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ORIGINAL

Evaluating the impact of real-time NPK sensor integration on crop productivity in smart farming systems

Evaluación del impacto de la integración de sensores NPK en tiempo real sobre la productividad de los cultivos en sistemas agrícolas inteligentes

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ABSTRACT

This research examines the impact of integrating real-time NPK (Nitrogen, Phosphorus, Potassium) sensors within smart farming systems on crop productivity. A model-based approach was employed to design and implement a precision nutrient management system that combines sensor data acquisition, cloud analytics, and algorithm-driven decision-making for fertilizer application. The objective was to optimize nutrient delivery based on current soil conditions, crop type, and growth stage. Field experiments were conducted with wheat crops across two controlled plots: one managed using conventional methods and the other utilizing the proposed sensor-based system. The results emphasize that sensor-integrated precision farming significantly enhances input efficiency, minimizes environmental impact, and boosts economic returns. These findings support the broader adoption of NPK sensor technology in smart agriculture. Recommendations are made for integrating such systems into scalable agricultural models, particularly in regions experiencing high input costs or facing environmental sustainability challenges.

Keywords: Smart Farming; NPK Sensors; Crop Productivity; Precision Agriculture; Real-Time Monitoring; Nutrient Management; IOT in Agriculture.

RESUMEN

Esta investigación examina el impacto de la integración de sensores NPK (nitrógeno, fósforo, potasio) en tiempo real dentro de los sistemas de agricultura inteligente en la productividad de los cultivos. Se empleó un enfoque basado en modelos para diseñar e implementar un sistema de gestión de nutrientes de precisión que combina la adquisición de datos de sensores, el análisis en la nube y la toma de decisiones basada en algoritmos para la aplicación de fertilizantes. El objetivo era optimizar el suministro de nutrientes en función de las condiciones actuales del suelo, el tipo de cultivo y la fase de crecimiento. Se realizaron experimentos de campo con cultivos de trigo en dos parcelas controladas: una gestionada con métodos convencionales y la otra con el sistema propuesto basado en sensores. Los resultados ponen de relieve que la agricultura de precisión integrada en sensores mejora significativamente la eficiencia de los insumos, minimiza el impacto ambiental y aumenta la rentabilidad económica. Estos resultados apoyan la adopción generalizada de la tecnología de sensores NPK en la agricultura inteligente. Se formulan recomendaciones para integrar este tipo de sistemas en modelos agrícolas escalables, especialmente en regiones con elevados costes de los insumos o que afrontan retos de sostenibilidad ambiental.

Palabras clave: Agricultura Inteligente; Sensores NPK; Productividad de los Cultivos; Agricultura de Precisión; Monitoreo en Tiempo Real; Gestión de Nutrientes; Iot in Agriculture.

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INTRODUCTION

The agricultural sector is undergoing a significant transformation as global food demands increase and climate conditions become more unpredictable. With the world population projected to reach nearly 10 billion by 2050, ensuring food security has become one of the most pressing global challenges. Traditional farming methods, which often rely on generalized fertilization and irrigation schedules, are increasingly inadequate in addressing the need for higher productivity and sustainability. This has led to the rise of smart farming, an approach that integrates modern technologies like the Internet of Things (IoT),[1] big data,[2] and automation into agricultural practices.[3,4] Among the critical aspects of smart farming is nutrient management. Efficient and targeted fertilization is essential for promoting healthy crop growth, reducing environmental impact, and minimizing input costs. However, one of the main challenges farmers face is determining the precise nutrient requirements of their crops at various growth stages. Overuse of fertilizers not only increases production costs but also contributes to soil degradation and water pollution. Conversely, underuse can limit crop yield and quality. To address this, real-time monitoring of soil nutrient levels through NPK sensors has emerged as a promising solution. NPK sensors are capable of measuring the concentrations of nitrogen (N), phosphorus (P), and potassium (K) in soil with high accuracy. These three macronutrients are essential for plant growth and directly influence productivity. Integrating these sensors into a smart farming system enables continuous monitoring of nutrient levels and supports the application of fertilizers precisely when and where they are needed. This technology not only promotes efficient resource utilization but also facilitates timely interventions that can significantly improve yield outcomes.

