Integrated IOT-Driven Decision Support System for Sustainable Soil and Crop Management in Indian Agriculture

C.Raasika,Student,B.Tech(IT) & CIT

G.Rekha,Student,B.Tech(IT) & CIT

E.Sonika,Student,B.Tech(IT) & CIT

---***---

Abstract - An integrated, research-based decision support system for sustainable crop and soil management in Indian agriculture is presented in this project. The platform provides actionable recommendations for fertilizer application, crop rotation, and yield prediction across rice, wheat, pulses, oilseeds, vegetables, and millets by fusing real-time IoT sensor data (measuring soil moisture, pH, NPK, and enzyme activities) with comprehensive historical datasets from ICAR, Soil Health Card, and satellite sources. In order to improve soil health, forecast yields, and optimize nutrient management, sophisticated machine learning models evaluate both historical and real-time data. Compatibility matrices are used by the system's crop rotation engine to recommend sequences that enhance soil C:N:P balance, reduce pests, and boost climate variability resilience.The solution, which is scalable and reasonably priced, helps smallholder and institutional users achieve greater productivity and long-term sustainability by bridging the gap between state-of-the-art agronomic research and real-world farm management.
Keywords: crop rotation, fertilizer recommendation, soil management, sustainable agriculture, yield prediction, and decision support system.

2. Introduction

The foundation of the Indian economy, agriculture provides for the livelihoods of millions of people and guarantees the country's food security. Traditional farming methods, however, frequently encounter difficulties like wasteful resource use, deteriorating soil health, erratic weather patterns, and below-average crop yields. The agricultural landscape has started to change in recent years due to the integration of digital technologies, particularly the Internet of Things (IoT), machine learning, and decision support systems. Using a network of sensors, IoT-based smart agriculture systems allow for real-time monitoring of environmental and soil parameters, giving farmers timely, data-driven insights to help them make better decisions.

The goal of this project is to create an integrated decision support system that optimizes crop rotation planning, fertilizer recommendations, and yield prediction for important Indian crops by utilizing IoT soil sensors, historical agronomic datasets, and advanced analytics. The system enables farmers and researchers to improve productivity, maintain soil health, and implement climate-smart, sustainable practices by fusing real-time field data with publicly available datasets and models supported by research. The method provides a scalable, cost-effective solution for smallholder and institutional users in India's varied agro-ecosystems by bridging the gap between state-of-the-art agronomic research and actual farm management.

3. Project Description

In order to optimize fertilizer recommendations, crop rotation planning, and yield prediction for important Indian crops like rice, wheat, pulses, oilseeds, vegetables, and millets, this project intends to create a comprehensive decision support system that makes use of real-time IoT soil sensors and sophisticated data analytics. The system gives farmers and researchers site-specific, actionable advice by combining historical data from ICAR, Soil Health Card, and satellite sources with real-time sensor data (moisture, pH, NPK, and enzyme activities). Dynamic, data-driven decisions that improve soil health, boost productivity, and promote climate-smart, sustainable agriculture are made possible by the platform's crop compatibility matrices and machine learning models. The solution bridges the gap between state-of-the-art agronomic research and real-world farm management by being modular, scalable, and accessible to institutional and smallholder users.

4. Key Concepts

Farmers and researchers can make data-driven decisions thanks to IoT-enabled smart agriculture, which uses networked sensors and devices to monitor and control crop, soil, and environmental conditions in real time. A Decision Support System (DSS), a software platform that integrates sensor data, historical datasets, and predictive models to produce practical recommendations for crop rotation, fertilizer application, and yield optimization, frequently incorporates these technologies. A key element of this strategy is soil health analytics, which evaluates soil quality using physical characteristics like moisture and texture, biological indicators like microbial diversity and enzyme activities, and chemical indicators like C:N:P ratios, pH levels, and NPK content. This ensures sustainable management practices. Planning for crop rotation is essential because it carefully arranges crops to preserve fertility, reduce pests and diseases, and increase resistance to climate change. By evaluating intricate, multi-source datasets to forecast yields, maximize input utilization, and model management situations, machine learning enhances these capabilities even more and makes it possible to implement more accurate and flexible strategies. These components work together to create climate-smart agriculture, which uses integrated, data-driven solutions to increase productivity, adjust to shifting weather patterns, and reduce greenhouse gas emissions.

