



Fertilizer Recommendation Using Geospatial Technology: A Review

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Abstract

Fertilizer suggestion utilizing geospatial technology provides a dramatic shift from traditional blanket application methods to precise, site-specific nutrient management techniques. Farmers and researchers can use tools like Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing (RS) to map soil fertility fluctuations, monitor crop health, and apply fertilizers precisely where and when they are needed. This method not only improves nutrient usage efficiency and waste reduction, but it also boosts crop productivity, often resulting in yield gains of 5-20% while cutting fertilizer inputs by 10- 30%. Furthermore, precise fertilization reduces environmental impacts including nutrient runoff and greenhouse gas emissions, resulting in more sustainable farming systems. Recent innovations, such as drones equipped with multispectral cameras, IoT-based soil sensors, and mobile decision support applications, are helping to bridge the gap between scientific data and on-farm operations, making precision agriculture more accessible to large-scale producers and smallholder's a like In China, the integration of NDVI imaging with GPS-guided systems increased yields by up to 20% while drastically reducing nitrogen consumption. Similar measures in Ethiopia's EthioSIS project have resulted in significant yield increases, while variable rate technology in the United States Midwest has lowered input costs and reduced nitrate leaching. In the future, merging artificial intelligence, cloud computing, block chain, and crowdsourcing soil data promises to improve these systems accuracy and scalability. Together these advances enable farmers to make informed, data-driven decisions and assist governments in developing targeted subsidies and sustainability policies. Finally, geospatial fertilizer suggestion is more than a technological upgrade it is a conceptual shift toward smarter, more resilient, and environmentally responsible agriculture.

Keyword: Geographical Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing (RS), Normalized Difference Vegetation Index (NDVI) etc.

Introduction

Fertilizer boosts agricultural productivity by replenishing soil nutrients for plant development. Farms have always administered fertilizers according to wide rules. This approach is convenient, but it often ignores crop variety, soil fertility, and environmental conditions, resulting in nutritional imbalances and low yield. Even on the same farm, nutritional content, texture, pH, and organic matter vary substantially. This geographical variability may cause some fields to get too little fertilizers and others too much. Thus, consistent fertilizer application may pollute groundwater, drain nutrients, or stunt crop development. As the world population grows, food consumption rises, putting pressure on farmers to enhance output. Indiscriminate fertilizer usage has harmed soil and the ecosystem. Precision agriculture optimizes inputs like fertilizers for field conditions, making it sustainable (Alazzai et al., 2024).

Population expansion puts pressure on farmers to produce more food. However, improper fertilizer usage has caused environmental and soil health issues. Precision agriculture offers a sustainable replacement by matching inputs like fertilizers to field conditions. Precision agriculture uses geospatial technology. Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing are used to collect, organize, evaluate, and visualize geographical data. These tools can reveal soil patterns and deviations that humans cannot. Geospatial technology enable site-specific nutrient management (SSNM), which applies fertilizers to each field area's needs (Bongiovanni & Lowenberg-Deboer, 2004).

Historically, fertilizer application has followed basic rules throughout agriculture. Usually, regional averages or guidelines from wide research inform these suggestions. Standard processes are easy to follow, but they ignore professional variation. Leaching and discharge from excessive fertilizer usage may eutrophicate water systems. In nutrient-deficient locations, underapplication may slow crop development and impair yields and profitability. Both circumstances suggest inadequate fertilizer consumption efficiency and threaten soil health. Due to population growth and food demand, sustainable agricultural output optimization is essential (Kushwaha et al., 2024).

To ensure food security, fertilizer application must be precise, targeted, and ecologically friendly. One of the most frequent agricultural geospatial applications is SSNM. This system optimizes fertilizer application for field zones, improving NUE, crop health, and the environment. The one-size-fits-all approaches of traditional agriculture contrast with SSNM. Using geospatial data and laboratory-based soil testing, farmers and agronomists may produce nutrient maps that show field variability. Variable rate technology (VRT) uses these maps to apply varied quantities of fertilizer to different zones in one pass (Gebbers & Adamchuk, 2010) (Karunathilake et al., 2023).

Recent improvements in geoinformatics, satellite imagery, and sensor-based data collection make mapping soil nutrient status over large regions simpler. This allows spatially varied fertilizer recommendations to increase productivity and sustainability. In developing nations, improper fertilizer use has degraded agricultural soils, lowering production. Geospatial technologies improve soil fertility management by assuring input efficiency. These tools help policymakers create regional fertilizer policies and extension initiatives. They also assess national initiatives like soil health cards and subsidies. Thus, this article examines geospatial technology's tools, methodology, case studies, advantages, drawbacks, and future possibilities in fertilizer suggestion (Khan et al., 2021).

The goal is to show how spatially intelligent solutions might change agriculture. Agriculture relies on fertilizers for crop development. Continuous farming and insufficient natural replenishment deplete soils of nitrogen (N), phosphorus (P), and potassium (K). Without fertilization, crop yields drop and soils can't support sustainable agriculture. This study examines geographic fertilizer recommendations. It discusses methodology, case studies, advantages, and drawbacks, and gives suggestions for future research and policy. Future convergence of AI, cloud computing, and geospatial analytics will increase. Sustainable, data-driven agriculture may improve production and protect the environment as data and technology become more accessible (Bhaduri et al., 2016).

2. Overview of Geospatial Technologies in Agriculture

Geospatial technology is a broad term encompassing tools and techniques used to collect, store, and analyze data that is associated with specific geographic locations. In agriculture, these tools allow the study of variability across fields and support data-driven decision-making. The three pillars of geospatial technology—GIS, GPS, and RS—are increasingly being used to develop fertilizer recommendation systems. (Escribà-Gelonch et al., 2024).