This research focuses on evaluating the impact of real-time NPK sensor integration on crop productivity using a model-based approach. A working model was developed that combines sensor data acquisition, cloud-based analytics, and an automated fertilizer recommendation algorithm.[5] The objective is to test whether such a system can lead to better decision-making, optimized input usage, and improved crop yield compared to conventional farming methods. By conducting field experiments and analyzing data from sensor-equipped and traditional plots, this study aims to provide empirical evidence supporting the effectiveness of sensor-based nutrient management systems. Furthermore, the research explores the economic benefits of adopting such technologies, including cost savings, return on investment, and potential scalability for larger agricultural operations.[6] Overall, this study contributes to the growing body of knowledge in precision agriculture and offers a practical framework for integrating real-time nutrient monitoring into everyday farming operations. It demonstrates how data-driven approaches can bridge the gap between technological potential and field-level implementation, ultimately contributing to more sustainable and productive agricultural systems.

METHOD

A working model was developed using NPK sensors, a microcontroller (Arduino Uno), a cloud-based data platform, and an automated recommendation system. Sensors were deployed in the soil to provide real-time readings of N, P, and K levels. Data was processed by a decision algorithm to recommend site-specific fertilizer application. The system was tested on wheat crops over one full growing season. The methodology is divided into three phases: system setup, data acquisition and processing, and implementation of recommendations.

System Components

- *NPK Sensor:* Measures real-time soil nutrient content. The sensor used in this study was calibrated using soil test kits and compared against lab-tested baseline values.
- *Microcontroller (Arduino Uno):* Collects and processes sensor data. It uses analog-to-digital conversion to translate raw sensor signals into readable values.
- *Wireless Module (Wi-Fi/LoRa):* Enables wireless communication from field devices to the cloud platform. LoRa was used in rural areas to extend transmission range.
- *Cloud Platform:* Google Firebase was used for real-time data storage and retrieval. Data analytics and trend mapping were conducted using Python scripts.
- *Mobile Interface:* Developed using a simple Android-based app to display soil nutrient levels, fertilizer recommendations, and alert notifications.

Algorithm Design

Input: Real-time NPK values (N, P, K), crop type, growth stage
Output: Fertilizer recommendation (type and quantity)
Algorithm NutrientManager(N, P, K, cropType, growthStage):

```
threshold = getCropThreshold(cropType, growthStage)
requiredN = threshold.N - N
requiredP = threshold.P - P
requiredK = threshold.K - K
if requiredN < 0: requiredN = 0
if requiredP < 0: requiredP = 0
if requiredK < 0: requiredK = 0
recommendation = calculateFertilizer(requiredN, requiredP, requiredK)
return recommendation
```

