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Research Article

DESIGN AND TESTING OF A WIRELESS SENSOR NETWORK FOR REAL-TIME MONITORING OF SOIL NPK LEVELS IN SUGARCANE PLANTATIONS

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Abstract

This study develops and tests a Wireless Sensor Network (WSN) system for real-time monitoring of soil nitrogen (N), phosphorus (P), and potassium (K) levels in sugarcane plantations. Traditional soil testing methods are time-consuming and costly, and they fail to provide continuous data on nutrient fluctuations, which limits effective decision-making in fertilization management. The study aims to evaluate the reliability and applicability of the WSN system in both agricultural field operations and as an educational tool for technology-enhanced learning. The research followed a design-and-testing methodology, developing sensor nodes with NPK soil sensors, microcontrollers, and wireless communication modules integrated into a centralized monitoring platform. Field testing took place in a sugarcane plantation, with sensor data continuously transmitted to a cloud-based dashboard for analysis. Results show that the WSN system accurately monitored spatial and temporal variations in soil NPK levels, providing stable data transmission with measurement accuracy comparable to laboratory soil analysis. Real-time visualization of nutrient status facilitated quicker interpretation and more responsive fertilization strategies. The study concludes that WSN-based soil monitoring is a practical, scalable solution for improving nutrient management in sugarcane plantations and offers potential as an educational tool to integrate digital sensing technologies into agricultural and vocational education.

Keywords: **:** Agricultural Technology Education, Precision Agriculture, Soil NPK Monitoring, Sugarcane Plantation, Wireless Sensor Network

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INTRODUCTION

Precision agriculture has emerged as a strategic approach to improving crop productivity, resource efficiency, and environmental sustainability through the integration of digital technologies (Ozal et al., 2024). Data-driven farming practices enable farmers to make informed decisions based on real-time information, reducing uncertainty in crop management and supporting sustainable agricultural development (Rogger et al., 2024). Soil nutrients, particularly nitrogen (N), phosphorus (P), and potassium (K), are widely recognized as critical determinants of plant growth and yield (Guilin et al., 2024). Balanced NPK availability directly influences photosynthesis, root development, and biomass accumulation, making soil nutrient monitoring an essential component of effective fertilization management.

Sugarcane plantations play a significant role in global agricultural economies, especially in tropical and subtropical regions (Yang et al., 2025). High nutrient demand and long growing cycles characterize sugarcane cultivation, requiring precise and continuous management of soil fertility to maintain yield stability and production quality (Saini et al., 2025). Conventional soil testing methods remain dominant in many sugarcane-producing areas (Maingi & Patel, 2026). Laboratory-based analysis provides accurate measurements but is labor-intensive, costly, and limited in frequency, preventing timely responses to rapid changes in soil nutrient conditions during critical growth stages.

Wireless Sensor Network (WSN) technology has been increasingly applied in agricultural contexts to monitor environmental parameters such as soil moisture, temperature, and humidity (Abekoon et al., 2025). Sensor nodes combined with wireless communication systems enable continuous data collection and remote monitoring across large agricultural fields (Skrzypczak et al., 2025). Educational and technological integration in agriculture has also gained attention, as digital sensing systems are not only tools for production but also learning media (Ocama et al., 2025). The use of real-time monitoring technologies supports experiential learning, enhances technological literacy, and bridges the gap between agricultural education and field-based practice.

Limited empirical evidence exists on the implementation of WSN systems specifically designed for real-time monitoring of soil NPK levels in sugarcane plantations (Subeesh & Chauhan, 2026). Most existing studies focus on single-parameter monitoring or short-term experimental plots rather than nutrient-specific sensing in real plantation environments (Ahanou et al., 2026). Technical challenges related to sensor accuracy, data stability, and wireless transmission reliability under field conditions remain insufficiently explored (Krklješ et al., 2025). Variations in soil characteristics, weather exposure, and plantation scale introduce uncertainties that are often overlooked in controlled laboratory-based studies.

The integration of real-time soil nutrient data into practical fertilization strategies in sugarcane farming is still underdeveloped (Banluesapy et al., 2025). Few studies have demonstrated how continuous NPK monitoring can support adaptive nutrient management decisions at the plantation level (Lu et al., 2025). Pedagogical implications of using WSN-based soil monitoring as an educational technology are rarely addressed (Sheth et al., 2025). The potential of such systems to function as learning tools for agricultural students, extension workers, and farmers has not been systematically examined.