Geographic Information Systems (GIS) are computer-based tools used to store, manipulate, and analyze spatial data. GIS enables the creation of detailed maps that can show the variability in soil nutrients, moisture, topography, and crop performance across different regions. These maps are essential for creating precise fertilizer application plans.

Global Positioning System (GPS) technology allows for the accurate geolocation of any point on the Earth's surface. GPS is used during soil sampling and fertilizer application to ensure that data is georeferenced and interventions are targeted to the right field locations. Precision agriculture machinery often includes GPS units for automated navigation and control. (Nayal et al., 2024).

Remote Sensing (RS) includes assessing land and agricultural parameters using satellite or drone data. RS detects NDVI, which indicates plant health and nutritional status. Temporal satellite imagery can track crop growth and diagnose nutrient stress (Moomen et al., 2024). Three tools complement each other. GPS can gather soil samples from precise locations, GIS can produce nutrient maps from laboratory data, and remote sensing may measure crop vigor to verify or update these maps. The results may guide site-specific fertilizer treatments. Agriculture geospatial systems are now more capable thanks to LiDAR, UAVs, and IoT sensors (Daley et al., 2023). High-resolution multispectral drones can measure nutrients in real time.

Table: 1 List of tools used for fertilizer recommendation

S. No.	Tool	Function in Fertilizer Recommendation
1	GIS (Geographic Information System)	Creates soil fertility maps, analyzes spatial variability, and supports nutrient zoning.
2	GPS (Global Positioning System)	Locates exact positions for soil sampling and variable fertilizer application.
3	Remote Sensing (RS)	Detects nutrient stress via satellite or drone imagery using vegetation indices.
4	UAVs/Drones	Provide high-resolution images to assess crop nutrient status and guide in-field actions.
5	Variable Rate Technology (VRT)	Applies fertilizers variably across fields based on mapped or sensed nutrient needs.
6	Soil Information Systems (SIS)	Large-scale databases of soil fertility for national/regional fertilizer planning.
7	Decision Support Systems (DSS)	Integrate geospatial, weather, and crop data to generate site-specific recommendations.
8	Mobile GIS Applications	Provide farmers with GPS-based mobile access to personalized fertilizer advice.
9	Digital Elevation Models (DEMs)	Analyze topography to understand nutrient runoff and soil movement.

10	Cloud-Based GIS Platforms	Allow real-time data access, processing, and visualization for collaborative decision-making.
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Furthermore, GIS software platforms like ArcGIS, QGIS, and Google Earth Engine allow for the integration of various data layers—topography, soil type, rainfall, vegetation indices—into one comprehensive decision-making system. This holistic view is critical for understanding the spatial interactions that influence crop nutrition. Mobile applications and cloud-based platforms now offer farmers direct access to geospatial data. These tools are helping democratize precision agriculture, even among smallholders, by reducing dependency on expensive desktop GIS software and expertise (Dilaver & Dilaver, 2024).

Through these advances, geospatial technologies have moved beyond research labs into mainstream agricultural extension systems. Their ability to provide detailed, actionable insights makes them indispensable for modern, resource-efficient fertilizer management. As climate change intensifies and soil degradation accelerates, geospatial technologies will play a critical role in adapting fertilizer strategies to changing conditions. The integration of AI and machine learning into geospatial analytics further enhances their predictive capabilities, allowing proactive nutrient management. (Ebert et al., 2024).

3. Soil Fertility Mapping and Data Collection

Soil fertility mapping is a foundational component of any site-specific fertilizer recommendation system. It involves the systematic assessment of soil nutrient levels across a geographic area to identify spatial variability in fertility. Such maps enable tailored nutrient management by showing which areas require specific fertilizers and in what quantities. The first step in soil fertility mapping is soil sampling, which should be done using a systematic grid or zone approach. Grid sampling involves dividing a field into uniform squares (e.g., 1-hectare blocks), while zone sampling is based on known variability (topography, crop yield, soil type). GPS is used to record the precise location of each sample point to ensure accurate spatial referencing. Once collected, soil samples are analyzed in the laboratory to determine the concentration of essential macro- and micronutrients, such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), and boron (B). Additionally, other parameters like soil pH, electrical conductivity (EC), and organic carbon content are assessed to understand overall soil health. The analyzed data is then entered into GIS software to interpolate values between sample points and create continuous surface maps. Common interpolation techniques include Inverse Distance Weighting (IDW), Kriging, and Spline, each of which has strengths depending on data distribution and sampling density (Nenkan et al., 2024).

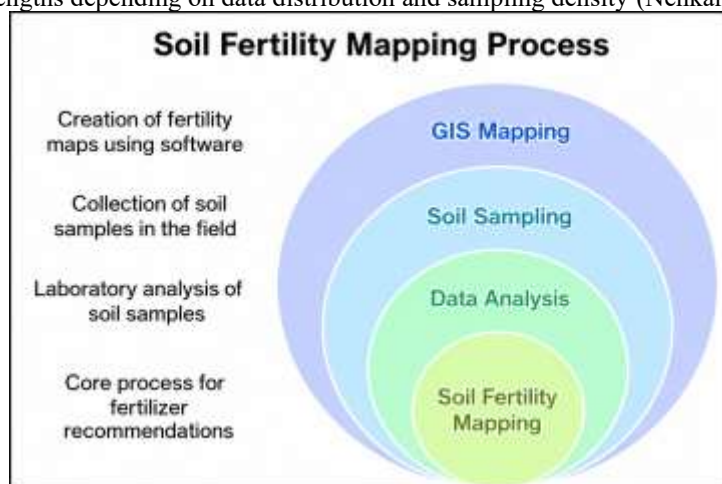


Fig.1 - Soil Fertility Mapping Process

These maps physically depict nutrient distribution, allowing farmers, agronomists, and planners to identify nutrient-deficient or surplus zones. For example, red spots on a phosphorus map may suggest a deficit, whereas green areas show acceptable levels. These maps serve as the foundation for fertilizer dosage recommendations (Nie et al., 2014). Remote sensing data is also utilized to enhance soil fertility maps. Spectral indices such as NDVI, EVI (Enhanced Vegetation Index), and SAVI (Soil Adjusted Vegetation Index) can provide information about vegetation health, which is frequently associated with soil fertility. These indices aid in identifying stress symptoms induced by nutritional insufficiency (Seelan et al., 2003).