5. Key Metrics

Important metrics and ideas serve as the cornerstone for developing and assessing IoT-driven decision support systems in contemporary sustainable agriculture. While soil pH indicates acidity or alkalinity, which directly affects nutrient availability and crop suitability, soil moisture, which is measured in real time as a percentage, is essential for irrigation scheduling and drought management. Soil organic carbon (SOC) in grams per kilogram is a vital indicator of fertility, structure, and carbon sequestration potential, whereas NPK levels, measured in milligrams per kilogram, inform specific fertilizer recommendations by evaluating available nitrogen, phosphorus, and potassium. (SOC), expressed in grams per kilogram, is an important measure of structure, fertility, and the capacity to sequester carbon. Biological indicators of microbial function and nutrient turnover, such as phosphatase and β-glucosidase, are complemented by the C:N:P ratio, which shows the balance of carbon, nitrogen, and phosphorus and provides insight into nutrient cycling and microbial health. While fertilizer use efficiency quantifies the percentage of applied nutrients absorbed by crops, indicating resource optimization, crop yield, measured in kilograms per hectare, continues to be the primary productivity metric and is frequently forecasted using sensor, weather, and management data. Crop sequence diversity is assessed by the rotation diversity index to improve soil health and control pests, and greenhouse gas emissions, measured in kilograms of CO_2-equivalent per hectare, measure the effects of climate change by measuring soil CH_4 and N_2O output. By evaluating productivity in relation to water input, water use efficiency—which is expressed in kilograms of yield per cubic meter of water—measures sustainability. Alert or threshold events document situations in which crop or soil parameters deviate from ideal ranges, prompting prompt interventions. When combined, these interrelated metrics allow for data-driven choices that improve agricultural resilience, sustainability, and productivity.

6. Operations of the Project

The project operates through a series of integrated processes designed to optimize soil and crop management using IoT and data analytics. It begins with sensor deployment and data collection, where IoT sensors are installed in the field to continuously monitor soil parameters such as moisture, pH, NPK content, temperature, and enzyme activities. These sensors transmit real-time data to a central microcontroller like an ESP32 or Arduino, which then uploads the information to a cloud database or local server. The next phase involves data integration and preprocessing, where live sensor inputs are combined with historical datasets from credible sources such as ICAR, the Soil Health Card Portal, and satellite imagery. The data is cleaned, normalized, and synchronized to ensure accuracy and consistency for further analysis.

Following this, the soil health and crop status analysis module evaluates chemical, biological, and physical parameters—including C:N:P ratios, microbial activity, and soil texture—to generate real-time soil health scores and detect nutrient imbalances. The fertilizer recommendation engine then applies agronomic rules and machine learning algorithms to suggest the optimal fertilizer type, dosage, and application timing based on the current soil and crop status, dynamically updating recommendations as environmental conditions change. In parallel, the crop rotation and planning module assesses crop compatibility, soil recovery needs, and historical yield data to recommend the most suitable crop rotation strategies, providing ranked options tailored to local agronomic conditions.

The yield prediction and scenario simulation process uses predictive modeling to estimate potential yields based on integrated data from soil, weather, and management practices. It enables users to perform "what-if" simulations, such as altering fertilizer strategies or rotation sequences, to visualize their potential impact on productivity. All analytical outputs are then presented through the visualization and decision support interface—an interactive dashboard incorporating GIS-based field maps, key soil health indicators, alerts, and downloadable reports. The system also offers mobile notifications and actionable recommendations for farmers and researchers. Finally, continuous system maintenance and user training are carried out to ensure stable operations, including sensor calibration, software updates, and training programs to help users effectively navigate the platform, interpret data insights, and troubleshoot issues.

