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Harnessing Artificial Intelligence for Soil Nutrient Assessment and Fertility Management

Authors

Akanksha Sikarwar[1],
Samiksha Gangadhar Ahire[2],
Amrutrao Hindurao Patil[3],
Rishabh Singh Chandel[4],
Mamta Sahu[5]

[1]Senior Research Fellow, Department of Soil Science, ICAR-IISS, Bhopal (Madhya Pradesh).
[2]Ph.D Scholar, Department of Soil Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra (413722).
[3]Assitant Professor, Department of Soil Science, BV's LMK College of Agriculture, Kadegaon.
[4]Senior Research Fellow, Division of Agronomy, ICAR-IARI, New Delhi 110012.
[5]Assistant Professor, Department of Life Science, Dr. C. V. Raman University Kargi Road Kota Bilaspur (C.G), Kota, Bilaspur (C.G) Pincode- 495113.

INTRODUCTION

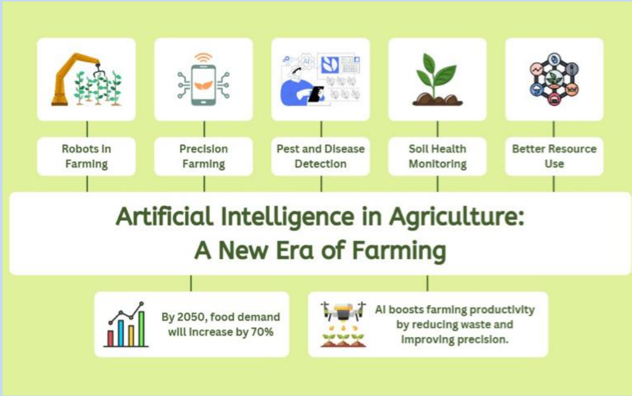
Soil fertility is an important factor for agricultural productivity and ecosystem functioning. It is governed by the soil chemical, physical, and biological characteristics as well as inputs of nutrients, including nitrogen (N), phosphorus (P), potassium (K), and micronutrients. These factors all control plant growth, crop yield and soil health over time, and thus soil fertility is a key component of sustainable agriculture. Conventional soil fertility evaluation is based on laboratory chemical analysis, which is time-consuming, laborious, and not applicable for real-time decision-making. Due to mounting strain on agricultural systems from population growth, climate change, and soil degradation, soil nutrient management systems that can provide rapid, accurate, and scalable support for timely and precise agricultural interventions are critically needed.

Emergence of Artificial Intelligence (AI) in Agriculture

Artificial intelligence (AI) is revolutionizing the modern farming and agricultural practices by making informed decisions on the data. AI is a technology that combines ML, DL, remote sensing, IoT, and big data analytics for better evaluation of soil health and management of nutrients.

AI-based soil fertility management offers:

- Rapid nutrient diagnosis
- Accurate fertilizer recommendations
- Nutrient management specific to the site
- Decreased environmental pollution
- Enhanced crop production and resource use efficiency



Role of ai in soil nutrient assessment

Soil analysis with AI is based on the application of powerful computing algorithms to large data sets of soil spectroscopy (visible, NIR, MIR), satellite and drone images, IoT-enabled soil probes, historical records of soil tests, and data on climate and crops. The incorporation of such a range of information allows AI to account for the spatial and temporal variability of soil characteristics better than traditional ones. Subsequently, several machine learning algorithms including the Random Forest, the Support Vector Machines, the Artificial Neural Networks and the Deep Learning models are utilized to detect hidden patterns and relations among the data, which are also capable of predicting the soil nutrient status with high accuracy for both macro- as well as micrnutrients. It is fast, accurate, and can be scaled to assess soil fertility to enable high-throughput and data-intensive nutrient management in precision agriculture.

Key Functions of AI in Soil Assessment

- Forecasting macronutrients (N, P, K)
- Prediction of micronutrients deficiency (Zn, Fe, Mn, Cu)

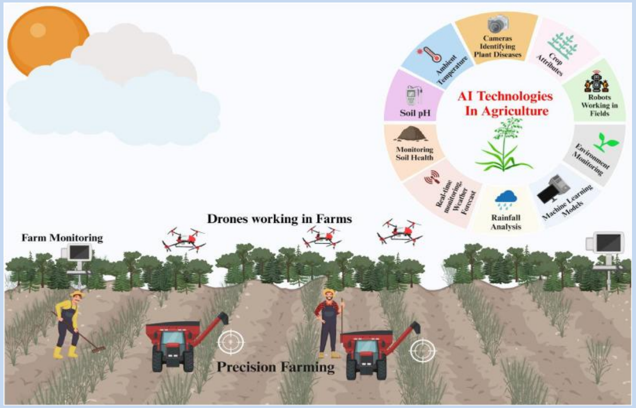
- Soil organic carbon mapping
- Prediction of soil pH and salinity
- Mapping of spatial nutrient variability

Advantages

- Fast and non-destructive analysis
- Mapping with spatial resolution
- More economical than conventional laboratory tests
- Real time monitoring availability

Ai techniques and technologies

ML methods consist in training models on soil data sets to recognize patterns and progressively enhance prediction. These models learn the relation between soil properties and nutrient contents, based on which they can provide a more accurate estimation of the fertility. Popular ML methods used in soil analysis were Random Forest Regression (RFR), Gradient Boosting Machines (GBM), Support Vector Regression (SVR) and K-Nearest Neighbours (KNN), all of which have been successfully used for estimation of soil nutrient status and aiding precision agriculture in data-driven decisions.