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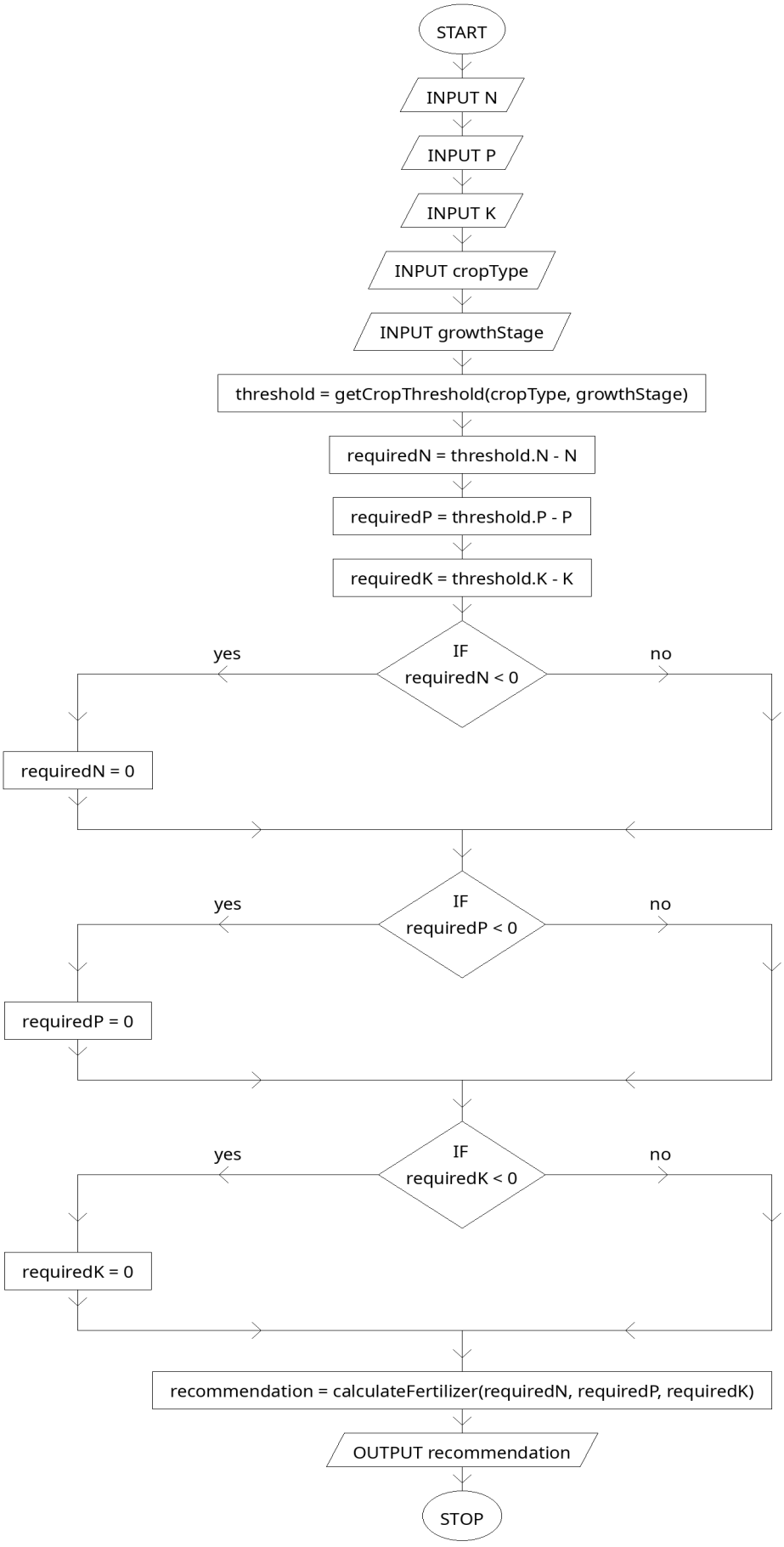


Figure 1. Flow Chart showing working Principal of Proposed Model

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Field Experiment

The study was conducted on two adjacent 1-hectare plots in Punjab, India. One plot used traditional fertilizer practices based on farmer intuition and seasonal schedules. The other plot was equipped with the NPK sensor system. Here, Figure1 above shows the flow chart.

Both plots received the same irrigation schedule and pest control measures. Soil and plant samples were collected biweekly for lab validation.[7] Data included yield per hectare, fertilizer usage, water consumption, and cost analysis. Environmental parameters such as rainfall and temperature were logged using a weather station for context.

The methodology ensured that all external variables were controlled or logged, allowing for a focused evaluation of the sensor-based system's effect on crop productivity.

DATA ANALYSIS

The data collected from the two experimental plots was analyzed to determine the effects of real-time NPK sensor integration on crop yield, input efficiency, and overall profitability. Key metrics included crop yield (kg/ha), fertilizer use (kg), water usage (litres/ha), input costs (USD), and net profit per hectare.