7.Literature Review:

[1] In their study of the effects of deep fertilizer application on soil carbon and nitrogen dynamics in rice paddies, Xie et al. (2025) discovered that subsurface fertilization improves organic matter content and nutrient retention, which in turn improves carbon sequestration and nitrogen transformation processes. Their approach, which combined biochemical assays with ongoing field measurements, revealed notable increases in nitrogen mineralization and microbial carbon cycling activity after deep application techniques. [2] Li et al. (2025) investigated how organic fertilization affected the nitrogen and carbon cycles in vegetable soils, finding that higher levels of organic inputs caused nitrogen limitation as opposed to phosphorus limitation. . Their findings underline the importance of organic matter in promoting microbially mediated cycling processes and the need for cautious control of C:N ratios in amendments. [3] The unique waterlogged conditions in rice paddy soils limit the decomposition of organic matter and promote complex nitrogen cycling involving denitrification, mineralization, and biological nitrogen fixation, according to a global synthesis by Liu et al. (2025). The study integrated simulation modeling, field trial meta-analysis, and remote sensing data. [5] The goal of Mansoor et al. (2025) was to track changes in soil carbon and nitrogen status over time by integrating smart sensors and IoT networks. They successfully implemented real-time monitoring and adaptive management, which improved nitrogen use efficiency and stabilized carbon under precision agriculture pathways. Their empirical validations included both rice and wheat cropping systems. [9] Zheng and Wang (2024) explored soil enzymatic reactions and microbial transformations that directly affect carbon and nitrogen cycles. They used advanced metagenomic sequencing to quantify microbial species responsible for C and N turnover and assessed the effects of fertilizer treatments on enzyme activities related to decomposition and mineralization. [14] Azeem et al. (2023) developed frameworks for climate-resilient crop rotations in semi-arid regions, showing that strategic crop selection and residue management maintain soil organic carbon levels and conserve available nitrogen. Both the rice and wheat cropping systems were used in their empirical validations. [9] Zheng and Wang (2024) investigated microbial changes and soil enzymatic reactions that have a direct impact on the nitrogen and carbon cycles. They evaluated the impact of fertilizer treatments on decomposition and mineralization-related enzyme activities and quantified the microbial species that cause C and N turnover using sophisticated metagenomic sequencing. [14] Frameworks for climate-resilient crop rotations in semi-arid areas were created by Azeem et al. (2023), who demonstrated that careful crop selection and residue management preserve soil organic carbon levels and available nitrogen. Their extensive field studies demonstrated connections between stable C:N cycling, crop sequence, and the frequency of organic amendments. [15] Yang et al. [16] Crop diversification and integrated weed control improve soil organic matter, supporting beneficial microbial communities involved in the cycling of carbon and nitrogen and enabling stable nutrient reserves in the soil, according to Weisberger et al. (2019). [19] Su et al. (2024) showed that co-cultivation of legumes and biochar both improve soil C:N:P stoichiometry and boost microbial activity, with legumes increasing nitrogen fixation rates and biochar improving long-term carbon storage. [20] Microbial communities, particularly those engaged in nitrogen fixation and carbon turnover, are catalyzed by cover crops, according to Gan and Scherer (2022), with data from replicated field trials demonstrating notable increases in soil organic carbon and available nitrogen. [21] [22][23][24] In order to establish a solid empirical connection between amendment strategies and the results of carbon and nitrogen cycling in important Indian agro-ecosystems, ICAR consortia provided a wealth of fertilizer response and N-fixation data from coordinated trials with wheat, pulses, oilseeds, and vegetable crops. [25] Using precision agriculture technologies, Singh et al. (2025) specifically monitored the carbon and nitrogen cycling in rice-wheat systems, highlighting the importance of real-time data analysis and adaptive management for sustainability and nutrient conservation.

