

Smart nutrient management practices

for sustainable crop production

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Global food security faces pressure from rising population, climate change, and shrinking natural resources. In India, the second-largest fertilizer consumer after China, fertilizers contribute ~40–50% of yield gains, making nutrient management essential. Yet, inefficient use results in poor utilization efficiencies i.e. 30–50% for nitrogen, 15–20% for phosphorus, 50–80% for potassium, and <5% for micronutrients—leading to widespread deficiencies and declining nutrient use efficiency (NUE), especially in cereals like rice, wheat, and maize. To address this, Smart Nutrient Management (SNM) practices are vital. Based on the 4R nutrient Stewardship principle, SNM integrates Soil-Test Crop Response (STCR), Integrated Plant Nutrient Supply (IPNS), and Site-Specific Nutrient Management (SSNM). Tools like SPAD meters, leaf colour charts, and GreenSeeker sensors guide in-season decisions, while organic residue recycling, microbial inputs, and crop residue management enhance soil health. Innovations like nano-fertilizers, green fertilizers, digital soil mapping, and IoT-enabled systems enable precision nutrient delivery. Together, SNM enhances productivity, improves NUE, lowers costs, and reduces environmental impacts.

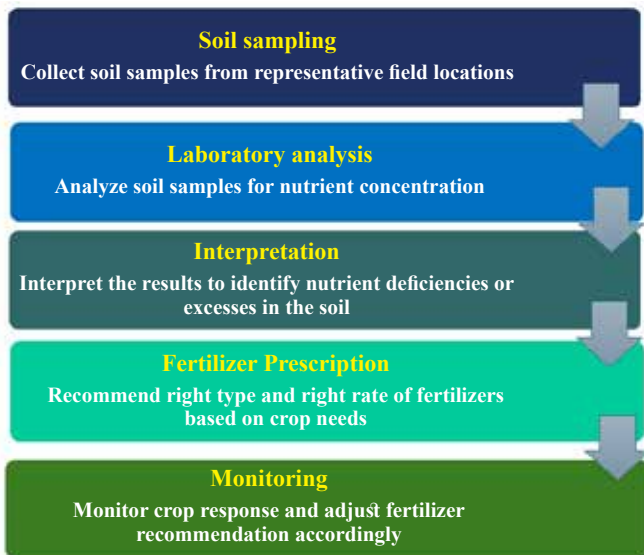
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SOIL health underpins sustainable agriculture, shaping productivity, food quality, and ecosystem resilience. Yet, soils globally face severe threats from erosion, nutrient depletion, salinization, compaction, organic matter loss, and declining microbiomes essential for nutrient cycling. Intensive agriculture and contamination by heavy metals, pollutants, and excess nutrients further compromise food safety and groundwater. Blanket fertilizer use has proven inefficient, with low utilization efficiencies—nitrogen (30–50%), phosphorus (15–20%), potassium (50–80%), and micronutrients (<5%)—leading to nutrient losses, environmental degradation, and greenhouse gas emissions. Smart Nutrient Management (SNM), rooted in the 4R principle, offers solutions by aligning inputs with soil and crop demand. Approaches like STCR, IPNS, and SSNM optimize nutrient delivery, supported by tools such as SPAD meters, LCC, and GreenSeeker sensors for real-time adjustments. Integrating organic residues, microbial inoculants, indigenous minerals, and residue recycling restores soil vitality. Emerging innovations such as nano-fertilizers, climate-smart

fertilizers, DSM, and IoT systems further improve efficiency. Collectively, SNM sustains soil health, boosts productivity, and strengthens climate-resilient food systems.

