



Real-time Nitrogen Leaching Monitoring using IoT Ground Probes

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Abstract

Nitrogen leaching from agricultural soils represents a significant environmental concern, contributing to groundwater contamination and eutrophication of surface water bodies. This research presents the development and field validation of an Internet of Things (IoT)-based monitoring system employing subsurface electrochemical probes for continuous nitrogen leaching detection. The system integrates ion-selective electrodes, soil moisture sensors, and temperature monitors connected via LoRaWAN communication protocol to a cloud-based analytics platform. Field trials conducted across three agricultural sites over eight months demonstrated measurement precision with correlation coefficient $r=0.96$ when compared against standard laboratory methods. The system achieved temporal resolution of 10-minute intervals, successfully identifying leaching events associated with rainfall and irrigation activities. Peak nitrate concentrations reached 82.3 mg/L, exceeding regulatory thresholds by 64%. Data analysis revealed strong correlations between soil moisture content and nitrate mobility ($r=0.89$, $p<0.01$). The IoT monitoring framework reduced operational costs by 58% compared to conventional sampling approaches while providing actionable insights for precision fertilizer management. This technology offers transformative potential for sustainable agricultural practices and environmental protection strategies.

Keywords: Nitrogen Leaching, Internet of Things, Precision Agriculture, Electrochemical Sensors, Groundwater Quality, Environmental Monitoring, Wireless Sensor Networks, Nutrient Management

1. Introduction

Global agricultural intensification has necessitated substantial increases in synthetic nitrogen fertilizer application, with annual consumption exceeding 110 million tonnes worldwide ^[1]. While nitrogen inputs enhance crop productivity and food security, inefficient utilization results in significant environmental losses through various pathways including volatilization, denitrification, and leaching ^[2]. Nitrate leaching represents the dominant loss mechanism in humid and irrigated agricultural regions, with reported efficiency rates indicating that 40-70% of applied nitrogen fails to contribute to crop uptake ^[3, 4].

The environmental ramifications of excessive nitrogen leaching are multifaceted and severe. Groundwater contamination by nitrate exceeding regulatory limits (50 mg/L NO_3^- in European Union, 10 mg/L NO_3^- -N in United States) poses direct threats to human health, particularly methemoglobinemia in infants and potential carcinogenic effects ^[5, 6]. Furthermore, nitrogen transport to surface waters accelerates eutrophication processes, generating algal blooms, hypoxic zones, and ecosystem degradation ^[7]. Traditional monitoring approaches rely on periodic manual sampling followed by laboratory analysis using spectrophotometric or chromatographic methods ^[8]. These conventional techniques present inherent limitations including low temporal resolution, delayed results, high labor costs, and inability to capture episodic leaching events that occur rapidly following precipitation or irrigation ^[9]. The temporal dynamics of nitrogen leaching demand continuous monitoring capabilities to adequately characterize transport processes and inform management interventions ^[10].

Recent technological advances in Internet of Things (IoT) frameworks, miniaturized electrochemical sensors, and low-power wireless communications have created unprecedented opportunities for environmental monitoring applications ^[11, 12].

IoT-enabled sensor networks facilitate real-time data acquisition, remote accessibility, and integration with decision support systems [13]. Despite these technological capabilities, comprehensive field-validated systems for continuous subsurface nitrogen monitoring remain limited in scientific literature.

This investigation addresses critical research gaps through development, deployment, and validation of an IoT-based ground probe system for real-time nitrogen leaching monitoring. Specific objectives include: (1) engineering robust electrochemical sensor probes for continuous subsurface nitrate detection; (2) implementing wireless data transmission architecture using LoRaWAN protocol; (3) validating measurement accuracy through comparison with standard laboratory methods; and (4) analyzing temporal patterns of nitrogen leaching events in relation to environmental variables.

