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No-18: Balanced Fertilization: AI/ML, Sensors, and Drones for Shaping Indian Agriculture

Introduction

Agriculture remains the backbone of the Indian economy, supporting the livelihoods of nearly half of the country's population and ensuring national food and nutritional security. Since the Green Revolution, the increased use of chemical fertilizers has played a pivotal role in enhancing crop productivity and transforming India from a food-deficit nation into one of the world's leading agricultural producers. However, the long-term and imbalanced use of fertilizers, particularly nitrogenous fertilizers such as urea, has created significant challenges related to soil health, nutrient imbalance, environmental sustainability, and input-use efficiency.

India is the world's second-largest consumer of fertilizers, with annual consumption exceeding 64 million tonnes of nutrients (NPK basis) during 2023–24. Nitrogenous fertilizers account for nearly 55–60% of total fertilizer use, reflecting a heavy dependence on urea-based nutrient management. Although this has significantly contributed to agricultural production, it has also led to nutrient imbalances and widespread deficiencies of secondary and micronutrients. Soil health assessments indicate that about 36% of Indian soils are deficient in zinc, 23% in boron, 11–12% in iron, and over 5% in manganese, while sulfur deficiency is emerging as a major concern in several agricultural regions. The declining health of Indian soils further aggravates the situation, with nearly half of the cultivated soils containing less than 0.5% soil organic carbon, adversely affecting nutrient availability, soil structure, water-holding capacity, and biological activity. Moreover, nutrient-use efficiency remains low, with crops utilizing only about 30–35% of applied nitrogen, 15–20% of phosphorus, and 40–50% of potassium, while the remaining nutrients are lost through leaching, runoff, volatilization, and fixation, causing economic losses and environmental degradation. These challenges are particularly critical in India, where agriculture is dominated by small and marginal farmers facing rising input costs, shrinking natural resources, and increasing climate variability. At the same time, the country's food demand is expected to increase substantially as the population approaches 1.6 billion by 2050. In this context, emerging digital agriculture technologies such as Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), sensors, drones, and remote sensing are opening new opportunities for precision nutrient management. These technologies enable real-time monitoring of soil and crop conditions, site-specific nutrient recommendations, and intelligent decision-making based on large datasets generated from farms, weather stations, satellites, and sensors.

The integration of these technologies represents a paradigm shift from conventional blanket fertilizer recommendations to data-driven precision nutrient management. Such an approach can significantly improve fertilizer-use efficiency, reduce production costs, enhance soil health,

increase crop productivity, and minimize environmental impacts. More importantly, it aligns with national initiatives such as Digital Agriculture Mission, Soil Health Card Programme, PM-Pranam, and the vision of sustainable and climate-smart agriculture.

As Indian agriculture enters the era of digital transformation, the convergence of agronomic practices with AI, sensors, drones, and machine learning is expected to revolutionize nutrient management practices. This technological revolution has the potential to empower farmers with real-time information, improve profitability, conserve natural resources, and ensure sustainable food production for future generations. The future of Indian farming lies not merely in applying more fertilizers, but in applying the right nutrients in the right amount, at the right time, and at the right place through intelligent and precision-based management systems.

What is Smart Nutrient Management?

Smart Nutrient Management (SNM) is emerging as a key component of future-ready agriculture, integrating advanced digital technologies such as sensors, Artificial Intelligence (AI), Machine Learning (ML), drones, satellite remote sensing, and the Internet of Things (IoT) to assess and manage crop nutrient requirements with greater precision. Unlike conventional fertilizer management practices, where nutrient applications are often based on farmers' experience or generalized recommendations, smart nutrient management utilizes real-time information on soil conditions, crop growth status, weather parameters, and yield targets to guide nutrient application decisions.

The primary objective of smart nutrient management is to ensure that crops receive the required nutrients at the right time and in the right quantity while minimizing nutrient losses and environmental impacts. By combining field-level observations with digital decision-support systems, SNM enables site-specific and need-based fertilizer recommendations that enhance nutrient-use efficiency, reduce input costs, and improve crop productivity. The approach is fundamentally based on the principles of 4R Nutrient Stewardship—applying the right nutrient source at the right rate, at the right time, and in the right place. In the context of Indian agriculture, where nutrient imbalances, declining soil fertility, and increasing fertilizer subsidies are major concerns, smart nutrient management offers a sustainable pathway toward improving farm profitability, resource-use efficiency, and environmental sustainability.

