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Site-specific nutrient management: Revolutionizing fertilization for future farming

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Abstract
The optimization of nutrient management is crucial for enhancing crop productivity and maintaining soil health while minimizing environmental impacts. Site Specific Nutrient Management (SSNM) is an innovative approach of supplying nutrients to plants optimally. To match their inherent spatial and temporal needs for supplemental nutrients by using different tools of SSNM such as remote sensing, GPS, GIS systems, VRT, yield monitoring. One critical application of SSNM is stress management, particularly in India, where most cultivated soils are acidic and exhibit significant spatial variability in pH. Integrating remote sensing data with GIS-based analytics allows for early detection of nutrient deficiencies, enabling targeted fertilizer application and soil amendments. Cutting-edge tools like Optical sensors, Crop Manager, Remote Sensing, Nutrient Expert®, fertility mapping, Active Canopy Sensors etc. further enhance SSNM's potential. This precision-driven approach not only optimizes nutrient application timing and rates but also maximizes crop yield and nutrient use efficiency, ensuring higher economic returns per unit of fertilizer applied rather than indiscriminately increasing or decreasing fertilizer inputs. This review explores recent advancements in SSNM, highlighting its core principles, practical applications, and potential benefits for Indian agriculture. It also examines the challenges and opportunities associated with its adoption. By integrating precision technologies, SSNM offers a sustainable pathway to enhance crop productivity, optimize resource use, and minimize environmental impact. Its widespread implementation can play a pivotal role in shaping the future of climate-resilient and resource-efficient farming systems.

Keywords: Site-specific nutrient management, precision agriculture, soil fertility, GIS, remote sensing, variable rate technology

1. Introduction

Over the past four decades, crop management in India has been driven by the increasing use of external inputs, with fertilizers playing a major role in improving crop productivity. In India, food grain production increased from 98 MT in 1967-68 to 257 MT in 2015-16, while fertilizer use rose more than 12 times from 1.95 MT to 25.4 MT over the same period, and projections indicate that by 2025, the country will need 350 MT of food grain, requiring 45 MT of fertilizer nutrients (ICAR, 2008) [5]. With almost no opportunity to increase the cultivated area beyond 142 million hectares, much of the desired increase in food grain production must come from yield enhancement per unit area, particularly in major staple food crops like rice, wheat, and maize, which responded significantly to Green Revolution technologies and contribute to more than 80% of total food grain production (Johnston *et al*., 2009) [7]. At the national level, soil deficiencies of N, P, K, S, Zn, and B are widespread, with nitrogen deficiency being prevalent across the Indian plains, potassium fertility being severely stressed due to excessive removal, and sulphur deficiencies reported in nearly 250 districts. Based on extensive data from 250,000 soil samples, 49% of soils were found deficient in Zn, 12% in Fe, and less than 5% in Cu and Mn, while boron deficiencies were detected in 33% of 36,800 soil samples analyzed (Singh, 2001) [17]. However, fertilizer nutrient recovery remains inefficient, with reported rates of 20-40% for N, 15-20% for P, 40-50% for K, and 5-12% for secondary and micronutrients (Rao, 2014). Since farmers often find that soil alone cannot meet crops' nutrient demands, fertilizers become essential, yet nutrient requirements vary across fields, seasons, and years due to differences in soil conditions, management practices, and climate.

SSNM provides tailored nutrient recommendations, sustaining or improving yields while optimizing fertilizer use, helping farmers reduce costs and mitigate environmental damage. In such a scenario, accelerating nutrient use efficiency through a balanced supply of nutrients from organic and inorganic sources is critical, making Site-Specific Nutrient Management SSNM a sustainable option to enhance soil health, increase agricultural productivity, and secure national food security. This approach allows for fine-tuning crop management systems following the 4R Nutrient Stewardship—right source, rate, time, and place of nutrient use—to enhance input efficiency, reduce nutrient losses, improve farm profitability, and minimize agricultural non-point source pollution.