In many places, national or state-level agencies are creating digitized soil maps based on extensive soil testing operations. Examples include India's Soil Health Card program and the USDA's Web Soil Survey in the United States. These systems collect and disseminate soil data for public use. Cloud-based mapping technologies now enable real-time updates and integration of new soil data. This means that soil fertility maps can change dynamically in response to weather, cropping cycles, and field management methods. Farmers can view these maps using mobile-enabled equipment on their smartphones. Data collection is increasingly aided by IoT-based sensors deployed in fields to measure moisture, EC, and nutrient concentrations in real time (Sarkar et al., 2025). These sensors eliminate the need for repetitive manual sampling and provide continuous monitoring to aid decision-making. Thus, by integrating systematic soil sampling, lab analysis, spatial modeling, and remote sensing, soil fertility mapping provides the spatial intelligence required to inform exact fertilizer recommendations. This lowers input costs, increases crop performance, and promotes long-term soil health.

4. Variable Rate Fertilizer Application

Precision agriculture relies on Variable Rate Fertilizer Administration (VRA or VRT) to apply fertilizers at varied rates over a field depending on zone-specific nutrient needs. In contrast to uniform application, VRT applies fertilizer to each field precisely, decreasing waste, increasing yields, and saving the environment. Map-based and sensor-based VRTs exist. GIS, soil sampling, and remote sensing develop soil fertility or yield maps for map-based systems. These maps are put into GPS-equipped agricultural equipment that applies fertilizer at predefined rates at field geolocations. Input data quality is crucial to VRT's performance. Correct GPS locations, high-resolution soil fertility maps, and equipment calibration are needed. Errors in any of these components might render the system useless by preventing fertilizer delivery. Variable rate controllers, GPS receivers, and software that converts maps into machine-readable instructions are needed for VRT. Cost reductions are a major benefit of VRT. Farmers may use less fertilizer by applying nutrients where needed and without over applying. Nutrient runoff and leaching are reduced, reducing eutrophication and water pollution.

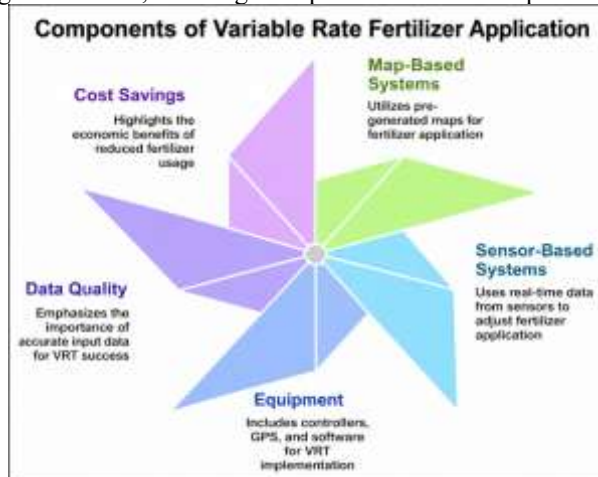


Fig.2:- Variable Rate Fertilizer Application

Yield enhancement is another major benefit. Studies have shown that VRT can increase yields by 5–20% by eliminating nutrient stress in deficient zones and preventing toxicity in over-fertilized zones. The technology enables plants to access nutrients more efficiently, promoting uniform growth and development. Environmental sustainability is also improved through VRT. It reduces the carbon footprint associated with fertilizer production and application, while also conserving natural resources. For instance, reducing nitrogen overuse helps mitigate emissions of nitrous oxide, a potent greenhouse gas (Shah et al., 2023).

Despite its benefits, adoption of VRT is still limited in many developing countries due to high initial investment costs, lack of technical expertise, and fragmented landholding systems. However, low-cost VRT kits and service-based models are emerging to address these challenges and increase accessibility for smallholders. Training and extension services play a crucial role in successful VRT implementation. Farmers need to be educated on map interpretation, equipment handling, and software usage. Partnerships between government agencies, agro-tech companies, and research institutions can help build this capacity. In summary, variable rate fertilizer application represents a paradigm shift in nutrient management. By aligning input use with spatial variability in the field, it enhances economic returns, ensures environmental stewardship, and supports the sustainable intensification of agriculture.

5. Integration of Crop Models and Decision Support Systems

Crop models are mathematical simulations of plant growth that estimate yield outcomes depending on inputs such as soil conditions, weather, crop variety, and management strategies (including fertilizer application). When combined with GIS technology, these models become useful tools for producing site-specific fertilizer recommendations based on both crop requirements and local conditions. One of the most widely used models is **DSSAT** (Decision Support System for Agro-technology Transfer), which simulates crop growth, development, and yield under various management strategies. Other models are **APSIM** (Agricultural Production Systems Simulator), **InfoCrop**, and **CropSyst**. These models account for fertilizer uptake, phenology, water balance, and pest impacts, providing a comprehensive picture of crop productivity under various fertilization regimes (Triantafyllou et al., 2019).

When fed geographical data, such as soil maps, elevation models, and meteorological variables, these models may simulate how crops might react to various fertilizer rates throughout a landscape. This spatial simulation aids in determining not only how much fertilizer to apply, but also when and where to apply it in order to maximize production while minimizing losses. A key application is the creation of response curves, which depict the relationship between yield and fertilizer rate for a specific field or zone (Vanlauwe et al., 2015). These curves are crucial for determining the economically best fertilizer dose, which ensures profitability and efficiency. Geospatially enabled crop models can generate such curves for each grid in a field, rather than a single average for the entire farm.

