Mapping the Invisible: Geospatial Technologies for Nutrient and Water Use Optimization in Agriculture

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ABSTRACT

Soil fertility is the backbone of agricultural productivity, yet its spatial variability across farms and landscapes is rarely captured by conventional methods. Geospatial technologies namely Remote Sensing (RS), Geographic Information System (GIS) and Global Positioning System (GPS) offers a powerful mean to map soil nutrient status with precision and efficiency. These tools help identify nutrient deficient and nutrient rich zones within fields enabling a farmer to apply fertilizers only where they are needed. Vegetation indices like NDVI, derived from satellite and drone imagery also help in monitoring crop health and irrigation efficiency in real time. Although challenges such as high costs and technical complexity remain, advances in artificial intelligence, drones and machine learning are making these technologies increasingly accessible for the farmers.

INTRODUCTION

Soil is the foundation of all crop production. Its ability to supply plants with essential nutrients largely determines how much a crop will yield and how efficiently fertilizers are used. Yet, most farmers across India still apply fertilizers uniformly across their entire fields not knowing that soil nutrient levels can vary

greatly from one corner of a field to another (Sharma *et al*. 2022). Geospatial technologies have emerged as a practical solution to this problem. By combining satellite images, GPS enabled soil sampling and digital mapping through GIS software, scientists can now create detailed maps of soil nutrient distribution across fields, districts and even entire river basins. These maps allow for what is called site-specific nutrient management i.e. applying the right fertilizer, at the right rate, in the right place.

What are these technologies?

Geospatial technologies are a family of modern tools that collect, process and display information tied to geographic locations. The three most important tools for soil management are: Remote Sensing (RS) involves capturing information about the Earth's surface using satellites or drones without any physical contact with the target. For instance, a healthy crop reflects more near-infrared light than a nutrient stressed one. Multispectral and hyperspectral sensors can map soil texture, moisture and nutrient levels with 85-90 percent accuracy (Zhai *et al*. 2024).

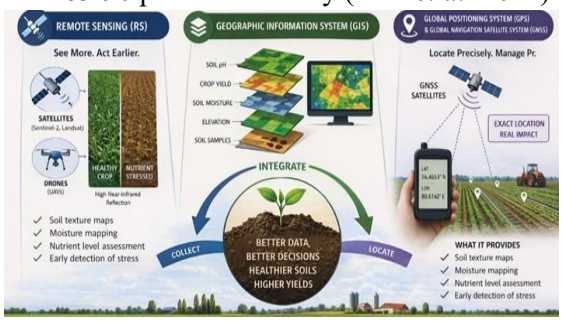

Figure: Various geo-spatial technologies for smart soil management.

Geographic Information System (GIS) is the digital map making engine. It brings together data from soil laboratories, GPS devices, satellite images in one integrated system. GIS lets scientists overlay multiple data layers such as a soil pH map with a crop yield map to identify patterns and plan actions. Studies show that GIS integration improves soil mapping accuracy by 30-40 percent compared to traditional methods (Sharma *et al*. 2022). The Global Positioning System (GPS) and its global counterpart GNSS provide the precise geographic coordinates for every soil sample collected in the field. When a soil sample is collected and its location is recorded with a GPS device the lab result can later be placed exactly on a digital map.

From soil sample to nutrient map: how does it work?

The process of creating a digital soil nutrient map follows a logical sequence. First soil scientists divide the study area into a regular grid and collect soil samples at each grid point recording the GPS coordinates. The samples are then analysed in a laboratory for nutrients. When combined with rigorous geostatistical methodologies and laboratory-based soil analysis these tools support the construction of digital soil nutrient maps that form the operational foundation for site-specific nutrient management (Moharana *et al*.2026).

Table 1: Key Geospatial Technologies and Their Role in Soil Nutrient Management

Technology	Primary Use	Key Advantage
GPS/GNSS	Georeferencing soil samples and guiding farm machinery	Centimetre-level positional accuracy
Remote Sensing (Satellite)	Regional soil/crop mapping; drought monitoring	Covers vast areas repeatedly and cost-effectively
UAV/Drone Sensing	Sub-field crop and soil monitoring	Very high-resolution imagery (<10 cm)
GIS Software	Nutrient map production; management zone delineation	Integrates multiple data layers for spatial analysis
Kriging (Geostatistics)	Interpolating soil nutrient data between sample points	Predicts values with spatial uncertainty estimates

Vegetation indices as a tool for monitoring crop health

Besides mapping soil, geospatial technology can also check crop health from above. One

popular tool is the Normalized Difference Vegetation Index (NDVI) which measures how crops reflect red and near-infrared light. Healthy crops absorb red light and reflect infrared giving a high NDVI score. Stressed or weak crops show a lower score.

In a Chinese field experiment on winter wheat, drone-based NDVI readings were linked to grain yield and water use across plots with different water and fertilizer levels (Zhai *et al*.2024). This means a farmer can simply fly a drone over a field check NDVI and spot which areas need more water or fertilizer no lab tests needed.

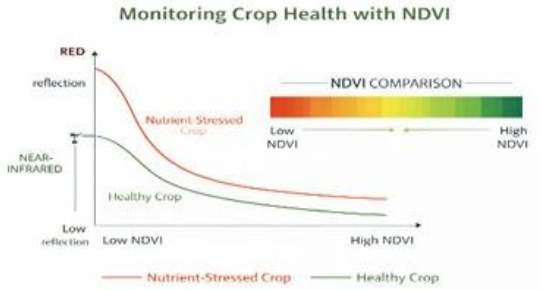

Figure: NDVI-Based Assessment of Crop Health

Challenges and limitations

- Geospatial technologies have great potential but also face real barriers in practical application.
- Equipment, satellite data and lab analysis are too costly for most small farmers.
- GIS software requires technical skills that are still rare at the ground level.
- Soil nutrients change with seasons, so a map made today may not be accurate a few months later.

Future Prospects

- AI and machine learning can now predict soil nutrient levels directly from drone images, reducing the need for costly lab work.
- Free platforms like Google Earth Engine allow anyone with internet access to process satellite data at a national scale.
- India's Soil Health Card Programme has already collected millions of soil test records.
- Linking this data with satellite imagery and GIS could create a powerful national digital soil map.
- This digital soil map could guide fertilizer policy and support farmers across the country.

CONCLUSION

Geospatial technologies have changed the way we understand and manage soil. By combining GPS, remote sensing and GIS scientists can now map soil nutrients across areas ranging from a single farm to an entire river basin and turn those maps into precise fertilizer recommendations. As drones get cheaper, AI becomes smarter and digital tools become easier to access the idea of every farmer receiving a digital nutrient map of their field is becoming a reality.

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