SSNM seeks to maximize economic yields by addressing the gap between high-yielding crops' nutrient demands and the naturally available supply from soil, crop residues, manure, and irrigation water, with no fixed goal of reducing or increasing fertilizer consumption (Buresh *et al.*, 2005) [3]. This strategy is a potential solution for eco-friendly, sustainable agricultural production, aiding in doubling farmers' income and promoting self-reliance in India (Sarkar *et al.*, 2017) [15]. By employing diagnostic tools like soil sampling, sensing technologies, and yield mapping, SSNM enables precision nutrient application, significantly reducing excessive fertilizer use and associated greenhouse gas emissions, potentially by up to 50% in some cases (Richards, 2015) [14].

Recent advancements in IT, electronics, computer science, communication, and space technology have significantly influenced agricultural development, supporting precision farming through SSNM technologies. Techniques such as lab testing, field-based soil analysis, map-and sensor-based fertilizer recommendations, yield mapping, and Variable Rate Application (VRA) of nutrients allow for data-driven, site-specific fertilization strategies. The integration of Farm Management Information Systems (FMIS) with Decision Support Systems (DSS) and predictive models has further improved nutrient application efficiency, enhancing productivity while reducing environmental impacts (Adhikari *et al*., 2011) [1].

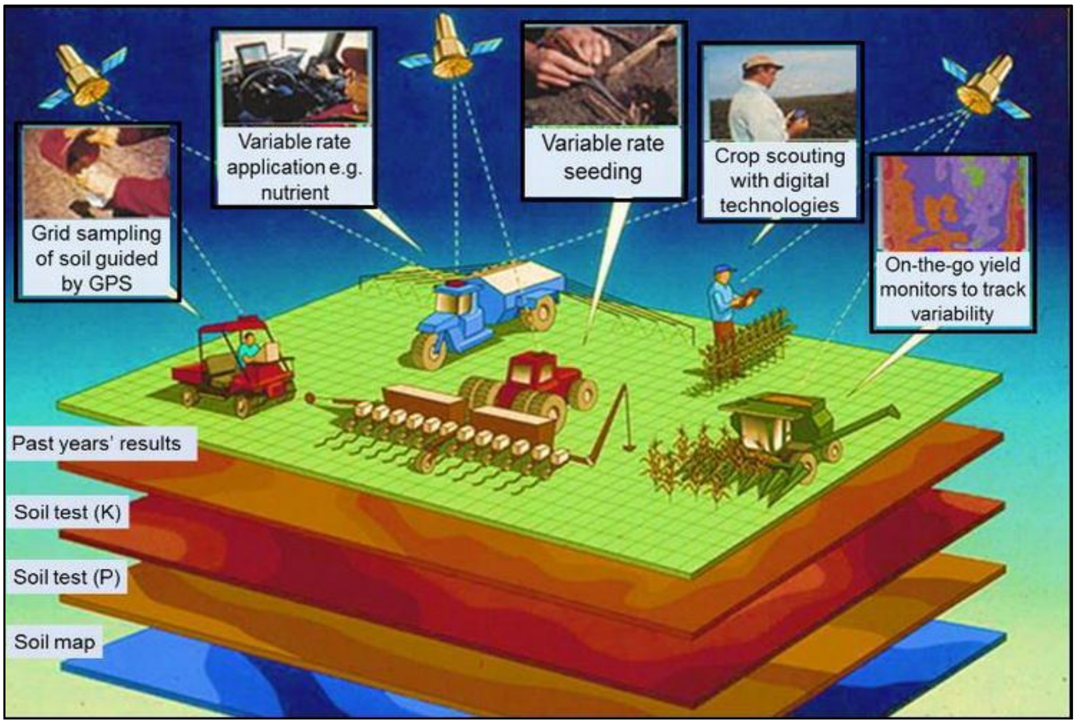

Fig 1: Illustration of various component practices and technologies commonly associated with specific precision agriculture systems (IPNI, Reetz, Better Crops, 1994) [12]. (Source: Reetz, H. F., Jr. 2016) [13]

2. Principles of SSNM

SSNM is based on the 4R nutrient stewardship principles (Bruulsema *et al*., 2016) [2]:

- **Right Source:** Selecting the appropriate type of fertilizer for specific soil and crop needs (Koley *et al*., 2024) [8].
- **Right Rate:** Applying fertilizers in quantities that match crop requirements.
- **Right Time:** Synchronizing fertilizer application with crop growth stages.
- **Right Place:** Placing nutrients where crops can efficiently absorb them while minimizing losses (Gupta, 2006) [4].