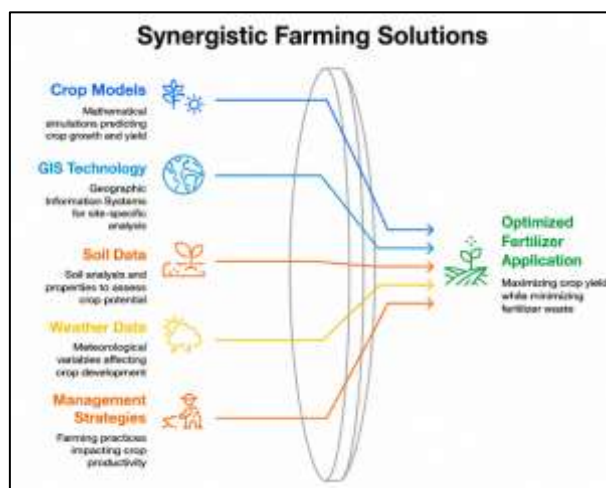


Fig: 3 - Integration of Crop Models and Decision Support Systems

Decision Support Systems (DSS) built around these models provide user-friendly platforms for farmers and planners to input data and receive recommendations. DSS tools integrate weather forecasts, market prices, soil fertility, and even satellite imagery to deliver real-time, actionable insights on fertilizer use. These systems are increasingly available on smartphones and tablets, improving accessibility. An example of this integration is the **Nutrient Expert** tool developed by the International Plant Nutrition Institute (IPNI) and CIMMYT, which combines soil and yield data with crop modeling algorithms to recommend site-specific fertilizer doses for maize, rice, and wheat. It has been successfully deployed in South and Southeast Asia. Crop models also help address **climate variability**. By incorporating seasonal forecasts or projected climate scenarios, models can suggest fertilizer plans that reduce risk in drought or flood-prone areas. This adds resilience to farming systems facing increasing climate uncertainty. Geospatial DSS also support regional and national-scale fertilizer planning. Governments can simulate fertilizer needs across states or districts and allocate subsidies accordingly. This spatial planning ensures efficient use of public resources and reduces fertilizer overuse in already nutrient-rich areas. One of the future directions is **machine learning-enhanced crop modeling**, where algorithms learn from historical and real-time data to improve the accuracy of recommendations. These systems can adapt over time, learning from new crop responses and farmer feedback to refine fertilizer prescriptions. In conclusion, integrating crop models with geospatial technologies enables both fine-scale (field-level) and broad-scale (regional) optimization of fertilizer use. These systems reduce guesswork, improve yields, enhance profitability, and support sustainable agricultural development under varying climatic and soil conditions.

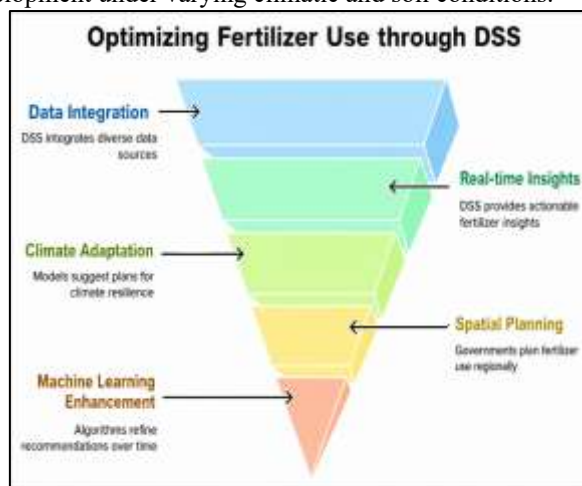


Fig 4 :- Optimizing Fertilizer Use through DSS

6. Case Studies and Applications- To understand the real-world impact of geospatial fertilizer recommendation systems, it is essential to look at case studies from different agro-ecological zones and technological settings. These case studies demonstrate how spatial tools have been applied, the challenges encountered, and the measurable outcomes in terms of yield, cost savings, and environmental protection. One of the most prominent examples is from **India's Soil Health Card (SHC) scheme**, initiated in 2015. Under this program, the government collected over 100 million soil samples across the country, analyzed them for key nutrients, and distributed individual soil health cards to farmers. The program integrated GPS-based sampling and GIS to develop village-level fertility maps, helping extension agents recommend balanced fertilizer use based on spatial variability.

In **China**, geospatial tools have been widely applied through initiatives like the **Nutrient Expert system**, developed by CIMMYT and IPNI. In trials conducted in China's rice-wheat belt, site-specific recommendations generated using GPS-tagged soil data and NDVI maps improved yields by 10–20% while reducing nitrogen use by 15–30%. These results highlighted the potential for achieving both economic and environmental gains. In the

United States, precision agriculture is widely adopted, particularly in corn and soybean production. Farmers use high-resolution satellite imagery, GPS-guided tractors, and variable rate applicators. Companies like John Deere and Climate Field View provide integrated geospatial platforms. A study in Iowa showed that adopting variable rate nitrogen application saved farmers an average of \$25 per acre and reduced nitrate runoff significantly. African countries have also begun implementing geospatial fertilizer management tools. In **Ethiopia**, the government launched a Soil Information System (EthioSIS) to create high-resolution fertility maps for every district. The maps, created with the help of GIS and remote sensing, were used to customize fertilizer blends for different agro-ecological zones, boosting yields by 20–40% for maize and teff. In **Brazil**, geospatial tools are commonly used in soybean and sugarcane production. Remote sensing, soil sensors, and GIS-based nutrient modeling are employed to create fertility zones within large farms. These zones receive differential fertilizer applications, leading to higher nutrient use efficiency and sustainability in a country known for extensive mechanized farming (Angnes et al., 2021).

