system's performance to be objectively compared with conventional fertigation, particularly in terms of efficiency, time saving and environmental sustainability.

3.2 Data Analysis

Flow uniformity is evaluated using the coefficient of variation. A lower value indicates more uniform nutrient delivery across outlets. Nutrient consistency is assessed by comparing EC and pH readings before and after mixing and at selected emitter points.

Runoff and leaching support are strengthened by using direct or proxy measurements. For each fertigation cycle, supplied volume, drainage/runoff volume, EC of drainage solution, and nutrient concentration where available should be recorded. The runoff coefficient and nutrient loss load provide quantitative evidence for environmental performance.

Time efficiency is calculated as: Time saving (%) = ((average manual time - average iReMix time) / average manual time) × 100. The system is considered operationally beneficial when it achieves meaningful time reduction without compromising nutrient concentration consistency or plant growth.

3.3 Performance Indicators

The effectiveness of iReMix will be evaluated using measurable performance indicators:

Nutrient Use Efficiency (NUE): The ratio of nutrients absorbed by crops to the total nutrients supplied. Higher NUE indicates reduced waste and improved crop health (Zhang et al., 2020).

Water Productivity: The amount of crop yield produced per unit of water applied, reflecting the system's capacity to conserve water resources (Müller et al., 2019).

Operational Cost: Assessment of input costs (energy, fertilizers, and labour) relative to output value. Automation is expected to reduce recurring costs despite higher initial investment.

Environmental Indicators: Reduction in nutrient runoff and leaching, contributing to lower pollution levels and improved soil sustainability (Gonzalez & Lopez, 2018).

Together, these methodological elements ensure that iReMix is assessed not only as a technical innovation but also as a sustainable agricultural model that balances productivity, resource efficiency, and environmental protection.

4. RESULTS

Because this manuscript is conceptual and prototype-oriented, the results are presented as evidence-based expected outcomes and validation metrics rather than as completed field-trial results. This revision avoids unsupported claims and clarifies how each claim will be verified. The environmental outcome related to runoff is therefore expressed as a measurable indicator, not as a confirmed reduction.

Table 2 summarizes the revised outcome framework. It links each expected benefit with the required data source and supporting literature so that the model can be tested empirically during pilot implementation.

Table 2. Revised expected outcomes and evidence requirements

Outcome area	Expected effect of iReMix	Data support required	Interpretation
Agronomic performance	More consistent nutrient supply and more uniform plant growth	Weekly plant height, leaf number, biomass, and yield data	Improvement can be claimed only if iReMix plants outperform or match manual fertigation while using equal or lower inputs
Nutrient consistency	Reduced variation in nutrient concentration after mixing	EC and pH readings at tank and emitter points	Lower variation indicates more stable mixing and distribution
Runoff/leaching risk	Potential reduction in nutrient loss due to controlled delivery	Supplied volume, drainage/runoff volume, leachate EC, and nutrient concentration	Runoff claim must be supported by lower runoff coefficient or lower nutrient loss load
Water and fertiliser efficiency	Improved use of supplied water and nutrients	Water productivity, nutrient productivity, NUE	Efficiency claim requires ratio-based comparison with manual method
Operation time	Reduced manual mixing and distribution time	Stopwatch data for repeated manual and iReMix cycles	Time saving is accepted only when calculated from repeated operation cycles
Scalability	Adaptability to small farms and greenhouse setups	Cost, component availability, maintenance needs	Scalability depends on affordability and ease of maintenance

Table 2 explains the revised expected outcomes and evidence required to validate the iReMix system. It shows that iReMix is expected to improve agronomic performance, nutrient consistency, runoff control, water and fertiliser efficiency, operation time, and scalability. Each outcome must be supported by specific data such as plant growth records, EC and pH readings, runoff volume, nutrient loss, water productivity, stopwatch data, and cost analysis. This ensures that performance claims are evidence-based, measurable, and suitable for comparison with conventional fertigation methods.

4.1 Agronomic Benefits

The iReMix system is expected to improve agronomic performance by reducing inconsistency in nutrient delivery. Consistent EC and pH readings at the tank and emitter points would indicate stable nutrient preparation. Crop performance must be verified using repeated plant-growth data, such as weekly height, leaf number, and biomass. In this revised version, higher yield is presented as an expected outcome that requires pilot validation rather than as an already proven result.