By adopting SSNM, farmers can enhance productivity while maintaining soil fertility and reducing environmental risks.

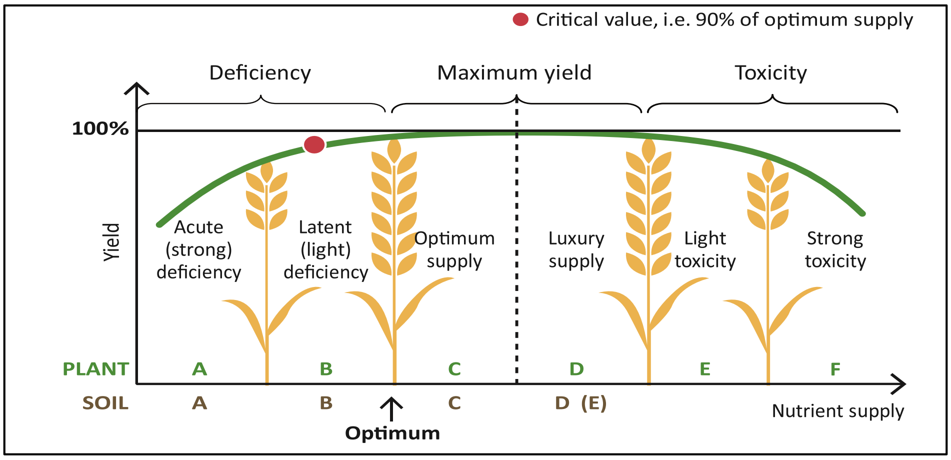

Fig 2: Effects of rate on wheat, showing potential deficiency and toxicity effects of not applying the right rate of nutrients. (Source: Reetz, H. F., Jr. 2016) [13]

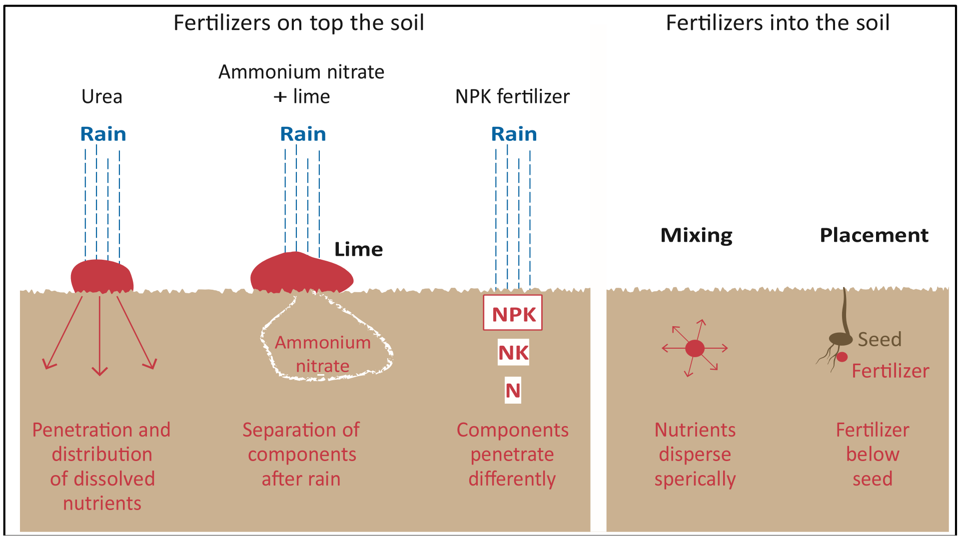

Fig 3: Diagram showing the impact of different fertilizer placement practices for movement of nutrients into the soil (adapted from IFA, 1992) [13]. (Source: Reetz, H. F., Jr. 2016) [13]