2. Literature Review

2.1. Nitrogen Transformation and Transport Processes

Nitrogen cycling in agricultural soils involves complex biogeochemical transformations mediated by microbial communities and abiotic factors [14]. Following fertilizer application, organic nitrogen undergoes mineralization to ammonium (NH_4^+), subsequently oxidized through nitrification to nitrate (NO_3^-) [15]. Unlike ammonium, which binds to negatively charged soil particles, nitrate remains highly mobile in soil solution due to electrostatic repulsion from soil colloids [16].

Leaching occurs when nitrate-enriched soil water percolates beyond the root zone, driven by gravitational and pressure gradients [17]. Transport velocity depends on soil hydraulic properties, precipitation patterns, irrigation practices, and antecedent moisture conditions [18]. Research demonstrates that leaching events are episodic, with 70-80% of annual nitrogen losses occurring during 10-15% of the time period, typically associated with intensive rainfall or irrigation events [19].

2.2. Conventional Monitoring Approaches

Standard nitrogen monitoring protocols employ suction lysimeters or ceramic cup samplers installed at predetermined depths to collect soil water samples [20]. Extracted samples undergo laboratory analysis using cadmium reduction methods, ion chromatography, or spectrophotometric techniques [21]. While these approaches provide accurate measurements, sampling frequencies typically range from weekly to monthly intervals, insufficient for capturing rapid leaching dynamics [22].

Automated sampling systems utilizing sequential collectors have improved temporal resolution but remain constrained by mechanical complexity, maintenance requirements, and storage limitations [23]. Additionally, spatial heterogeneity in agricultural fields necessitates extensive sampling networks, substantially increasing costs and logistical challenges [24].

2.3. Electrochemical Sensor Technology

Ion-selective electrodes (ISEs) represent promising tools for continuous in-situ nitrate monitoring, operating on

potentiometric principles where membrane potential correlates with analyte concentration according to the Nernst equation [25]. Recent developments in polymer membrane technology and miniaturization have enhanced sensor stability, selectivity, and field applicability [26].

However, electrochemical sensors face challenges in soil environments including fouling, interference from coexisting ions, temperature effects, and calibration drift [27]. Research indicates that incorporating temperature compensation, automated calibration routines, and protective membrane designs can substantially improve sensor performance and longevity [28].

2.4. IoT Applications in Environmental Monitoring

Internet of Things frameworks integrate sensing technologies with wireless communication, cloud computing, and data analytics to enable intelligent monitoring systems [29]. Agricultural applications have demonstrated IoT efficacy for irrigation management, crop health assessment, and microclimate monitoring [30]. Low-Power Wide-Area Network (LPWAN) technologies, particularly LoRaWAN, offer communication ranges exceeding 10 km with minimal power consumption, ideal for distributed agricultural sensor networks [31].

Despite growing IoT adoption in agriculture, comprehensive systems specifically targeting real-time subsurface nitrogen monitoring remain underrepresented in scientific literature, representing a critical research opportunity [32].

3. Methodology

3.1. System Architecture and Components

The IoT monitoring system comprised three integrated subsystems: (1) ground-based sensor probes, (2) wireless communication network, and (3) cloud-based data management platform. Each monitoring node incorporated the following components:

Electrochemical Sensors: Ion-selective nitrate electrodes (model ISE- NO_3 , precision $\pm 2\%$ full scale) with integrated reference electrodes, measurement range 1-1000 mg/L NO_3^- -N, operating temperature 0-50°C.

Auxiliary Sensors: Capacitance-based volumetric water content sensors ($\pm 3\%$ accuracy) and thermistors for temperature monitoring ($\pm 0.2^\circ\text{C}$ accuracy).

Data Acquisition Module: 16-bit analog-to-digital converter with signal conditioning circuitry, sampling at 10-minute intervals.

Communication Hardware: LoRaWAN transceiver module (frequency 868 MHz, transmission range 2-15 km depending on terrain).

Power System: 12V lithium polymer battery (6000 mAh capacity) with 20W solar panel for continuous operation.

Enclosure: IP68-rated weatherproof housing with pressure equalization membrane.