Organic Fertilization and Nutrient Limitation

[2] Li et al. (2025) examine the effects of continuous organic fertilization in vegetable soils, noting a change from phosphorus to nitrogen limitation and stressing the significance of controlling the C:N:P balance for the best nutrient supply and crop health. [14] Climate-resilient crop rotations that include organic amendments maintain soil organic carbon and nitrogen stocks, reducing nutrient losses and imbalances, as demonstrated by Azeem et al. (2023). [19] Su et al. (2024) show that growing legumes and using biochar improves soil nutrient cycling, especially by boosting nitrogen-fixing microbial populations and soil C:N:P stoichiometry.. [20] Gan and Scherer (2022) discover that through

improved residue decomposition, cover crop-mediated enhancements in soil microbial communities fortify the organic nitrogen supply and lessen constraints. [21][22][23][24] In order to demonstrate how organic amendments and rotations can modulate nutrient limitations, organic input efficiency, and soil fertility, the ICAR consortia compile field trial data from wheat, pulses, oilseeds, and vegetables. Additional studies show that organic fertilizers improve soil fertility and environmental quality, optimize nutrient cycling, and increase crop yields while lowering reliance on synthetics.

IoT and AI Applications in Agriculture

To optimize input application and track nutrient cycling dynamics, Kadam and Bansod (2025) suggest an Internet of Things-based system for real-time soil analysis and yield prediction using machine learning models. [5] Mansoor et al. (2025) improve field monitoring for soil and crop parameters related to fertility and yield by integrating a network of smart sensors and Internet of Things devices for precision agriculture. [6] In order to improve soil health assessment with real-time sensing and predictive analytics for precise fertilizer guidance, Cheema et al. (2025) create an AIoT-based nutrient recommendation platform. [8] Liang and Shah (2023) use real-time soil and weather data for dynamic input scheduling in IoT-driven smart farming systems for automated resource optimization. [12] Using multi-source data streams, Mowla et al. (2023) employ machine learning to monitor soil health predictively, spot trends, and suggest management. Numerous studies demonstrate how AI and IoT applications simplify agricultural processes, from autonomous machinery control to soil health monitoring, supporting the development of intelligent and sustainable farming systems.

Crop Rotation and Soil Fertility Decision Support

In order to maximize soil fertility and pest control, Aggarwal et al. (2022) develop an integrated decision support framework for crop rotation utilizing empirical and model-based techniques. [10] To suggest efficient crop rotations, Sujata et al. (2025) combine historical data with GIS-based land suitability assessments. [11] Theodorou et al. (2023) introduce VELOS, a digital decision support tool that uses data from remote sensing to plan rotations and make recommendations at the field level. [16] Weisberger et al. (2019) highlight the advantages of crop diversification for long-term fertility and support it as a component of an integrated nutrient and pest management strategy. [17] Singha et al. (2020) introduce algorithmic decision support for sequence planning by optimizing crop suitability and rotation through AHP-GIS analysis. [18] AgroTutor, a geolocated advisory platform that suggests crop sequencing based on region-specific datasets, is created by Bayas et al. (2020). Further research looks at digital decision support tools and redesigned rotation strategies intended to improve soil health, profitability, and resilience at scale.

Soil Microbial Processes and Enzyme Activities

[9] Zheng and Wang (2024) leverage enzymatic assays and metagenomics to detail the microbial mechanisms underpinning soil nitrogen and carbon cycling, particularly the enzymes facilitating mineralization. Molecular and field techniques are used to clarify the abundance of genes involved in soil nitrogen cycling and how these genes affect ecosystem function. Research assesses how crop management decisions affect changes in soil microbial communities and enzymatic activity, emphasizing the significance of these factors in preserving soil health. Numerous studies demonstrate that techniques such as the addition of biochar, the production of legumes, and cover crops enhance the variety and functionality of microbial populations that are vital for the cycling of nutrients in the soil and enzyme-mediated transformation.

Remote Sensing and GIS Techniques

Crop rotation is optimized using GIS-based land suitability mapping, which takes field history and soil nutrient content into account. With the help of satellite data, VELOS's remote sensing platforms allow for spatial monitoring and planning for crop sequencing and fertilizer management. In order to provide thorough, spatiotemporal analyses of soil and crop indicators and to inform management decisions, GIS applications are combined with in-field trials. Reviews highlight the role of IoT, Big Data, and satellite imagery in data-driven agriculture by summarizing their applications in environmental monitoring and farm optimization.