Table 1: Essential Scientific Principles and Corresponding Practices of 4R Nutrient Stewardship

Sl. No	Principle Involved	Scientific Basis	Associated Practices
1	Right Product	• Ensure a balanced supply of nutrients • Suit soil properties	• Commercial fertilizer • Livestock manure • Compost • Crop residue
2	Right Rate	• Assess nutrient supply from all sources • Assess plant demand	• Test soil for nutrients • Balance crop removal
3	Right Time	• Assess dynamics of crop uptake and soil supply • Determine timing of loss risk	• Apply nutrients: • Pre-planting • At planting • At flowering • At fruiting
4	Right Place	• Recognize crop rooting patterns • Manage spatial variability	• Broadcast • Band/drill/inject • Variable-rate application

(**Source:** Richards *et al*., 2015) [14]

Table 2: Softwares, Tools, and Equipment for Implementing SSNM

Sl. no	Technology	Function	Benefits
1	Optical Sensors	• Measures leaf reflectance to calculate NDVI (Normalized Difference Vegetation Index) for nitrogen management. • A digital decision-support tool for site-specific fertilizer recommendations based on soil and crop data.	• Detects plant nutrient status in real time. • Helps optimize nitrogen application. • Cost-effective handheld versions available (~USD 500).
2	Crop Manager	• A digital decision-support tool for site-specific fertilizer recommendations based on soil and crop data.	• Provides customized nutrient plans. • Available for rice, wheat, and maize. • Accessible via mobile phones & computers.
3	Remote Sensing	• Uses satellite and aerial imaging to monitor crop health, field variability, and nutrient status.	• Helps in precision field mapping. • Improves large-scale nutrient monitoring. • Identifies nutrient deficiencies & pest outbreaks.
4	Nutrient Expert®	• A computer-based SSNM tool that provides fertilizer recommendations without soil testing.	• Predicts achievable yields. • Conducts cost-benefit analysis. • Available for wheat & maize in South Asia.
5	GIS-Based Fertility Mapping	• Integrates GPS-referenced soil & crop data to create fertility maps for precision agriculture.	• Visualizes spatial nutrient variability. • Optimizes site-specific fertilizer application. • Tracks long-term soil fertility trends.
6	Real-Time Kinematic (RTK) System	• High-precision GPS navigation system for accurate nutrient application and field operations.	• Ensures row-to-row precision (~1-2 cm). • Reduces fertilizer wastage & overlaps. • Useful for seeding, starter fertilizer application.
7	Active Canopy Sensors (ACS)	• Real-time nitrogen stress detection for variable-rate nitrogen application.	• Measures NDVI & chlorophyll index. • Improves nitrogen use efficiency. • Reduces over-fertilization risks.
8	Variable Rate Technology (VRT)	• Adjusts fertilizer application rates based on soil variability and crop needs.	• Reduces nutrient wastage. • Ensures precise nutrient application. • Compatible with sensor-driven & map-based systems.
9	Global Positioning System (GPS)	• Provides precise location-based nutrient application for SSNM.	• Enables accurate data collection. • Helps in yield monitoring & fertilizer placement. • Supports long-term soil health tracking.
10	GreenSeeker	• A handheld optical sensor for nitrogen management based on crop reflectance and NDVI values.	• Determines real-time nitrogen needs. placement. • Improves fertilizer efficiency. • Available for wheat & maize systems.
11	Nutrient Omission Plot Technique	• Determines soil's natural nutrient supply by comparing plots with and without specific nutrients.	• Identifies crop-specific nutrient deficiencies. placement. • Helps develop balanced fertilization plans. • Reduces excessive fertilizer use.