Sensors for Transform Fertilizer Management

Sensor technology is expected to revolutionize fertilizer management in Indian agriculture by enabling continuous, real-time monitoring of soil and crop conditions. Traditionally, fertilizer application decisions are often made without detailed knowledge of the spatial and temporal variability of soil properties within a field. As a result, fertilizers are frequently over- or under-applied, leading to reduced nutrient-use efficiency and increased production costs.

Modern soil and crop sensors provide accurate and continuous measurements of critical parameters such as soil moisture, soil pH, electrical conductivity (EC), soil organic carbon, nutrient availability (nitrogen, phosphorus, and potassium), temperature, and crop stress indicators. These sensors can be installed in fields or integrated into portable devices, generating real-time data that can be transmitted directly to cloud-based platforms or mobile applications through IoT-enabled communication systems.

The information generated by these sensors enables farmers to identify nutrient deficiencies at specific locations within a field and apply fertilizers only where and when they are needed. For instance, if sensor data indicate adequate nitrogen availability in a particular field zone, unnecessary urea application can be avoided. Such precision-based nutrient management helps reduce fertilizer wastage, lower input costs, and improve nutrient-use efficiency. Furthermore, by minimizing excess fertilizer application, sensor-based systems can significantly reduce nutrient leaching, greenhouse gas emissions, and contamination of water resources.

For Indian farming systems, particularly under smallholder and resource-constrained conditions, the development of affordable indigenous sensor technologies integrated with mobile-based advisory services can significantly support informed decision-making and accelerate the transition from blanket fertilizer recommendations to precision nutrient management. Indigenous sensors, designed and manufactured to suit local agro-climatic conditions and farming needs, can substantially reduce technology costs and improve accessibility for farmers.

Role of Sensors in Nutrient Management

In addition to soil sensors, crop-based sensors are expected to play a crucial role in future nutrient management systems. Technologies such as SPAD meters, GreenSeeker sensors, canopy reflectance sensors, and hyperspectral imaging sensors assess the nutritional status of crops by analyzing leaf characteristics and canopy reflectance. These tools can detect nutrient deficiencies, particularly nitrogen and micronutrient deficiencies, at an early stage before visible symptoms appear. For example, in wheat cultivation, a GreenSeeker sensor can identify developing nitrogen deficiency and provide real-time recommendations for corrective fertilizer application. Such timely interventions help minimize nutrient stress, improve nutrient-use efficiency, and enhance crop productivity.

Monitoring Fields through Drones and Satellites

Drone and satellite technologies are opening new frontiers in precision agriculture and nutrient management. Equipped with multispectral and hyperspectral cameras, drones can capture high-resolution images of agricultural fields and assess crop nutritional status, moisture conditions, pest infestations, and disease incidence. These technologies enable the development of nutrient maps that identify spatial variability in nutrient availability across fields. Similarly, satellite-

based remote sensing platforms provide continuous monitoring of crop health over large geographical areas.

Artificial Intelligence (AI) can analyze imagery obtained from drones and satellites to identify nutrient-deficient zones and generate site-specific fertilizer recommendations. Instead of applying uniform fertilizer doses across entire fields, farmers can adopt need-based nutrient management strategies tailored to specific field conditions. Such approaches can significantly improve fertilizer-use efficiency, reduce input costs, and enhance environmental sustainability in Indian agriculture.



Artificial Intelligence and Machine Learning: The Digital Agricultural Advisor

Artificial Intelligence (AI) and Machine Learning (ML) are rapidly emerging as powerful digital advisors for agriculture. These technologies can analyze large volumes of data generated from soil testing, sensors, drone imagery, weather forecasts, crop growth records, and fertilizer application histories to provide precise nutrient management recommendations.

AI-driven decision-support systems can determine the nutrient requirements of crops at different growth stages and recommend optimal fertilizer doses and application timings. Machine learning models continuously improve their predictive capabilities by learning from new datasets. For instance, if a particular region consistently exhibits zinc deficiency over several years, ML algorithms can predict the likelihood of future deficiencies and recommend preventive measures before crop productivity is affected. Such predictive nutrient management systems can help

farmers make proactive decisions, improve fertilizer-use efficiency, and minimize production risks.

Mobile Phones as Agricultural Experts

In the era of digital agriculture, mobile phones are becoming powerful tools for delivering real-time agricultural advisory services. AI-powered mobile applications and chatbots can provide field-specific recommendations in local languages, enabling farmers to access scientific information directly from their farms.