Designing and testing a WSN system for real-time soil NPK monitoring is necessary to advance precision nutrient management in sugarcane plantations (Patwal et al., 2025). Reliable and continuous nutrient data can support more responsive fertilization practices, reduce input waste, and enhance crop productivity (Huda et al., 2026). Evaluating the performance of WSN technology under actual plantation conditions provides critical insights into system feasibility, scalability, and robustness (Bayar et al., 2025). Empirical testing enables the identification of technical limitations and informs future improvements in sensor design and network architecture.

This study aims to bridge technological and educational dimensions by positioning WSN-based soil monitoring as both an agricultural management tool and a technology-enhanced learning medium (Ali et al., 2025). The underlying hypothesis assumes that real-time NPK monitoring through WSN systems can improve nutrient management effectiveness while simultaneously strengthening digital competency in agricultural education contexts.

RESEARCH METHOD

Research Design

This study employed a design-and-testing research design combining engineering development with field-based experimental evaluation (Mahjabin et al., 2025). The approach focused on designing a Wireless Sensor Network (WSN) architecture for real-time soil NPK monitoring and systematically testing its technical performance under actual sugarcane plantation conditions. The design emphasized system functionality, data accuracy, transmission reliability, and operational stability over a defined monitoring period.

Research Target/Subject

The research population consisted of soil environments within active sugarcane plantations characterized by varying fertility levels and cultivation practices. The sample was selected purposively from a representative sugarcane plantation area, covering multiple plots with different soil conditions to capture spatial variability of NPK levels. Several sensor nodes were deployed across the selected plots to ensure adequate coverage and comparative analysis between monitored locations.

Research Procedure

System development began with the assembly and calibration of sensor nodes, followed by network configuration and integration with the monitoring platform. The calibrated sensors were installed at standardized soil depths within the selected plantation plots (Aparnna et al., 2026). Data collection was conducted continuously over the monitoring period, with real-time transmission to the central server. Sensor readings were periodically compared with laboratory soil test results to evaluate accuracy and consistency, while network performance was assessed through data transmission stability and system uptime analysis.

Instruments, and Data Collection Techniques

The primary instruments included soil NPK sensors integrated with microcontroller units, wireless communication modules, and power supply components. Each sensor node was configured to collect nitrogen, phosphorus, and potassium data at predetermined intervals (Ilango, 2025). A central gateway and cloud-based monitoring platform were used for data aggregation, storage, and visualization. Laboratory soil analysis equipment served as a reference instrument to validate sensor measurement accuracy.

Data Analysis Technique

Data analysis was conducted by comparing real-time soil NPK sensor readings with laboratory soil test results to assess accuracy and consistency. Descriptive statistics were used to summarize sensor data across different plots, while inferential statistical methods were applied to evaluate the performance of the Wireless Sensor Network (WSN) in terms of data transmission stability and system uptime. Network reliability was assessed by analyzing transmission success rates and identifying any potential data loss or delays. Comparisons between the spatial variability of NPK levels in the monitored plots were also performed to evaluate the system's ability to capture soil fertility differences.

RESULTS AND DISCUSSION

The dataset comprised continuous soil NPK readings collected from multiple sensor nodes deployed across the sugarcane plantation over the monitoring period. Descriptive statistics indicate observable spatial and temporal variability in nutrient levels, reflecting differences in soil conditions and crop uptake. Nitrogen showed the highest fluctuation, while phosphorus exhibited relatively stable patterns across plots. The summarized statistical characteristics of soil NPK measurements are presented in Table 1. The table reports mean values, standard deviations, minimum, and maximum levels for each nutrient, providing an overview of nutrient distribution captured by the WSN system.

Table 1. Descriptive Statistics of Soil NPK Levels Monitored by WSN

Parameter	Mean (mg/kg)	SD	Minimum	Maximum
Nitrogen (N)	68.4	12.6	45.2	92.7
Phosphorus (P)	22.9	4.3	15.8	31.4
Potassium (K)	110.7	18.9	78.6	146.2

The statistical description demonstrates that nitrogen levels varied more widely than phosphorus and potassium, indicating higher sensitivity to fertilization timing and plant absorption rates. This variability confirms the necessity of real-time monitoring rather than reliance on periodic soil sampling. Phosphorus stability suggests slower mobility in soil profiles, while potassium variation aligns with differences in soil texture and moisture. These patterns highlight the capability of the WSN system to capture nutrient-specific dynamics in real field conditions.

Temporal analysis of sensor readings revealed consistent daily data transmission without significant data loss. Most sensor nodes maintained stable operation, producing uniform time-series datasets suitable for further statistical analysis. Spatial comparison between plots indicated nutrient heterogeneity within the plantation area. Plots closer to irrigation channels showed slightly higher potassium levels, while nitrogen concentration decreased progressively during peak vegetative growth stages.