One innovative example comes from **Bangladesh**, where a project by the International Fertilizer Development Center (IFDC) used GIS, mobile apps, and community engagement to train farmers in site-specific fertilizer management. As a result, urea consumption was reduced by 25%, and rice yields improved by 12–15%. The mobile apps provided location-specific advice based on real-time field data. In **Europe**, the EU's Common Agricultural Policy (CAP) has incentivized the use of precision technologies, including spatially variable fertilizer application. Programs in countries like Germany and the Netherlands show that combining soil nutrient mapping with weather data and predictive crop models leads to higher farm profitability and lower environmental impact. Several **private agri-tech companies** have also contributed significantly. For instance, India's AgNext, CropIn, and SatSure offer GIS-based farm advisory services that include soil mapping, fertilizer recommendations, and monitoring through satellite imagery. These startups bridge the gap between scientific tools and farmer-level decision-making.

While the results from these case studies are promising, they also highlight challenges like the cost of equipment, need for farmer training, and integration with local knowledge systems. However, through public-private partnerships, subsidies, and awareness programs, these hurdles are being addressed in many regions. Overall, these global applications validate the effectiveness of geospatial fertilizer recommendation systems. They demonstrate that such approaches are not only technologically feasible but also economically and environmentally advantageous when tailored to local contexts.

Country/Region	Project / Program	Technologies Used	Key Outcomes	Contribution to Food Security & Sustainability
India	Soil Health Card (SHC)	GPS-based sampling, GIS fertility maps	Village-level tailored fertilizer recommendation s; improved nutrient management	Balanced fertilizer use; enhanced productivity; large-scale soil health monitoring
China	Nutrient Expert system (CIMMYT & IPNI)	GPS-tagged soil data, NDVI maps	10–20% higher yields; 15–30% less nitrogen use	Improved efficiency; reduced environmental impact; increased food production
USA	Precision agriculture (John Deere, Climate FieldView)	Variable rate applicators, GPS-guided tractors, satellite imagery	Reduced nitrate runoff; average \$25/acre cost savings	Better nutrient use; environmental protection; economic gains for farmers
Ethiopia	Ethiopian Soil Information System (EthioSIS)	GIS, remote sensing	Fertility maps for district-level recommendation s; 20–40% higher maize & teff yields	Targeted nutrient management; improved food production; sustainable practices
Brazil	Large-scale precision farming	Remote sensing, soil sensors, GIS nutrient modeling	Creation of fertility zones; diverse fertilizer treatments	Higher nutrient use efficiency; sustainable large-scale agriculture
Bangladesh	IFDC site-specific fertilizer project	GIS, mobile applications, community participation	25% less urea use; 12–15% higher rice yields	Localized recommendations; farmer empowerment; reduced input costs

Europe (Germany, Netherlands, etc.)	EU Common Agricultural Policy (CAP) initiatives	Soil nutrient mapping, weather data, predictive crop models	Increased profitability; reduced environmental impact	Integration of precision tools; sustainable farming practices
India (Private sector)	AgNext, CropIn, SatSure	GIS-based advisory, satellite monitoring	Soil mapping, real-time fertilizer advice	Bridging science & farmer decisions; increased accessibility to precision tools

Benefits and Impact- The incorporation of GIS technology into fertilizer recommendation systems provides numerous advantages—economic, environmental, agronomic, and social. These benefits are critical to fostering sustainable agriculture and achieving food security while conserving natural resources. Geospatial fertilizer suggestion increases input efficiency by ensuring that nutrients are provided where and when they are required. This avoids excessive fertilizer consumption, which lowers farmers' production expenses. Numerous field trials and research have demonstrated that variable rate treatment can save 10-30% of inputs, depending on field variability and crop variety. Increased fertilizer efficiency frequently leads to increased yields. Crops develop more consistently and are better able to withstand pests, illnesses, and abiotic challenges when they receive the appropriate amount of nutrients based on their soil demands. Studies have shown that site-specific nutrient management can improve crop productivity by 10–25%, especially in soils with high spatial heterogeneity (Finger et al., 2019).

The **environmental benefits** are probably the most persuasive. Excessive fertilizer use causes nitrate leaching, phosphate runoff, eutrophication of water bodies, and greenhouse gas emissions such as nitrous oxide. Geospatial tools reduce these hazards by applying only the necessary amounts in the appropriate locations, so making agriculture more environmentally sustainable. Another significant advantage is soil health preservation. The repeated use of large amounts of certain fertilizers can cause nutritional imbalances, acidity, and organic matter depletion. Site-specific suggestions encourage balanced fertilization strategies that preserve or increase soil quality over time, which is critical for long-term productivity.

In **terms of policy**, spatial fertilizer maps and decision support systems assist governments in developing more tailored input subsidy programs. Resources can be directed to places that require them the most, so increasing the effectiveness of public investment. This promotes transparency and data-driven governance in agricultural development. Socially, smallholder farmers benefit from increased profitability and resource efficiency. Precision fertilizer application allows them to make informed decisions, which are frequently backed by mobile-based GIS applications in local languages. This helps to close the digital gap and democratize access to technology.

Geospatial fertilizer technologies allow for response to weather variability, which contributes to climate resilience. By merging soil fertility maps with climate data and crop models, recommendations can be updated to account for shifting rainfall patterns or extreme temperatures. This allows farmers to decrease risk and maintain stable output in uncertain conditions. There are educational and research implications. Students, researchers, and extension agents have access to real-time data and interactive platforms for studying and experimenting with fertilizer dynamics in various environments. This improves agricultural education by strengthening the feedback loop between research and practice. Importantly, geospatial fertilizer methods promote precise conservation agriculture. Farmers can improve soil fertility, absorb carbon, and prevent erosion by combining nutrient management with low tillage and residue retention, all of which contribute to environmental sustainability. In conclusion, the benefits of geospatial fertilizer recommendation systems extend well beyond just improved crop yields. They represent a shift toward knowledge-intensive, data-driven agriculture that optimizes inputs, conserves resources, enhances livelihoods, and contributes to global sustainability goals.