Table 1. Metrics

Metric	Traditional Plot	Sensor-Based Plot
Average Yield (kg/ha)	4100	4900
Fertilizer Used (kg)	220	180
Water Usage (litres/ha)	8000	7200
Input Cost ($)	180	155
Net Profit ($/ha)	620	950

Yield Analysis

The plot using the NPK sensor system recorded a 19,5 % increase in yield compared to the traditional plot. This improvement is attributed to timely and balanced nutrient application based on real-time data, which optimized plant health and growth throughout the season.

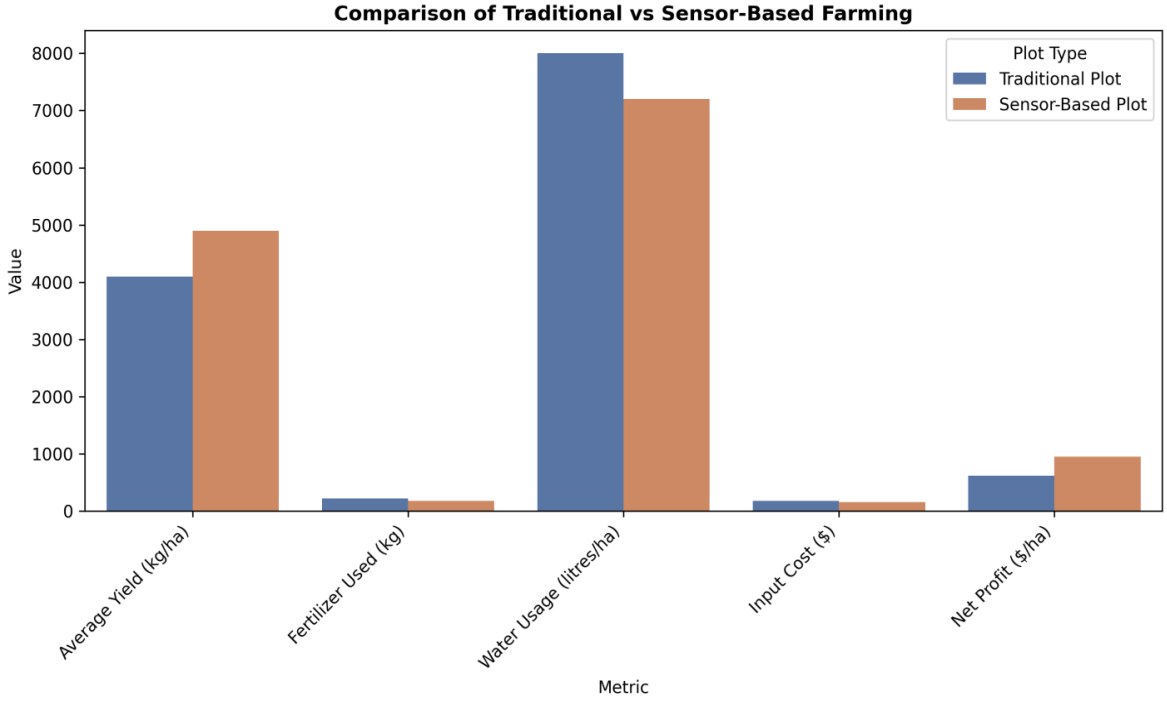


Figure 2. Data showing comparative analysis between both farming techniques

Fertilizer Efficiency

Despite producing a higher yield, the sensor-assisted plot used 18 % less fertilizer. This outcome highlights the potential of NPK sensors to reduce input waste and environmental impact while maintaining or enhancing productivity.

Water Utilization

A reduction of 800 litres per hectare in water usage was observed in the sensor-based plot. This likely results from improved nutrient uptake efficiency, which in turn minimizes the need for excessive irrigation.

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Economic Impact

Input costs were lower in the sensor-based system due to more efficient use of fertilizers. The resulting increase in net profit (from $620 to $950 per hectare) demonstrates the financial viability of adopting smart farming technologies.

Data Correlation and Trend Analysis

A correlation analysis showed strong negative correlation (-0,84) between real-time nutrient imbalances and yield, indicating that deviations from optimal nutrient levels directly reduce crop output. Temporal trend analysis across the growing season also showed that the sensor-based system maintained nutrient levels within optimal thresholds for a higher percentage of time than the traditional plot.