(**Source:** Sarma *et al*., 2024 and Yadav *et al*., 2020) [16, 22]

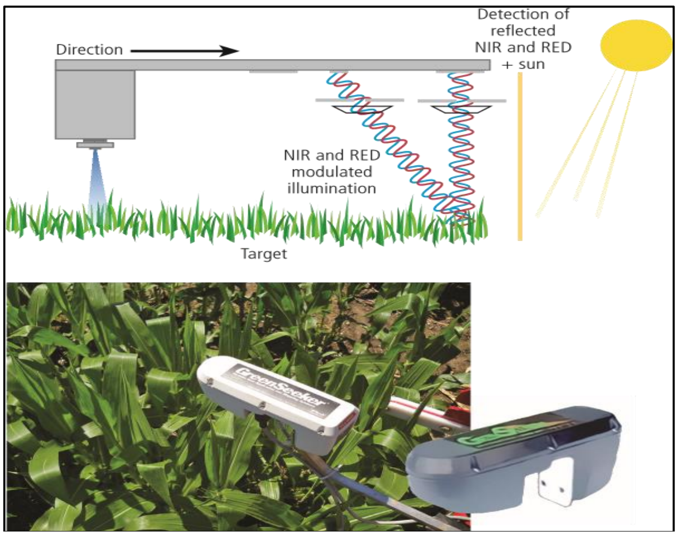

Fig 4: Photo of the system in use in the field. Diagram of the operation of the GreenSeeker on-the-go sensing system (top). (Source: Reetz, H. F., Jr. 2016) [13]

Table 3: Steps in Site-Specific Nutrient Management (SSNM)

Sl. No	Step	Description
1	Assessment of Soil and Crop Variability	Collect soil samples and analyze nutrient status to determine spatial and temporal variations in nutrient availability. Use GIS and remote sensing for mapping variability.
2	Determination of Nutrient Requirements	Estimate crop-specific nutrient demands based on growth stages, expected yield targets, and soil test results.
3	Nutrient Application Strategy	Develop site-specific fertilizer recommendations using the 4R principles (Right Source, Right Rate, Right Time, Right Place).
4	Implementation of SSNM	Apply fertilizers using precision tools such as Variable Rate Technology (VRT), GPS-guided spreaders, and site-specific application methods.
5	Monitoring and Adjustment	Track crop response through chlorophyll meters, remote sensing, and yield monitoring. Adjust nutrient applications dynamically based on plant growth and soil conditions.
6	Evaluation and Refinement	Analyze yield data and nutrient use efficiency to refine SSNM recommendations for future seasons. Continuous improvement through research and farmer feedback.

(**Source:** Koley *et al*., 2024) [8]

3. Applications of SSNM

3.1 Cereal Crops

Cereal crops, being the backbone of food security, have greatly benefited from SSNM-based fertilization strategies. In rice cultivation, SSNM has been shown to increase yields by 7-15% compared to traditional blanket fertilization methods while significantly reducing nitrogen losses by 30-50% (Pasuquin *et al*., 2014) [10]. Similarly, wheat yields have improved by 18-27%, accompanied by a 15-20% increase in nitrogen uptake efficiency (Jat and Satyanarayana, 2013) [6]. Maize, another major cereal, has recorded a 10-20% yield increase due to SSNM interventions, along with a 10-15% reduction in fertilizer costs (Kumar *et al*., 2014) [9]. The ability of SSNM to match nutrient supply with crop demand ensures better plant growth, higher grain filling, and improved resilience to abiotic stresses such as drought and heat.

3.2 Horticultural Crops

Precision nutrient management plays a crucial role in horticulture, where fruit quality, size, and shelf life determine market value. SSNM in fruit crops like citrus has led to a 12-18% increase in fruit yield while enhancing fruit size, color, and shelf life (Srivastava *et al*., 2009) [19]. In vegetable crops such as tomato and capsicum, SSNM has resulted in a 15-20% improvement in marketable yield and an 10-12% increase in vitamin C content (Gupta, 2006) [4]. Furthermore, in banana production, SSNM coupled with fertigation has boosted yields by 22-25% compared to conventional fertilization practices (Wood *et al*., 2003) [21]. By ensuring a balanced nutrient supply throughout critical growth stages, SSNM minimizes physiological disorders and improves post-harvest storage.