Limitations and Challenges- Despite the promising potential and proven advantages of using geospatial technology for fertilizer recommendation, several limitations hinder its widespread adoption, particularly in developing and resource-constrained settings. These challenges are technological, economic, infrastructural, institutional, and social in nature.

The **high initial cost** of acquiring geospatial tools and equipment—such as GPS receivers, remote sensing imagery, drones, and variable rate applicators—is a major barrier. Smallholder farmers, who make up the majority of agricultural producers in developing countries, often cannot afford such investments. Even though prices have declined over time, affordability remains a key concern. **Technical expertise and training** are also limited. Effective use of GIS software, remote sensing platforms, and decision support systems requires a certain level of digital literacy and understanding of spatial data. Most farmers and even extension workers lack the necessary skills to collect, process, and interpret geospatial information. **Limited infrastructure and connectivity** in rural areas pose another challenge. High-speed internet access, electricity supply, and reliable mobile networks are essential for real-time data acquisition and cloud-based analysis. Many rural regions in Africa, South Asia, and Latin America still lack this basic infrastructure, reducing the effectiveness of geospatial platforms.

Data quality and availability are critical to the accuracy of fertilizer recommendations. In many regions, soil databases are outdated, sparse, or inconsistent. Interpolation techniques like kriging depend on dense and high-quality sample points, but in practice, data collection is often constrained by funding and logistics. **Maintenance**

of equipment and data systems is another overlooked issue. GPS units, sensors, and drones require regular calibration and upkeep. Without proper maintenance, data accuracy deteriorates over time. Similarly, GIS databases must be updated periodically to reflect changing soil fertility and land-use patterns.

Resistance to change from traditional farming practices can limit adoption. Farmers may be skeptical of new technologies, especially if immediate benefits are not evident or if recommendations contradict generational knowledge. Overcoming this cultural barrier requires participatory approaches that involve farmers in data collection and interpretation. **Privacy and data ownership** concerns are emerging as more farms adopt digital tools. Farmers may be hesitant to share soil and yield data with private companies or government platforms without clear regulations on data use, security, and compensation. Establishing transparent data governance frameworks is crucial.

Fragmented landholdings pose a logistical challenge to spatial mapping and VRT application. In many regions, fields are small and irregularly shaped, making it difficult to implement zone-based management or use large equipment. Custom-hiring services and cooperative models may help, but operational scalability remains a concern. **Institutional coordination** is often weak. Fertilizer recommendation systems require collaboration between soil testing laboratories, agricultural universities, extension departments, and private companies. In many countries, these actors operate in silos, leading to duplication of efforts or poor data integration. Lastly, **scalability and sustainability** of pilot projects is a persistent issue. While many donor-funded initiatives have demonstrated the benefits of geospatial fertilizer recommendations, few have been scaled to the national level or sustained beyond the project lifecycle. Long-term success requires institutional ownership, financial investment, and continuous innovation.

Future of Geospatial Technology in Fertilizer Recommendations -The future of fertilizer recommendation is increasingly driven by cutting-edge digital technologies and data-rich approaches. Advanced **AI and machine learning** algorithms can ingest massive spatial and temporal datasets (satellite images, weather records, soil tests) to uncover patterns of nutrient demand. For example, machine-learning models are now able to “process vast amounts of soil data to predict nutrient deficiencies with remarkable accuracy,” learning from each season to improve recommendations. (Fritz et al., 2018).

AI-powered systems continually refine their predictions as new data arrive, enabling more precise, zone-specific fertilizer dosing across diverse agro-ecological regions. These tools can integrate historical yield maps, crop models, and near-real-time satellite indices to anticipate nutrient shortfalls before symptoms appear, helping farmers apply the right nutrients at the right time. (Galaz et al., 2021).

Unmanned Aerial Vehicles and Remote Sensing Unmanned aerial vehicles (UAVs) or **drones** are transforming field-scale nutrient management. Modern drones carry multispectral and hyperspectral cameras that capture high-resolution imagery over entire fields. Analysis of these images (for example via vegetation indices such as NDVI or custom spectral indices) can reveal early nutrient stress or variability in plant vigor that is invisible to the naked eye. In practice, farmers use drone-acquired data to **Delineate management zones** within fields – areas needing higher or lower fertilizer rates – and to monitor crop condition throughout the season. Studies have shown that aerial imaging can identify patches of nitrogen stress well before yield loss occurs. Because drones can be deployed quickly and cover many hectares per flight, they provide an affordable, high-resolution monitoring solution – even for small and medium-sized farms that may lack access to expensive satellite services. Overall, drone-based sensing greatly increases the timeliness and precision of fertilizer recommendations by providing on-demand field maps of crop health.