DISCUSSION

The results from the field experiments clearly demonstrate that integrating real-time NPK sensors into smart farming practices significantly enhances crop productivity and resource efficiency. An increase in yield of 19,5 % indicates that timely and accurate nutrient application is crucial for plant health and output. This finding aligns with previous research, which shows that site-specific nutrient management substantially boosts plant growth and productivity.[8] Moreover, the reduction in fertilizer usage by 18 % without compromising yield serves as a major indicator of improved input efficiency. This addresses a longstanding issue in agriculture: the excessive use of fertilizers, which not only raises costs but also leads to environmental degradation, such as nutrient leaching and water pollution. By reducing over-application, the system promotes more sustainable farming practices. The observed decrease in water usage further emphasizes the indirect benefits of improved nutrient management. When plants receive balanced nutrients, their physiological processes become more efficient, resulting in better water uptake and retention. This is particularly valuable in regions experiencing water scarcity, underscoring the relevance of this technology in climate-resilient agriculture.[9] Economic analysis confirms the financial viability of adopting NPK sensor technology. A 53 % increase in net profit per hectare illustrates that the benefits outweigh the costs of system installation and operation. Additionally, the long-term savings from reduced input use and improved yields present a strong case for widespread adoption, especially among medium- and large-scale farms. Correlation analysis further supports the importance of precision nutrient management.[10] The significant negative correlation between nutrient imbalances and yield highlights the necessity of maintaining nutrient levels within crop-specific optimal ranges. This validates the effectiveness of the model's decision-support algorithm and suggests potential for further refinement and adaptation for other crop types and environments. However, there are limitations to consider. The system's effectiveness may vary depending on soil types, weather patterns, and crop species. Additionally, smallholder farmers may encounter barriers to adoption due to initial setup costs or a lack of digital literacy. Future research could explore scalable models that incorporate low-cost sensors and mobile training modules.[11] Overall, the study provides strong evidence that real-time NPK monitoring can revolutionize nutrient management in agriculture. By leveraging data-driven insights, farmers can increase productivity, reduce waste, and improve their environmental footprint, supporting both economic and ecological sustainability.

CONCLUSIONS

This study concludes that integrating real-time NPK sensor systems into smart farming frameworks can significantly enhance crop productivity, reduce unnecessary input usage, and improve profitability. The experimental results confirm the value of precision nutrient management, demonstrating improvements in yield, reductions in fertilizer and water use, and stronger economic returns. The proposed model illustrates how a combination of real-time data, cloud analytics, and algorithm-driven decision-making can provide practical benefits to farmers, particularly in managing soil fertility with high precision.[3] This approach has direct implications for sustainability, promoting more environmentally responsible agricultural practices. Furthermore, the economic analysis indicates that the system is not only agronomically effective but also financially sustainable in the long term. The increased net profit per hectare makes investing in sensor-based infrastructure a worthwhile consideration for progressive farmers and agribusiness stakeholders. However, for broader adoption, accessibility challenges must be addressed.[12] This includes reducing costs, simplifying user interfaces, and providing training for farmers who may be unfamiliar with digital tools. Integrating this model into government extension programs or cooperative farming initiatives could help overcome these barriers. Future research should explore the application of the system across different crops, regions, and environmental conditions to validate its versatility. Additionally, incorporating weather forecasting and remote sensing data could further enhance the precision of fertilizer recommendations.[13,14] In summary, real-time NPK sensor technology offers a promising step toward smarter, more sustainable farming. With the right support systems in place, this approach could significantly contribute to global food security and resource conservation efforts.

FINANCING

None.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORSHIP CONTRIBUTION

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Writing - original draft: Deepa Sonal, Md. Abu Azhar Wasi, Aprajita Krishna, Sangeeta Kumari.
Writing - review, editing: Deepa Sonal, Md. Abu Azhar Wasi, Aprajita Krishna, Sangeeta Kumari.

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