Approaches of smart nutrient management (SNM) practices

Soil-test based fertilizer recommendation (STCR): STCR is widely regarded as the cornerstone of balanced and efficient nutrient management in modern agriculture. It ensures that nutrient inputs are aligned with both the inherent nutrient-supplying capacity of the soil and the precise requirements of the crop. The process begins with the systematic collection of representative soil samples, which is a critical step to capture the true fertility status of the field. Thereafter, soil samples are subjected to laboratory analysis to assess key soil properties including soil texture, pH, electrical conductivity, organic carbon, and the availability of major nutrients (N, P, K), secondary nutrients (Ca, Mg, S), as well as micronutrients (Zn, Fe, Cu, Mn, B, etc.). Based on soil analysis, nutrient recommendations are developed through correlation and calibration that link



Soil-test based fertilizer recommendation



Site-Specific Nutrient Management (SSNM)

soil test values with crop response. Such an approach not only enhances NUE and crop yield but also reduce nutrient losses and production costs, and contributes to environmental sustainability by preventing over or under use of fertilizers.

Integrated plant nutrient supply system (IPNS): IPNS emphasizes the balanced and combined use of inorganic fertilizers with organic amendments such as FYM, compost, vermicompost, crop residues, green manures, and biofertilizers, along with the inclusion of legumes in cropping systems. The primary objectives of IPNS are to reduce dependence on chemical fertilizers, restore and maintain soil organic matter, improve nutrient-use efficiency, and sustain soil quality in terms of its physical, chemical, and biological properties. By ensuring a steady supply of macro- and micronutrients, IPNS supports higher productivity, reduces input costs, and promotes environmentally sustainable farming. Long-term studies on vertisols have shown that such integrated practices enhance soil organic carbon, improve nutrient availability, while also contributing to carbon sequestration improving the energy use efficiency while reducing carbon footprint. Its adaptability to local conditions makes it a practical and eco-friendly strategy for long-term agricultural sustainability.

Site-specific nutrient management (SSNM): The SSNM is a nutrient management practice that aims to provide crops with nutrients following the 4R nutrient stewardship idea: The right nutrient source, at the right rate, at the right time, and in the right place, based on site-specific conditions. It targets field level variability in native nutrient (NPK) supply, temporal variability in plant N status occurring within a growing season and medium-term changes in soil P and K from actual nutrient balance. There are

three basic approaches for SSNM such as 1) Nutrient omission plot technique: Site-specific nutrient (N, P, K) recommendations can be developed using the nutrient omission plot technique, which quantifies the indigenous nutrient supply from the soil. This approach helps determine the actual fertilizer requirement for achieving target yields under specific site conditions. 2) Nutrient Expert/Decision-Support tools: Use of models, algorithms, or digital tools (e.g. Nutrient Expert for maize and rice) to estimate crop nutrient requirements based on site conditions, yield targets, and nutrient balances. 3) Real-Time Nutrient Management (RTNM): Involves in-season diagnosis using tools like SPAD chlorophyll meter, Leaf Colour Chart (LCC), or sensors to apply nutrients especially nitrogen-based on crop demand and growth stage.

Chlorophyll-meter (SPAD-meter): The chlorophyll meter (SPAD meter) is a handheld diagnostic tool that estimates relative leaf chlorophyll content, which is closely associated with leaf nitrogen status. It provides a rapid, non-destructive, and real-time assessment of crop N nutrition, thereby helping in site-specific and in-season nitrogen management. Studies across a range of crops including maize, wheat, cotton, and apple have



Chlorophyll-meter (SPAD-meter)



Leaf colour chart

shown a strong relationship between SPAD readings and crop nitrogen status. Basically, the SPAD reading reflects the chlorophyll content in leaves, which in turn correlates with plant nitrogen concentration and yield potential. Thus, by using the SPAD meter, farmers can apply nitrogen at the right time and in the right amount, avoiding wastage and reducing costs while improving productivity. Hence, the chlorophyll meter is an effective tool for guiding balanced nitrogen application and improving crop productivity while minimizing losses to the environment.

Leaf colour chart (LCC): LCC is easy to use, low cost and helps farmers give the right amount of nitrogen fertilizer to many crops. LCC is a plastic, ruler-shaped strip containing four or more panels that range in colour from yellowish green to dark green. The standardized LCC is five inches long, made of high-quality plastic, and consists of six colour shades from yellowish green to dark green. The colour strips are fabricated with veins resembling crop leaves. By matching the colour of the leaf to the colour on the LCC, farmers can decide the proper time and amount of N fertilizer for application. In maize, the LCC helps decide the right time for N application. Every 7 to 10 days from the time of sowing until tasseling, compare the topmost fully opened leaf with the LCC.