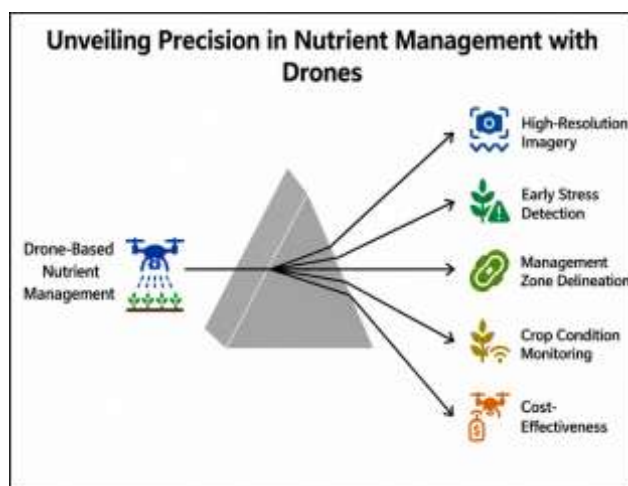


Fig 5:- Unveiling Precision in Nutrient Management with Drones

IoT and Soil Sensor Networks

The **Internet of Things (IoT)** is adding a new layer of real-time soil monitoring. Networks of low-cost sensors (measuring soil moisture, electrical conductivity, and even nitrate levels) can be deployed throughout a farm. These sensors stream live data to cloud dashboards, enabling “dynamic fertilizer scheduling and immediate interventions”. For instance, if soil moisture sensors indicate unusually dry patches, irrigation and fertilizer plans can be adjusted on the fly. Soil nutrient probes can send daily readings of available nitrogen, prompting a

recommendation to apply supplemental fertilizer before crops become deficient. By linking on-farm sensors with cloud analytics, farmers gain continuous visibility into below-ground conditions, allowing truly site-specific and time-specific fertilizer dosing.

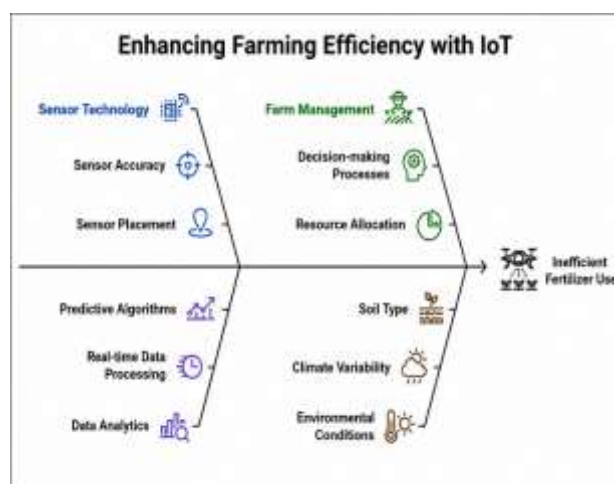


Fig 6 :-Enhancing Farming Efficiency with IoT

Mobile Advisory and Digital Platforms-As digital agriculture expands, **mobile apps and web platforms** are emerging as key tools to deliver field-specific recommendations to farmers' phones. Next-generation advisory services combine GPS location, local soil data, weather forecasts, and crop models in the cloud to generate tailored advice. These systems often support local languages and incorporate real-time market or rainfall alerts, making them accessible even to resource-poor farmers. Importantly, mobile platforms can operate offline or via SMS, ensuring usability where internet access is limited. By putting digital decision-support into the farmer's hand, these tools democratize precision agriculture – empowering smallholders to make data-driven fertilizer decisions without needing advanced GIS expertise.



Fig 7 : - Digital Agriculture Empowerment

Crowdsourced Data and Block chain Integration Community-driven data initiatives are rapidly expanding the soil information base. Farmers, extension agents, and citizen scientists can now upload soil test results, yield records, and agronomic observations via smartphone apps into open-access databases. The resulting “crowdsourced” soil maps have much higher data density than legacy surveys, improving the accuracy of fertilizer recommendation models. For example, publicly available digital soil maps (like those from Soil Grids and national projects) now support policy and advisory functions by revealing nutrient hotspots. Alongside this, emerging **block chain** solutions promise to secure and certify all stages of fertilizer use and data management. By timestamping soil and fertilizer records on an immutable ledger, block chain can guarantee data provenance and help build farmer trust. In practice, a fertilizer recommendation platform built on block chain could ensure that a farmer's soil data remain under their control, while providing transparent traceability of fertilizer sources and application records. This transparency can encourage wider participation in shared data platforms and reduce concerns about privacy or manipulation of recommendations.

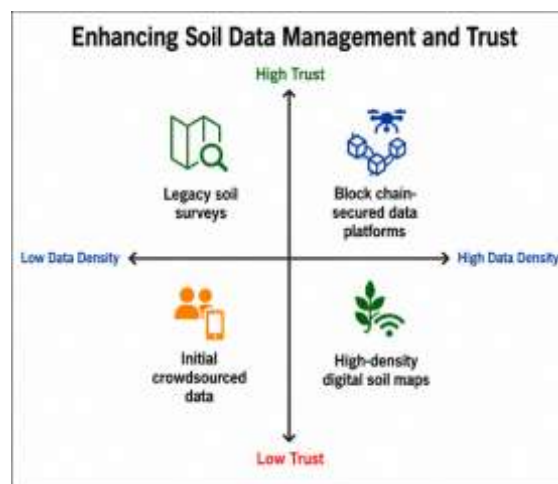


Fig 8 :- Enchaining Soil Data Management and trust

National Soil-Information Systems and Policy Support Governments and institutions are increasingly building integrated soil-information systems to support fertilizer policy. These national digital platforms link laboratory soil analyses, satellite imagery, and historical yield data to create detailed regional soil fertility maps. For instance, Ethiopia’s “EthioSIS” project combines extensive field sampling with satellite mapping to produce high-resolution soil maps covering most districts. The platform provides localized fertilizer-blending recommendations and has even spurred the construction of new mixing plants to supply custom N-P-K blends. Similar national efforts are underway in India (through the Soil Health Card program) and Brazil, where spatially-explicit soil productivity maps are being developed. These systems furnish policymakers and extension services with the scientific basis for defining agro-climatic zones, allocating input subsidies, and monitoring environmental impact on a large scale. In short, national digital soil databases translate millions of lab analyses into actionable recommendations for field-level fertilizer use.