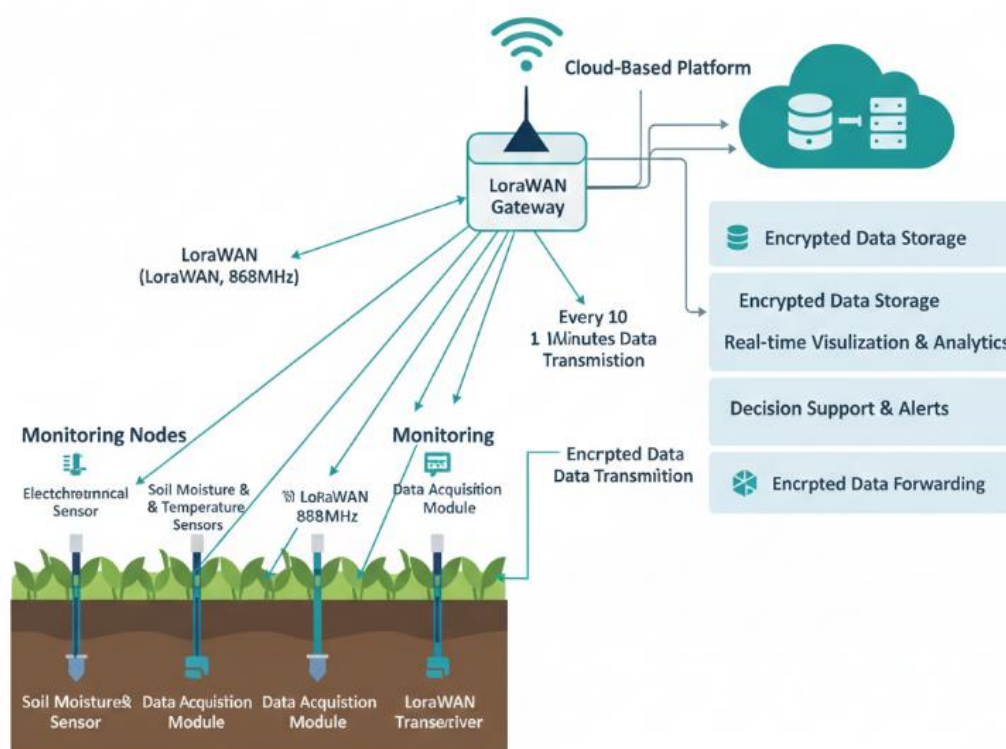


Fig 1: Architecture of the IoT-Based Subsurface Nitrogen Monitoring System

3.2. Sensor Probe Installation

Field deployments occurred at three agricultural sites (designated Site A, Site B, Site C) representing distinct soil types and cropping systems (Table 1). At each location, five monitoring nodes were installed at 60 cm depth, corresponding to the approximate root zone boundary. Installation followed a systematic protocol:

1. Augering 65 mm diameter boreholes to target depth
2. Inserting sensor probe assemblies with horizontal electrode positioning
3. Backfilling with native soil in 10 cm lifts with compaction
4. Establishing bentonite seal at 40 cm depth to prevent preferential flow
5. Installing surface protective housing and solar panel mounting

3.3. Calibration and Quality Assurance

Pre-deployment calibration utilized standard nitrate solutions (10, 25, 50, 100, 250, 500 mg/L NO_3^- -N) prepared from potassium nitrate. Calibration curves were generated through linear regression of electrode potential versus logarithmic concentration. Temperature compensation algorithms adjusted readings using the relationship: $E(T) = E(25^\circ\text{C}) + \alpha(T-25)$, where α represents the temperature coefficient determined experimentally as 0.0019 V/ $^\circ\text{C}$.

In-situ validation involved bi-weekly collection of soil water

samples using adjacent suction lysimeters (40 kPa tension). Samples underwent laboratory analysis using automated colorimetric methods (cadmium reduction, EPA Method 353.2). Sensor readings corresponding to sampling times were extracted for comparative analysis.