Irrigation and Resource Management

[8] Liang and Shah (2023) present IoT-powered automation systems that maximize efficiency and sustainability by optimizing resource allocation, including irrigation scheduling, to match crop and soil needs. [13] Using soil-moisture Internet of Things sensors, Pratama et al. (2021) create autonomous irrigation systems that show decreased over-irrigation and increased water use efficiency. In order to precisely manage water inputs, IoT-powered automated irrigation systems are said to integrate soil data and weather forecasts. By reducing waste and enhancing soil fertility and structure, optimized management—including intelligent irrigation—supports soil health and climate resilience.

Agricultural Trials and Empirical Data

[21] [22] [23] [24] The All India Coordinated Research Projects' foundational, multi-year datasets from the ICAR Wheat, Pulses, Oilseeds, and Vegetable Crops

Consortia quantify fertilizer responses, residual N, yield impacts, and amendment effects under various management scenarios. Models and management suggestions are validated by a number of field-based investigations and long-term trials; these projects compare fertilizer regimes, examine the effects of rotation, and examine decomposer activities under various agronomic practices. The shift to best management practices based on solid trial data is further supported empirically by insights from farm decision-making surveys.

8. Novelty

By combining soil biology, chemistry, and real-time Internet of Things sensing, the suggested system offers a comprehensive and intelligent framework for managing and assessing soil health. It combines real-time IoT data, such as moisture, pH, and NPK levels, with sophisticated biological indicators, such as enzyme activity and microbial diversity, to provide a thorough understanding of soil vitality, in contrast to traditional platforms that only track basic parameters like moisture or nutrients. Fundamentally, a research-driven crop rotation engine moves beyond static crop calendars by using compatibility matrices and historical ICAR datasets to produce site-specific, adaptive rotation strategies that preserve C:N:P balance, reduce pests, and improve long-term soil resilience. The system's modular design makes it appropriate for both large institutions and smallholder farmers, and it also includes climate-smart features that model greenhouse gas emissions (CH_4, N_2O) and carbon sequestration potential. Additionally, it incorporates dynamic multi-criteria decision support that uses real-time IoT and environmental data for adaptive crop and rotation planning; field-deployable microbial biosensors that provide in-field biological insights that directly link microbial activity and enzyme function to management decisions; and real-time participatory validation and learning, where farmer feedback and trial results continuously refine recommendations. These characteristics work together to create a bio-chemical, IoT, and AI convergence system that connects research and real-world agriculture and makes it possible for adaptive, sustainable, and biologically informed soil management that is not yet possible with current platforms.

9. Future Directions:

The project's suggested roadmap places a strong emphasis on technological integration and substantial expansion to accommodate various regional agricultural needs. Crop coverage will be expanded to include a broad range of horticultural and plantation crops in addition to traditional rice and staple cultivation, with recommendations being tailored to local circumstances. To improve crop and soil health monitoring with high spatial and temporal precision, advanced remote sensing technologies will be introduced, such as drone-based multispectral and thermal imaging. Natural language processing will be used in the development of autonomous farmer advisory systems, allowing for real-time voice and chat interactions that provide tailored advice with ease. The system will integrate metagenomic data analysis and high-throughput sequencing to enhance precision microbiome management by providing a better understanding of the dynamics of microbial communities and their impact on soil fertility.Strong supply chain traceability, carbon credit verification, and safe, transparent farm data management are all made possible by blockchain integration. In order to support sustainable agricultural planning in the face of climate variability, modules for adaptive climate resilience will be developed using long-term forecasts and scenario modeling. The system will be directly connected to farm equipment through interoperable APIs, enabling autonomous operations and precise input application. Through farmer networks and citizen science, crowdsourced data will help enrich datasets, increasing the robustness and accuracy of models. In order to balance environmental sustainability, yield efficiency, and profitability, economic modeling will be incorporated. In order to support smallholder farmers in areas with poor connectivity, the project will also give priority to offline, mobile-first solutions. Co-development of region-specific management protocols and validation studies will be supported by strong partnerships with government organizations and academic institutions, guaranteeing that the system stays locally relevant and scientifically sound.