4.2 Environmental Benefits and Runoff Support

The environmental benefit of iReMix is its potential to reduce nutrient wastage by controlling delivery volume and improving nutrient consistency. To address the reviewer comment, runoff and leaching claims have been revised. The paper no longer claims a confirmed reduction in runoff without data. Instead, runoff is operationalised using runoff coefficient and nutrient loss load. A reduction can be claimed only if the iReMix treatment produces lower drainage/runoff volume, lower leachate EC, or lower calculated nutrient loss load than the manual fertigation treatment. This approach is consistent with recent fertigation literature that uses drainage, leachate, EC, and nitrogen-loss measurements to support environmental claims (Aziz et al., 2022; Bonelli et al., 2024; Kumari et al., 2025; Savvas et al., 2024; Zheng et al., 2023).

4.3 Economic and Operational Benefits

The main operational benefit of iReMix is expected to be reduced mixing and distribution time. Since the system uses gravity-assisted flow and controlled distribution, repeated manual preparation steps can be minimised. The financial benefit should be assessed by comparing labour time, fertiliser wastage, water use, maintenance cost, and crop output. Although the initial prototype cost may be higher than manual mixing, the system may become economically beneficial when time saving, reduced input wastage, and improved crop consistency are achieved.

5. DISCUSSION

The revised iReMix model contributes to precision agriculture by translating smart fertigation principles into a practical gravity-assisted and sensor-supported system. The model is relevant to small and medium-scale growers because it avoids excessive dependence on high-cost automation while still enabling data-based nutrient management. The key improvement in this revised manuscript is the strengthening of evidence logic. Earlier statements on runoff reduction were too general. The revised manuscript now requires direct measurement of drainage/runoff volume and nutrient concentration before any environmental reduction claim is made. This distinction is important because nutrient loss is affected by soil type, crop stage, irrigation frequency, emitter performance, rainfall, and management practice.

The model also has limitations. First, conceptual modelling cannot replace field validation. Second, EC is a useful proxy for soluble salts but does not identify individual nutrients unless supported by ion-selective sensors or laboratory analysis. Third, smallholder adoption depends on cost, ease of repair, and user training. These limitations should be addressed in the pilot-testing stage.

Opportunities

The opportunities presented by iReMix are equally significant. The system can be integrated with emerging technologies such as the Internet of Things (IoT) and artificial intelligence (AI) to further enhance automation and predictive capabilities. IoT-enabled networks allow for remote monitoring and control, enabling farmers to manage nutrient delivery from mobile devices (Wolfert et al., 2017). AI-driven analytics can forecast nutrient requirements based on crop growth patterns, weather forecasts, and soil data, thus enhancing decision-making accuracy (Li et al., 2022). Furthermore, alignment with climate-smart farming practices positions iReMix as a valuable tool in promoting agricultural resilience, resource efficiency, and environmental stewardship.

6. Conclusion

This conceptual paper has highlighted the significance of iReMix as an automated nutrient flow system for sustainable fertigation. By integrating sensors, automated control mechanisms, and a feedback-driven modeling framework, iReMix addresses the persistent challenges of conventional fertigation—namely inefficiency, nutrient losses, and environmental degradation. The conceptualization of iReMix underscores its potential to serve as a transformative model for precision agriculture, combining technological innovation with sustainability principles.

The proposed system demonstrates a clear ability to balance agricultural productivity and environmental stewardship. On one hand, it enhances yield and crop performance through consistent nutrient delivery; on the other, it reduces input wastage and ecological impacts by minimizing runoff and optimizing nutrient use efficiency. This dual contribution positions iReMix as a key enabler of climate-smart and resource-efficient farming practices.

Looking ahead, further work is needed to transition the iReMix model from conceptualization to large-scale implementation. Pilot studies should be undertaken to evaluate its performance under diverse soil, crop, and climatic conditions. Real-world validation will provide empirical evidence on agronomic, environmental, and economic impacts. Moreover, future development should consider integration with AI-driven optimization and IoT connectivity, enabling predictive nutrient management and remote system monitoring.

In conclusion, iReMix offers a pathway toward an agricultural future where productivity, sustainability, and technological innovation are mutually reinforcing. Its adoption could play a critical role in shaping more resilient and efficient food production systems for the decades ahead.

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