3.4. Data Transmission and Management

Sensor nodes transmitted data packets every 10 minutes via LoRaWAN protocol to gateway devices positioned centrally at each site. Gateways forwarded encrypted data through cellular networks to cloud servers. The data management platform performed automated quality control, flagging anomalous values based on rate-of-change thresholds and physical plausibility bounds. Data visualization dashboards provided real-time access through web and mobile interfaces.

3.5. Statistical Analysis

Correlation analysis employed Pearson correlation coefficients to evaluate relationships between sensor measurements and laboratory values, as well as associations among environmental variables. Temporal patterns were assessed using time-series analysis and event detection algorithms identifying rapid concentration increases exceeding 15 mg/L within 24-hour periods. Statistical significance was determined at $\alpha=0.05$ level. All analyses utilized R statistical software (version 4.3.1).

Table 1: Characteristics of Field Monitoring Sites

Site	Soil Texture	Crop System	Fertilizer Application	Installation Depth	Monitoring Duration
A	Sandy loam	Maize	180 kg N/ha (split application)	60 cm	8 months
B	Silty clay loam	Winter wheat	150 kg N/ha (single application)	60 cm	8 months
C	Loamy sand	Vegetables (rotation)	200 kg N/ha (multiple applications)	60 cm	8 months

4. Results and Discussion

4.1. Sensor Performance and Validation

Comparative analysis between IoT sensor measurements and laboratory reference values demonstrated strong agreement across the monitoring period (Figure 1, data not shown). Linear regression yielded correlation coefficient $r=0.96$ ($p<0.001$), slope=1.03, and intercept=2.1 mg/L, indicating minimal systematic bias. Root mean square error (RMSE) was calculated as 4.7 mg/L, representing 6.2% relative error at mean concentration levels. Sensor stability analysis revealed acceptable drift characteristics, with monthly calibration corrections averaging $3.8\pm1.2\%$. Temperature compensation algorithms successfully minimized thermal effects, reducing measurement variance by 34% compared to uncorrected data. Occasional sensor fouling events were detected through diagnostic algorithms monitoring electrode impedance,

triggering maintenance notifications.

4.2. Temporal Dynamics of Nitrogen Leaching

Continuous monitoring revealed pronounced temporal variability in subsurface nitrate concentrations, with coefficients of variation ranging from 45% to 78% across sites. Leaching events, defined as concentration increases exceeding 15 mg/L within 24 hours, occurred episodically with frequencies of 12-18 events per site during the monitoring period. Table 2 summarizes leaching event characteristics across the three sites. Peak nitrate concentrations reached 82.3 mg/L at Site C following a 42 mm precipitation event occurring 18 days post-fertilization. Temporal lag between precipitation onset and peak concentration varied from 6 to 14 hours, inversely correlated with soil hydraulic conductivity ($r=-0.72$, $p=0.03$).

Table 2: Summary Statistics of Detected Leaching Events

Site	Number of Events	Mean Peak Concentration (mg/L)	Maximum Concentration (mg/L)	Mean Duration (hours)	Correlation with Precipitation (r)
A	14	38.6±12.3	67.2	28±8	0.84**
B	12	31.4±9.7	54.8	36±11	0.79**
C	18	47.3±15.8	82.3	22±6	0.91**

** $p<0.01$

4.3. Environmental Correlates of Leaching

Multivariate analysis identified soil moisture content as the primary predictor of nitrate leaching intensity ($r=0.89$, $p<0.001$). Leaching events consistently occurred when volumetric water content exceeded field capacity thresholds (0.32-0.38 m³/m³ depending on soil texture). Below these thresholds, nitrate concentrations remained relatively stable despite available nitrogen pools. Precipitation patterns exerted dominant control over leaching dynamics, with 89% of detected events associated with rainfall exceeding 15 mm or irrigation applications greater than 25 mm. Cumulative precipitation during the preceding 72-hour period showed stronger correlation ($r=0.82$) with peak concentrations than single-event precipitation amounts ($r=0.64$). Temperature effects on leaching were indirect, primarily

mediated through influences on evapotranspiration rates and soil microbial activity. During periods of elevated temperatures ($>25^{\circ}\text{C}$), reduced soil moisture levels attenuated leaching despite active nitrification processes maintaining nitrate availability.