Farmers can receive updates on soil health, weather forecasts, crop growth stages, irrigation requirements, and nutrient management recommendations through mobile platforms. Advanced image-based diagnostic systems allow farmers to upload photographs of crops and receive instant recommendations regarding nutrient deficiencies, fertilizer requirements, and corrective measures. Such digital advisory systems reduce dependence on physical extension services and facilitate the rapid dissemination of scientific knowledge among farming communities across India.

Nano Fertilizers: A Promising Future Technology

Nanotechnology is introducing a new paradigm in nutrient management through the development of nano fertilizers such as Nano Urea and Nano DAP. These products contain nutrients in nanoscale particles, enabling enhanced absorption and utilization by plants compared to conventional fertilizers.

Nano fertilizers release nutrients in a controlled manner, thereby reducing nutrient losses through volatilization, leaching, and runoff. Their higher nutrient-use efficiency allows lower application rates while maintaining crop productivity. In addition, reduced transportation, storage, and handling requirements contribute to lower logistical costs. As research and development continue to advance, nano fertilizers are expected to become an important component of balanced nutrient management strategies in Indian agriculture.

Variable Rate Technology (VRT)

Variable Rate Technology (VRT) represents one of the most advanced applications of precision agriculture. Using GPS-guided equipment, sensors, and digital nutrient maps, VRT enables fertilizer application at variable rates across different zones within a field.

Since soil fertility and nutrient availability vary spatially, uniform fertilizer application often results in inefficiencies. VRT ensures that fertilizers are applied according to the specific nutrient requirements of each field zone. This targeted approach improves nutrient-use efficiency, reduces fertilizer consumption, increases productivity, and minimizes environmental impacts.

Although VRT adoption is currently limited in India, advances in indigenous technologies, custom hiring services, and digital agriculture initiatives are expected to facilitate wider adoption in the future.

Benefits of Smart Nutrient Management

The adoption of smart nutrient management offers numerous direct and indirect benefits to farmers. Need-based fertilizer application reduces input costs while improving crop yields and quality. Enhanced nutrient-use efficiency results in higher profitability and better resource utilization.

Balanced nutrient management also reduces nutrient losses, thereby minimizing groundwater contamination, surface water pollution, and greenhouse gas emissions. Furthermore, improved soil biological activity, maintenance of nutrient balance, and enhancement of soil organic matter contribute to long-term soil fertility and sustainability. Consequently, smart nutrient management provides economic, agronomic, environmental, and social benefits, making it a key component of sustainable agricultural development.

Smart Farm of the Future

The future smart farm will be a data-driven and digitally connected production system. Soil sensors installed across fields will continuously monitor soil moisture and nutrient status, while drones and satellites will assess crop health and detect nutrient deficiencies. Automated weather stations will provide real-time climatic information, and AI-based platforms will integrate and analyze these datasets to support farm-level decision-making.

Mobile applications will deliver customized recommendations directly to farmers, while GPS-enabled machinery and precision applicators will ensure accurate application of fertilizers and irrigation water. Such integrated digital ecosystems will maximize resource-use efficiency, reduce production costs, enhance productivity, and strengthen climate resilience. The convergence of these technologies will redefine nutrient management and transform Indian agriculture into a more sustainable, profitable, and knowledge-driven sector.

Conclusion

Indian agriculture is rapidly transitioning toward a data-driven, precise, and intelligent farming paradigm in which nutrient management decisions are increasingly based on scientific data rather than intuition alone. Advanced technologies such as sensors, drones, Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), remote sensing, and nano fertilizers are enabling farmers to adopt site-specific nutrient management practices tailored to field conditions.

These technologies facilitate accurate assessment of soil fertility, crop nutrient demand, and weather variability, thereby improving fertilizer-use efficiency and promoting balanced nutrient application. In the future, agricultural success will depend not on the quantity of fertilizers applied, but on the effective implementation of the 4R Nutrient Stewardship principles—applying the right nutrient source, at the right rate, at the right time, and in the right place.

By embracing smart and balanced nutrient management, farmers can enhance crop productivity and quality, reduce production costs, improve soil health, conserve water resources, and minimize environmental impacts. The integration of digital technologies with nutrient management practices will play a pivotal role in developing sustainable, profitable, and climate-smart agricultural systems in India. The farmers of the future will be those who effectively leverage digital innovations and scientific nutrient management to optimize productivity and ensure long-term sustainability.

The guiding principle of future agriculture is: “Data-driven decisions, balanced nutrition, and sustainable production.”

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