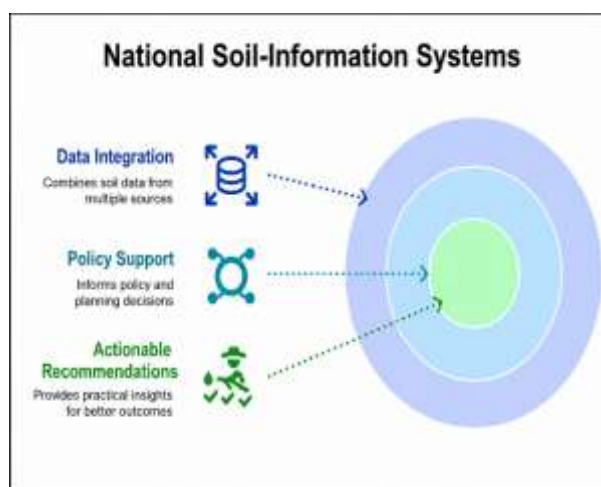


Fig 9 :- National Soil- Information System

Integrated Decision-Support Systems (DSS) - Future precision agriculture tools will layer soil, crop, weather, and even economic data into **multi-criteria decision-support systems**. Beyond maximizing yield, these DSS platforms will evaluate outcomes such as profit margins, carbon footprint, and long-term soil health for various fertilizer strategies. For example, a next-generation DSS might simulate how alternative nutrient regimes affect net revenue under future climate scenarios, or compare the trade-off between maximizing output versus minimizing nutrient runoff. By integrating economic models and environmental metrics, such systems help stakeholders choose fertilizer plans that are productive, sustainable, and profitable. Advances in cloud computing and AI mean these complex calculations can be delivered to end users in near real-time. Importantly, as one recent review notes, **digital agriculture platforms** will bring farmers “real-time data, decision support tools, and agronomic services, empowering them to make informed decisions and optimize farm operations”. This holistic approach ensures fertilizer advice considers multiple goals – from yield and income to ecosystem health.



Fig 10 :- Optimizing Fertilizer Strategies

Capacity Building, Inclusivity, and Collaboration- These technological breakthroughs demand effective extension and training. Digital literacy and local-language tools are needed to make current geospatial guidance inclusive for smallholders and disadvantaged farmers. Small and medium farmers face high upfront expenses and restricted connection, so future projects will require subsidies, training seminars, and user-friendly interfaces. Usability will also depend on participatory design—co-developing tools with farmers. International partnership between governments, research institutions, NGOs, and the corporate sector will boost innovation. Successful methods may be scaled via open-data efforts, cross-border research, and precision agricultural financing (like the World Bank's EthioSIS program). One summary states that digital agriculture platforms “foster collaboration, knowledge sharing and innovation across the agricultural value chain”. Global alliances will create scalable, flexible, and egalitarian geospatial fertilizer-recommendation systems to enable farmers globally acquire the correct nutrients at the right time for higher yields and sustainability.

Conclusion

Fertilizer suggestion utilizing geospatial technology is a game-changing method to sustainable agriculture, allowing farmers to apply nutrients in exact amounts, at the appropriate time, and in the right places. This invention arose in reaction to the constraints of standard blanket fertilizer application, which overlooks natural variability in soil fertility and often results in environmental damage, economic inefficiency, and poor crop performance. Geospatial fertilizer recommendation systems leverage techniques like as Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing (RS) to provide a data-driven method to optimizing nutrient utilization. These technologies use spatial analytics and modeling to create soil fertility maps, monitor crop health, identify management zones, and assist real-time decision-making.

The combination of these technologies with crop growth models and Decision Support Systems (DSS) provides an additional layer of intelligence. These systems model crop responses to various fertilizer regimes and environmental circumstances, allowing farmers and policymakers to make educated, spatially explicit choices. The accuracy and flexibility of such technologies are critical in the face of climate change and rising resource scarcity. Real-world case studies from India, China, the United States, and Ethiopia give compelling evidence of the advantages of geospatial fertilizer schemes. These include higher yields, less fertilizer usage, a lesser environmental effect, and more cost efficiency. However, these triumphs have brought to light difficulties such as cost, technical capability, infrastructural shortages, and data quality.

Despite these limitations, the future of GIS fertilizer management seems bright. Emerging technologies, like AI, IoT, drones, blockchain, and mobile computing, are quickly eliminating barriers and increasing accessibility. These technologies provide scalable and cost-effective solutions that may extend the advantages of precision agriculture to smallholders, cooperatives, and agribusinesses. Furthermore, national and regional initiatives to develop digital soil information systems, as well as cloud-based platforms and mobile advisory services, are making spatial nutrient intelligence more accessible. When combined with training and capacity-building initiatives, these technologies may help farmers make more informed choices, minimize reliance on foreign inputs, and enhance long-term soil health. Geospatial fertilizer management promotes climate-smart agriculture by decreasing nutrient losses, cutting greenhouse gas emissions, and preserving natural ecosystems. It provides a route for sustainable agricultural intensification while maintaining ecological integrity and addressing food security needs.

Adoption of geospatial technology allows policy makers and development agencies to better focus subsidies, monitor input usage, and assess environmental implications. Because of its potential for large-scale effect, this method is especially important for accomplishing the Sustainable Development Goals (SDGs), particularly those connected to zero hunger, climate action, and responsible consumerism. Finally, employing geospatial technology to prescribe fertilizer is more than simply a technological enhancement; it is a mindset change. It replaces

conformity with accuracy, guesswork with science, and exploitation with care. To reach its full potential, concerted efforts are required to upgrade infrastructure, provide user-friendly technologies, and promote stakeholder participation. As agriculture transitions to the digital era, spatially intelligent fertilizer management will be critical to the development of sustainable and resilient food systems.

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