10. Conclusion:

An important development in precision agriculture that is specifically suited for Indian agro-ecosystems is the creation of an integrated Internet of Things-based decision support system for sustainable soil and crop management. This project optimizes crop rotation techniques, forecasts crop yields, and provides precise fertilizer recommendations by combining real-time sensor data, extensive historical datasets, and cutting-edge machine learning. Enzyme activity and microbial diversity are examples of biological soil health indicators that are included to enhance the understanding of soil dynamics beyond traditional chemical measurements, allowing for more comprehensive management techniques. The system promotes environmental sustainability and productivity improvement by fusing climate-smart agriculture concepts with models of the carbon and nitrogen cycles. Accessibility for researchers, agricultural institutions, and smallholder farmers is guaranteed by its scalable and modular design. Using state-of-the-art research in soil science, agronomy, IoT, and data analytics, the literature supports the necessity and validity of such an approach. This system has the potential to bridge the gap between research and workable farming solutions for a sustainable agricultural future by increasing farm profitability, preserving soil health, and mitigating the effects of climate change.

Table -1:Comparative Analysis

S.no	Methods	Domain	Strengths	Limitations	Performance	Metrics	Inference from Data	Significant Gap
1	Deep Fertilizer Application Experiments	Soil Carbon and Nitrogen in Rice Paddies	Improves nutrient availability, reduces losses	Limited to rice paddies, long-term effects unclear	Enhanced soil C and N functions	Soil C and N levels, yield	Deep application increases soil carbon and nitrogen retention	Impact on different crops and regions not studied
2	Organic Fertilization Field Trials	Vegetable Soils Nutrient Limitation	Shows nutrient dynamics under organic amendments	Focus on N limitation only, short study duration	Observed N rather than P limitation	Soil N and P content, yield	Organic fertilization leads to nitrogen limitation	Long-term sustainability and other nutrients missing
3	Global Synthesis, Carbon Stock Assessment	Rice Paddy Soil Carbon Storage	Quantitative global analysis	Meta-analysis dependent on data quality	Confirms rice paddies as important C stores	Soil carbon stock levels	Rice paddies have significant soil carbon storage capacity	Regional variation effects undefined
4	IoT & Machine Learning Yield Prediction	Smart Agriculture, Crop Yield	Real-time data use, ML accuracy	Requires sensor network infrastructure	Accurate yield prediction	Prediction accuracy, sensor data volume	ML improves yield forecasting	Low-resource setting adaptation
5	Smart Sensor and IoT Integration	Precision Agriculture Systems	Comprehensive sensor coverage	High cost and complexity	Improved precision farming outcomes	Yield, input efficiency	IoT sensors optimize input use	Cost-effective solutions needed for small farms
6	AIoT Soil Nutrient Analysis	Soil Nutrient Monitoring	Integration of AI with IoT for recommendations	Complex calibration and model training	Automated nutrient recommendations	Recommendation accuracy, soil parameters	AIoT enhances nutrient management	Model generalization across soil types
7	Decision Support for Crop Rotation	Crop Rotation and Soil Fertility	Focus on sustainable rotation planning	Limited practical validation	Improved rotation strategies	Soil fertility, yield stability	Rotation supports soil fertility	Field scale trials required
8	IoT-Driven Resource Automation	Smart Farming Resource Optimization	Automation of resource inputs	Dependency on sensor accuracy	Resource use efficiency	Water, nutrients usage	Automated IoT improves resource allocation	Scalability to diverse farms
9	Enzymatic and Microbial Soil	Soil Microbial	Biochemical insights into soil processes	Lab conditions	Understanding	Enzyme activity levels	Key enzymes influence nutrient cycling	Field application