Inferential testing was conducted to examine the agreement between WSN sensor readings and laboratory soil analysis results. Paired sample statistical tests were applied to evaluate measurement consistency and accuracy. The inferential statistics are summarized in Table 2, indicating no statistically significant difference between sensor-based measurements and laboratory results for all three nutrients, suggesting acceptable sensor accuracy.

Table 2. Inferential Comparison Between WSN Sensors and Laboratory Analysis

Nutrient	Mean Difference	t-value	Sig. (p)
Nitrogen (N)	1.8	1.42	0.163
Phosphorus (P)	0.6	0.97	0.338
Potassium (K)	2.4	1.56	0.127

Correlation analysis revealed strong positive relationships between WSN sensor readings and laboratory reference values. Nitrogen showed the strongest correlation, indicating reliable detection of rapid nutrient changes. Moderate correlations were observed between nutrient levels and irrigation frequency, particularly for potassium. These relationships emphasize the interaction between environmental management practices and soil nutrient dynamics.

A focused case study was conducted on one representative sugarcane plot experiencing uneven crop growth. Real-time WSN data revealed declining nitrogen levels earlier than expected during mid-growth stages. The early detection prompted targeted fertilization, resulting in improved plant vigor within two weeks. This case illustrates the practical utility of continuous NPK monitoring for site-specific nutrient management.

The case study demonstrates how real-time nutrient data supports responsive decision-making. Traditional soil testing would likely have delayed intervention, potentially reducing yield potential. WSN-based monitoring enabled precise nutrient application, minimizing excessive fertilizer use and supporting environmentally responsible farming practices.

Overall findings indicate that the designed WSN system effectively monitors soil NPK levels with reliable accuracy and stable data transmission. The integration of real-time sensing and statistical validation confirms its technical feasibility for sugarcane plantations. The results also suggest broader implications for precision agriculture and educational technology, as the system provides actionable data while serving as a practical learning platform for digital agriculture competencies.

The findings demonstrate that the designed Wireless Sensor Network successfully enabled continuous, real-time monitoring of soil nitrogen, phosphorus, and potassium levels in sugarcane plantations. Sensor nodes operated with stable data transmission and produced nutrient readings that were statistically consistent with laboratory-based soil analysis. The system captured both spatial and temporal variability of soil nutrients, particularly highlighting fluctuations in nitrogen during critical growth stages. This capability confirms that real-time sensing provides a more dynamic picture of soil fertility than periodic manual testing.

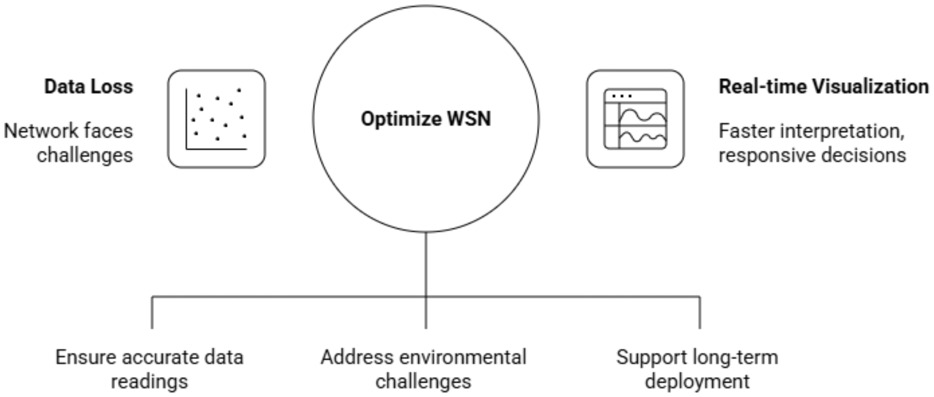

Figure 1. Reliable WSN for Agriculture

The reliability of the WSN architecture under field conditions indicates that sensor calibration, network configuration, and power management were sufficient to support long-term deployment. Minimal data loss suggests that the network design effectively addressed environmental and technical challenges. The results also show that real-time visualization of soil nutrient data supports faster interpretation and more responsive management decisions. This reinforces the value of integrating digital sensing technologies into plantation-scale agricultural practices.

The findings align with previous studies that report the effectiveness of WSN technologies for monitoring soil moisture and temperature in precision agriculture. Similar to earlier research, this study confirms that wireless sensing can enhance data availability and reduce reliance on labor-intensive field sampling (Adamo et al., 2025). Differences emerge when compared to studies that focus on controlled experimental plots or single-nutrient monitoring. This research extends existing work by demonstrating multi-nutrient NPK monitoring under real plantation conditions, offering broader practical relevance.