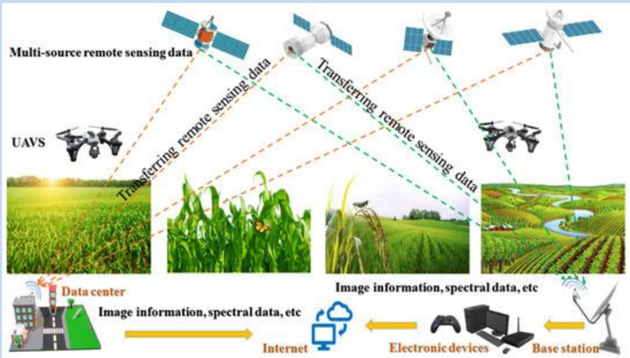


Deep Learning (DL) Applications

Deep learning employs sophisticated neural network architectures to capture intricate patterns in soil data and enhance prediction performance. It is commonly used in soil science: CNNs are employed for soil image classification, RNNs for time-series soil and environmental data, and hybrid deep learning models are used for multi-source data integration for precise nutrient forecasting and soil fertility prediction.

Remote Sensing and GIS

Satellite imagery from the Sentinel and Landsat platforms in conjunction with artificial intelligence methods is of utmost importance for the monitoring of soils and crops nowadays. AI algorithms process satellite data to map spatial variability of soil nutrients, detect degraded or nutrient-poor soils, and track the link between health of vegetation and the nutrient status of soil beneath. Such a combination allows for the large-scale, time-sensitive, and cost-efficient evaluation of soil fertility dynamics, thereby facilitating precision agriculture and sustainable land use management.

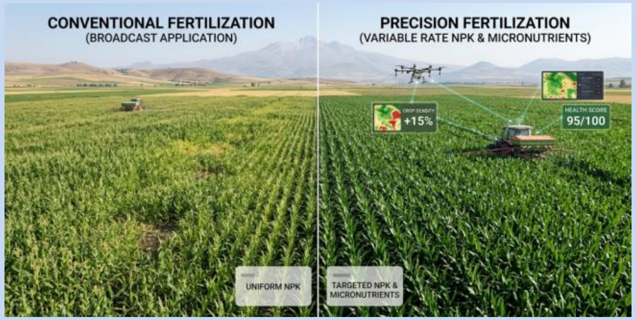


IoT-Based Smart Sensors

- Real-time soil moisture and nutrient sensing
- Automated data transmission to AI platforms
- Precision irrigation and fertilization integration

Ai in fertility management

Precision nutrient management employs AI to offer site-specific fertilizer recommendations considering soil heterogeneity, crop needs, and weather. AI-based Decision Support Systems (DSS) facilitate the optimization of the fertilizer dose, the nutrient timing for a specific crop, the prediction of yield and the diagnosis of nutrient deficiency. Owing to Variable Rate Technology (VRT), which combines AI and intelligent machinery to complete fertilizer application at variable rates in fields, nutrient losses are minimized and nutrient-use efficiency is enhanced, leading to more sustainable agriculture.



Benefits

- Improved crop yield (between 10-30%)
- Reduced fertilizer cost (15-25%)
- Reduced greenhouse gas emissions
- Enhanced soil health and sustainability

Challenges and limitations

Various data, technology, model and end-user adoption related challenges exist in applying AI to soil fertility management. Data constraints to be encountered include absence of high-quality labeled soil datasets, non-uniform soil sampling and limited regional soil repositories. Technological obstacles include the significant expense of AI hardware and sensors, scarce availability in developing areas and the specialized technical knowledge required. Model-related constraints are overfitting in small datasets, poor generalization to the other agro-ecological zones and strong reliance on the quality of training data. Also, agri-business unawareness and low digital literacy among farmers, poor linkage with traditional extension system and policy and institutional barriers limit the diffusion of AI-driven solutions for soil fertility management.

Future perspectives

- AI and blockchain integration for soil data transparency
- Creation of affordable AI-driven mobile apps
- Multi-source data fusion (soil, climate, crop, satellite)
- Explainable AI (XAI) for transparent recommendations
- Precision farming systems that are autonomous

CONCLUSION

AI is a game changer for assessing soil nutrients and fertility management, delivering accurate, fast, and evidence-based decisions that contribute to the enhancement of sustainability and productivity of the agricultural sector. Yet, the successful adoption of it requires a robust data infrastructure, transdisciplinary research, and innovation systems focusing on farmers. Therefore, it is safe to say that soil management based on AI may transform traditional agriculture into an extremely efficient, sustainable, and climate-resilient system.