	Reactions Study	Transformations		may not reflect field	enzymatic activity			linkage missing
10	GIS Land Suitability Mapping	Crop Rotation Planning	Spatial analysis for rotation	Accuracy depends on GIS data quality	Enhanced rotation plans	Suitability index, yield projections	GIS aids rotation optimization	Integration with real-time data needed
11	Remote Sensing Decision Support Tool	Rotation Planning	High-resolution satellite data	Satellite data latency and cost	Improved rotation planning accuracy	Remote sensing indices, yield	Remote sensing supports rotation decisions	Real-time integration with ground sensors needed
12	Machine Learning Predictive Soil Monitoring	Soil Health Monitoring	Predictive analytics integration	Data quality sensitivity	Improved soil health forecasts	Prediction accuracy, soil indicators	ML enables proactive soil health management	Scalability and generalization issues
13	Autonomous Irrigation via Soil Moisture Sensors	Irrigation Management	Automated water regulation	Dependence on reliable sensor data	Water use efficiency gains	Water consumption, crop yield	Automation reduces water wastage	Adaptation to varying crop types not studied
14	Climate-Resilient Crop Rotation Framework	Semi-Arid Region Agriculture	Focus on climate change adaptation	Region-specific applicability	Increased resilience and yields	Yield stability, soil health	Rotation improves climate resilience	Broader geographic testing needed
15	Diversified Rotations to Reduce Pathogens	Soilborne Pathogen and Emissions Reduction	Dual benefits for pests and emissions	Requires long-term implementation	Reduced soil pathogens and N2O emissions	Pathogen levels, GHG emissions	Diverse rotations reduce pests and emissions	Mechanisms require further study
16	Crop Diversification for Weed Management	Weed Control in Diverse Cropping	Supports integrated weed management	Complexity of crop mixes	Reduced weed pressure	Weed density, crop yield	Diversification aids weed suppression	Optimization of crop combinations
17	AHP-GIS Multi-Criteria Analysis	Crop Suitability and Rotation	Decision support for crop selection	Subjectivity in criteria weighting	Improved crop and rotation suitability	Suitability scores, yield	Multi-criteria analysis aids decisions	Dynamic updates with sensor data needed
18	Mobile Geolocalized Advisory System	Crop Sequencing Advice	Accessible in-field farmer guidance	Dependency on mobile connectivity	Improved crop sequencing decisions	Farmer adoption, yield	Geolocalized advice supports sequencing	Integration with IoT sensors desired

19	Biochar and Legume Co-Cultivation Trials	Soil C:N:P Stoichiometry	Enhanced nutrient cycling	Field-scale implementation challenges	Improved soil nutrient balance	Soil C:N:P ratios, enzyme activity	Biochar and legumes improve stoichiometry	Long-term impacts understudied
20	Cover Crop Microbial Community Enhancement	Soil Microbial Ecology	Promotes beneficial microbes	Regional specificity of crops	Enhanced microbial diversity	Microbial biomass, soil health	Cover crops support soil microbial health	Effect on different soil types unclear
21	Fertilizer Response Trials	Wheat Fertilizer Efficiency	Large-scale coordinated trials	Limited to wheat crops	Optimized fertilizer use	Yield response, nutrient uptake	Response varies by region and genotype	Crop diversification needed
22	N-Fixation and Residual N Studies	Pulses Nutrient Cycling	Focus on nitrogen dynamics in pulses	Regional focus	Improved N fixation understanding	Residual soil N, crop yield	Pulses contribute to soil nitrogen	Integration with crop rotation systems
23	Nutrient Response Trials	Oilseeds Nutrient Efficiency	Field-scale nutrient optimization	Limited crop types	Enhanced nutrient use efficiency	Yield, nutrient uptake	Oilseeds respond well to balanced fertilization	Expansion to mixed cropping systems
24	Soil Amendment and Yield Trials	Vegetable Crops Soil Health	Focus on vegetable crop soil amendments	Localized trials	Improved yield and soil quality	Yield, soil nutrient levels	Amendments enhance vegetable crop growth	Scaling for diverse conditions
25	Precision Agriculture for Nutrient Cycling	Rice-Wheat Systems Fertility	Integrated nutrient management in staple crops	Complex system to manage	Improved carbon and nitrogen cycling	Soil C and N, yield	Precision approaches optimize nutrient cycles	Adoption barriers among smallholders

References

[1] Xie, Q.-H., Yao, X.-B., Yang, Y., Li, D.-J., Qi, J.-Y. (2025). Effects of Deep Application of Fertilizer on Soil Carbon and Nitrogen Functions in Rice Paddies. *Agronomy*, 15, 938. https://doi.org/10.3390/agronomy15040938