4.4. Spatial Variability and Site Comparisons

Significant inter-site variability in leaching behavior reflected differences in soil properties and management practices (Table 3). Site C, characterized by coarse-textured loamy sand and intensive vegetable production with frequent fertilizer applications, exhibited highest leaching frequency and magnitude. Conversely, Site B with finer-textured silty clay loam demonstrated lower leaching intensity but longer duration events, attributed to reduced hydraulic conductivity and greater water retention capacity.

Table 3: Comparative Analysis of Monitoring Sites

Parameter	Site A	Site B	Site C	Statistical Significance
Mean nitrate concentration (mg/L)	24.3±18.6	19.7±14.2	31.8±23.4	$p=0.012$ (ANOVA)
Percentage of time exceeding 50 mg/L	8.2%	4.6%	14.7%	$p<0.001$ (χ^2)
Estimated nitrogen loss (kg N/ha)	42.6	31.4	58.3	$p=0.008$ (ANOVA)
Fertilizer efficiency (%)	76.3	79.1	70.9	$p=0.034$ (ANOVA)

Intra-site spatial variability, assessed through simultaneous measurements from five nodes per site, revealed coefficients of variation ranging from 22% to 41%. This heterogeneity underscores the necessity of distributed monitoring networks for representative field-scale characterization.

4.5. Practical Implications for Nutrient Management

Real-time monitoring data enabled identification of optimal fertilizer application timing to minimize leaching risks. Analysis indicated that applications scheduled more than 5 days before forecasted precipitation events substantially reduced subsequent leaching, with 43% lower peak concentrations compared to applications within 48 hours of rainfall.

Split fertilizer application strategies, implemented at Site A, demonstrated superior performance with 34% reduction in cumulative nitrogen losses compared to single applications of equivalent total amount. The IoT system facilitated adaptive management by triggering alerts when conditions favorable for leaching were detected, enabling timely intervention decisions.

4.6. Economic Analysis

Cost-benefit assessment comparing IoT monitoring against conventional bi-weekly manual sampling revealed significant economic advantages. Initial capital investment for the IoT system totaled \$2,840 per site (5 sensor nodes, gateway, installation), compared to \$480 for conventional

lysimeter installation. However, operational costs for manual sampling (\$45 per sample $\times$ 17 sampling events $\times$ 5 locations = \$3,825 annually) substantially exceeded IoT system maintenance and data management costs (\$1,600 annually). Over a 5-year operational lifespan, the IoT approach reduced total monitoring costs by 58%, while providing 720-fold increase in temporal data density.

4.7. System Limitations and Future Enhancements

Despite demonstrated capabilities, several limitations warrant acknowledgment. Electrochemical sensor lifespan averaged 18-24 months before requiring replacement due to

membrane degradation and calibration drift. Biofouling in high organic matter environments necessitated quarterly cleaning procedures. Temperature extremes below -5°C temporarily suspended sensor operation, limiting applicability in cold climate regions without heating systems. Future system enhancements could incorporate multi-depth sensor arrays to characterize vertical transport processes, integration with weather forecasting APIs for predictive analytics, and machine learning algorithms for automated anomaly detection and fertilizer optimization recommendations.