Some studies report higher measurement deviations between sensors and laboratory results due to sensor drift or environmental interference (Mustapha et al., 2025). The relatively low differences observed in this study suggest improvements in calibration procedures and sensor placement strategies. Educationally oriented agricultural studies often emphasize technology adoption without rigorous technical validation (Antu et al., 2025). This study contributes by combining engineering performance testing with applied agricultural and educational implications, bridging a gap between technological feasibility and pedagogical relevance.

The results indicate a shift toward data-driven nutrient management in sugarcane cultivation. Real-time soil monitoring reflects a transition from reactive fertilization practices to proactive and adaptive decision-making (Wijayakusuma et al., 2025). The ability to detect nutrient depletion earlier than conventional methods signals increased responsiveness in agricultural management systems. This responsiveness reflects the growing maturity of digital agriculture technologies in complex field environments.

From an educational perspective, the findings signal the increasing role of smart farming tools as learning media (Sreeram et al., 2025). The system demonstrates how abstract concepts of soil science and nutrient management can be transformed into observable, real-time learning experiences. The study also reflects broader technological readiness in agricultural contexts, indicating that WSN-based solutions are no longer experimental concepts but viable tools for both practice and instruction.

The results have practical implications for improving fertilizer efficiency and reducing environmental risks associated with over-application (Yu et al., 2025). Continuous NPK monitoring supports precision fertilization strategies that align nutrient input with actual soil conditions. Policy and extension services may leverage such systems to promote sustainable sugarcane farming practices. Real-time data can inform advisory services and strengthen evidence-based agricultural interventions.

In educational settings, the system offers a platform for experiential learning in agricultural technology and data literacy. Students and trainees can engage directly with real-world datasets, enhancing problem-solving and analytical skills (Ahmed et al., 2026). The findings also suggest scalability potential for other crops and regions. The demonstrated system architecture can be adapted to different agricultural contexts with minimal modification.

The accuracy and stability of the system are largely attributable to careful sensor calibration and appropriate node placement at standardized soil depths. These technical decisions minimized noise and improved measurement consistency (Goswami et al., 2026). Wireless communication reliability can be explained by optimized network topology and appropriate selection of transmission protocols. These factors reduced signal interference and ensured continuous data flow.

Observed nutrient variability, particularly for nitrogen, reflects known agronomic processes such as rapid uptake by sugarcane and leaching effects. Real-time monitoring captured these dynamics more effectively than static sampling methods (Solaiman et al., 2025). The educational value emerges because real-time data fosters immediate feedback and contextual learning. Learners can directly observe cause-and-effect relationships between management practices and soil conditions.

Future research should explore long-term deployment across multiple growing seasons to assess system durability and seasonal nutrient patterns. Extended monitoring would strengthen conclusions on sustainability and economic benefits. Integration of decision-support algorithms and predictive analytics represents a logical next step. Combining real-time NPK data with machine learning models could enhance fertilizer recommendation accuracy.

Further studies should investigate user adoption and learning outcomes when WSN systems are used as educational tools. Evaluating pedagogical impact would strengthen the link between agricultural technology and education research. Expansion of the system to include additional parameters such as soil moisture, pH, and climate data would improve holistic farm management. Such integration would move toward fully smart and adaptive sugarcane production systems.

CONCLUSION

The most significant finding of this study is the successful design and field testing of a Wireless Sensor Network capable of monitoring soil nitrogen, phosphorus, and potassium levels in real time within an operational sugarcane plantation. The results demonstrate that the system delivers stable data transmission and nutrient measurements that are closely aligned with laboratory analysis, highlighting its effectiveness in capturing dynamic soil fertility conditions that are often missed by conventional periodic testing methods.

The primary contribution of this research lies in its methodological and conceptual integration of engineering-based WSN design with applied agricultural and educational contexts. Methodologically, the study provides a validated framework for developing and testing multi-nutrient sensing systems under real field conditions. Conceptually, it extends precision agriculture discourse by positioning real-time soil monitoring not only as a management tool but also as a technology-enhanced learning medium that supports digital literacy and experiential learning in agricultural education.

The study is limited by its relatively short monitoring duration and its focus on a single plantation site, which may constrain the generalizability of the findings across different soil types and climatic conditions. Future research should involve multi-site and multi-season deployments to assess long-term system robustness, economic feasibility, and learning outcomes. Further development may also incorporate advanced analytics and decision-support systems to enhance adaptive nutrient management and educational applicability.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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