[2] Li, Q., Xu, M., Xu, L., Wu, X., Zhang, Y., Xin, J., Shen, Y., Gao, J. (2025). Organic Fertilization Leads to N Limitation Rather than P Limitation in Both Vegetable Soils. *Agronomy*, 15, 190. https://doi.org/10.3390/agronomy15010190

[3] Liu, Y., Ge, T., van Groenigen, K. J., Yang, Y., Wang, P., Cheng, K., Zhu, Z., Wang, J., Li, Y., Guggenberger, G., Sardans, J., Penuelas, J., Wu, J., Kuzyakov, Y. (2025). Rice paddy soils are a quantitatively important carbon store according to a global synthesis. *Nature Geoscience*. https://doi.org/10.1038/s41561-025-00938-2

[4] Kadam, A.D., Bansod, N.S. (2025). Smart Agriculture: IoT-Based Yield Prediction Through Real-Time Soil Analysis and Machine Learning Models. *Journal of Neonatal Surgery*, 14(4S).

[5] Mansoor, S., et al. (2025). Integration of Smart Sensors and IoT in Precision Agriculture. *Frontiers in Plant Science*.

[6] Cheema, S.M., et al. (2025). AIoT-Based Soil Nutrient Analysis and Recommendation System. *Science of the Total Environment*.

[7] Aggarwal, R., et al. (2022). Integrated Decision Support for Promoting Crop Rotation and Soil Fertility. *Ecological Informatics*.

[8] Liang, X., Shah, S. (2023). IoT-Driven Smart Farming: Automated Resource Optimization. *Sensors and Actuators B*.

[9] Zheng, C., Wang, H. (2024). Advancements in Enzymatic Reaction-Mediated Microbial Transformations in Soil. *Journal of Agricultural and Food Chemistry*.

[10] Sujata, R., et al. (2025). GIS-Based Land Suitability Mapping for Crop Rotation Optimization. *International Journal of Agriculture and Food Science*.

[11] Theodorou, M., et al. (2023). VELOS: Remote Sensing Decision Support Tool for Rotation Planning. *Precision Agriculture*.

[12] Mowla, M., et al. (2023). Machine Learning for Predictive Soil Health Monitoring. *Computers and Electronics in Agriculture*.

[13] Pratama, F., et al. (2021). Autonomous Irrigation Management via Soil-Moisture IoT Sensors. *Computers and Electronics in Agriculture*.

[14] Azeem, M., et al. (2023). Climate-Resilient Crop Rotation Framework for Semi-Arid Regions. *Agriculture, Ecosystems & Environment*.

[15] Yang, H., et al. (2024). Diversified Rotations Reduce Soilborne Pathogens and N_2O Emissions. *Global Change Biology*.

[16] Weisberger, D., et al. (2019). Crop Diversification Supports Integrated Weed Management. *Weed Science*.

[17] Singha, S., et al. (2020). AHP-GIS Multi-Criteria Analysis for Crop Suitability and Rotation. *Land Use Policy*.

[18] Bayas, A., et al. (2020). AgroTutor: Mobile Geolocalized Advisory for Crop Sequencing. *Agricultural Systems*.

[19] Su, Z., et al. (2024). Biochar and Legume Co-Cultivation Effects on Soil C:N:P Stoichiometry. *Soil Biology & Biochemistry*.

[20] Gan, Y., Scherer, H.W. (2022). Cover Crop-Mediated Microbial Community Enhancement. *Applied Soil Ecology*.

[21] ICAR Wheat Consortium (2024). All India Coordinated Research Project on Wheat: Fertilizer Response Trials. ICAR Technical Bulletin.

[22] ICAR Pulses Consortium (2024). All India Coordinated Research Project on Pulses: N-Fixation and Residual N Data. ICAR Technical Bulletin.

[23] ICAR Oilseeds Consortium (2024). All India Coordinated Research Project on Oilseeds: Nutrient Response Trials. ICAR Technical Bulletin.

[24] ICAR Vegetable Crops Consortium (2025). ICAR Vegetable Crops Soil Amendment and Yield Trials. ICAR Technical Bulletin.

[25] Singh, R., et al. (2025). Precision Agriculture for Carbon and Nitrogen Cycling in Rice-Wheat Systems. *Agronomy*, 15.