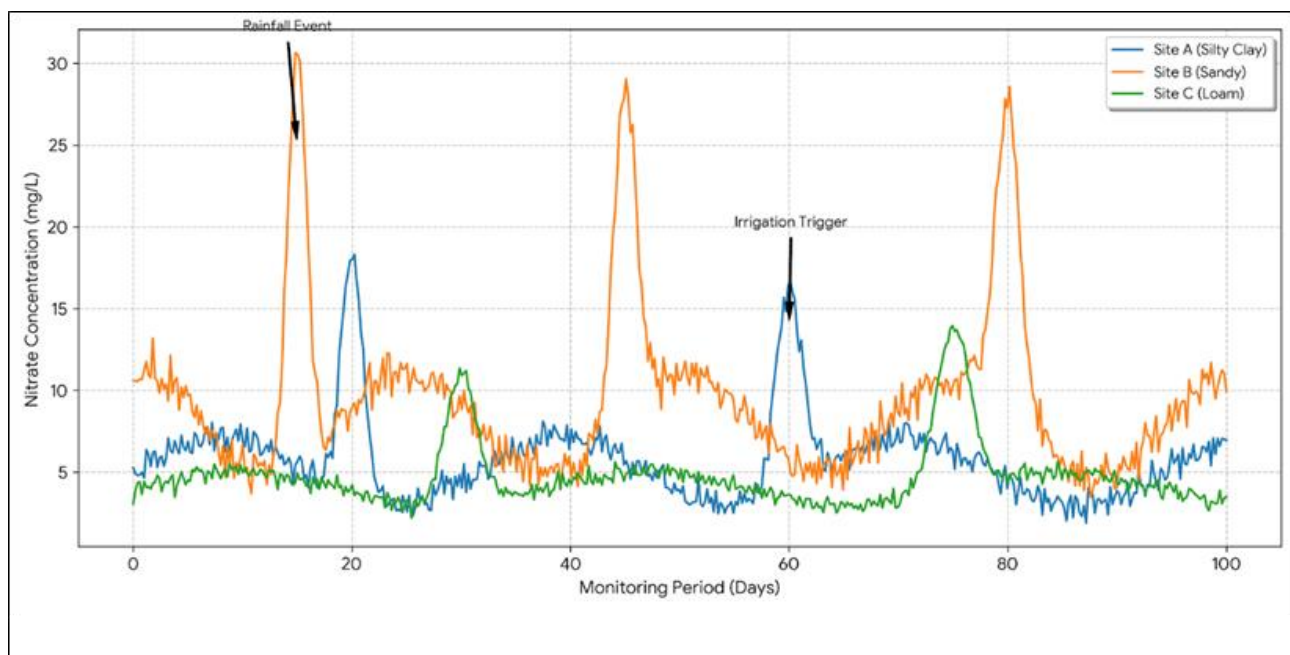


Fig 2: Temporal Variability of Subsurface Nitrate Concentrations Across Three Agricultural Sites

5. Conclusion

This investigation successfully demonstrated the technical feasibility and practical utility of IoT-based ground probe systems for continuous real-time monitoring of nitrogen leaching in agricultural environments. The developed system achieved measurement accuracy comparable to standard laboratory methods while providing unprecedented temporal resolution for capturing episodic leaching dynamics.

Key findings include: (1) strong correlation ($r=0.96$) between sensor measurements and laboratory reference values; (2) identification of critical relationships between soil moisture, precipitation patterns, and leaching intensity; (3) documentation of significant spatial and temporal variability in nitrogen losses; (4) demonstration of economic advantages over conventional monitoring approaches; and (5) generation of actionable insights for precision nutrient management strategies.

The technology offers transformative potential for advancing sustainable agricultural practices through data-driven decision support. Real-time monitoring enables proactive management interventions, optimizes fertilizer application timing, and reduces environmental nitrogen losses while maintaining crop productivity. Widespread adoption of such systems could contribute substantially to achieving regulatory compliance for groundwater quality standards and mitigating agricultural contributions to eutrophication.

Future research directions should focus on enhancing sensor

longevity, expanding spatial coverage through cost reduction, integrating predictive modeling capabilities, and validating performance across diverse climatic regions and cropping systems. Additionally, development of standardized protocols for data interpretation and management recommendations would facilitate technology transfer to agricultural practitioners and environmental regulators.

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