3.3 Pulses and Oilseeds

Leguminous crops and oilseeds have distinct nutrient demands that require precise management for optimizing yield and quality. In soybean, SSNM has contributed to a 15-20% increase in seed yield, along with an 5-8% improvement in oil content through balanced phosphorus and potassium application (Singh *et al*., 2012) [18]. Groundnut, another important oilseed crop, has shown a 20-25% increase in pod yield when site-specific phosphorus and sulfur applications were implemented. Mustard production has also benefited from SSNM, with seed yields increasing by 18-22%, while improved nitrogen-use efficiency has led to reduced fertilizer input costs (Gupta, 2006) [4]. Moreover, micronutrient applications in SSNM have enhanced protein content and seed formation in pulses, further improving nutritional value.

3.4 Agroforestry and Plantation Crops

SSNM is highly relevant in perennial cropping systems such as agroforestry and plantation crops, where long-term nutrient management is critical for sustainability. In oil palm cultivation, SSNM has increased fresh fruit bunch (FFB) yield by 18-22%, while reducing fertilizer costs by 15% (Pasuquin *et al*., 2014) [10]. Similarly, in tea plantations, SSNM-based nutrient recommendations have improved leaf quality and yield by 12-16% while maintaining soil health. In coffee, precision micronutrient management through SSNM has enhanced bean size and caffeine content by 8-10%. The targeted application of nutrients in plantation systems prevents soil degradation, ensuring consistent productivity over multiple growing seasons.

3.5 Dryland and Rainfed Agriculture

In moisture-stressed environments, SSNM helps optimize fertilizer use by accounting for variable rainfall patterns and soil nutrient availability. In crops like sorghum and pearl millet, SSNM has improved grain yields by 10-18%, while increasing water use efficiency under rainfed conditions (Thornton and Herrero, 2014) [20]. Similarly, in chickpea, targeted phosphorus application through SSNM has resulted in a 15-20% increase in pod yield and enhanced drought resilience. In cotton, SSNM-based nutrient management has led to a 12-15% increase in lint yield while reducing nutrient runoff losses. The integration of SSNM with conservation agriculture practices helps maintain soil fertility and ensures long-term sustainability in rainfed regions.

3.6 Protected Cultivation (Greenhouse Farming)

SSNM is widely used in greenhouse farming, where nutrient and water management must be highly precise to optimize plant growth. In high-value crops like cucumber and bell pepper, SSNM with real-time nutrient monitoring has increased yields by 25-30% compared to conventional fertilization (Gupta, 2006) [4]. In hydroponic lettuce production, SSNM strategies have improved nutrient uptake efficiency by 30-35%, reducing overall fertilizer use while enhancing plant health. By integrating SSNM with controlled environment agriculture, farmers can achieve sustainable and profitable production while minimizing nutrient losses through leaching.

4. Conclusion
SSNM represents a transformative shift in fertilizer management, aligning nutrient application with crop demand to enhance productivity and sustainability. By employing advanced tools and precision agriculture techniques, SSNM minimizes nutrient losses, improves soil health, and optimizes input use. Its successful application across cereals, horticultural crops, oilseeds, and plantation systems underscores its adaptability and effectiveness in diverse agricultural landscapes. The continued adoption of SSNM, supported by digital innovations and farmer education, will be instrumental in ensuring food security, environmental sustainability, and economic viability in modern agriculture. As nutrient management practices evolve, integrating real-time monitoring, AI-driven decision support, and climate-smart strategies will further enhance SSNM's potential to sustain global agricultural productivity in the aspect of growing challenges.

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6. Competing Interests
Authors have declared that no competing interests exist.

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