The middle part of the leaf is placed on the LCC and compared with the colour panel. If most leaves are lighter than shade 4, apply nitrogen; if equal to or darker, no fertilizer is needed. Regular use ensures need-based

N application, saving fertilizer and improving yield.

GreenSeeker™ sensor technology: The Green Seeker is an active optical sensor designed to assess in-season crop nitrogen (N) status and guide site-specific N management. This instrument is used to measure Normalized Difference Vegetation Index (NDVI) of plants and the value of NDVI is correlated with the N content in the plant. The sensor operates by emitting red and near-infrared light onto the crop canopy and measuring the reflectance to calculate the NDVI. Higher NDVI values indicate greener, healthier, and N-sufficient crops; lower values indicate nitrogen stress. GreenSeeker-based measurements allow for real-time estimation of crop N demand, thereby enabling precise, need-based fertilizer application. A small plot in the field is fertilized with a non-limiting dose of nitrogen (N-rich strip). The GreenSeeker sensor measures the NDVI of this N-rich strip, which is then used as a reference to compare the nitrogen status of the crop in the rest of the farmer's field. For optimal performance, the instrument is operated by walking across the field while holding the sensor 24–48 inches (60–120 cm) above the crop canopy. NDVI values from the field are compared with those from the N-rich strip, and calibration models are then used to convert NDVI differences into site-specific nitrogen requirements (kg N/ha).

Microbial interventions: Sustainable crop production requires nutrient management strategies that not only enhance yield but also protect soil health and reduce environmental degradation. Chemical



GreenSeeker sensor



fertilizers have led to declining soil fertility, nutrient imbalances, and other environmental risks. So, microbial interventions within SNM practices offers an innovative pathway to ensure balanced nutrient supply, improved nutrient-use efficiency, and long-term sustainability. Microorganisms play a pivotal role in mobilizing, fixing, and transforming nutrients in the soil–plant system. Key microbial interventions include:

- **Biofertilizers:** *Rhizobia*, *Azotobacter*, and *Azospirillum* fix atmospheric nitrogen and reduce dependence on synthetic N-fertilizers.
- **Phosphate-solubilizing microorganisms (PSMs):** *Bacillus* and *Pseudomonas* species release organic acids that solubilize insoluble phosphates, enhancing P availability.
- **Potassium and zinc solubilizers:** Certain bacteria and fungi mobilize micronutrients, ensuring balanced nutrition.
- **Mycorrhizal fungi:** Improve phosphorus uptake, micronutrient acquisition, and water-use efficiency through extended hyphal networks.
- **Microbial consortia:** Synergistic combinations of bacteria and fungi provide multiple nutrient benefits and resilience under variable field conditions.

In situ management of crop residue: Crop residue management is crucial for sustainable farming, as burning residues leads to pollution, nutrient loss, and soil degradation. *In situ* approaches like incorporation, mulching, and residue retention improve soil health, organic matter, microbial activity, and water conservation, while releasing nutrients (N, P, K, micronutrients) to reduce fertilizer dependence. Conservation tillage with residue retention enhances SOC, prevents erosion, and sustains productivity compared to conventional tillage. Zero tillage with stubble retention further preserves soil aggregates and long-term SOM. Integrating residue management with site-specific nutrient management and precision tools ensures balanced nutrient supply, reduces losses,

enhances NUE, and supports resilient, resource-efficient crop production systems.

Climate smart green fertilizer: Green intelligent fertilizers are the latest emerging technology in which high-quality fertilizers were produced based on the principles of synchronizing plant nutrition based on crop demand, kind of soil and prevailing environmental situations. It relies on use of artificial intelligence for managing the specific supply-demand based upon requirement, enhancing the root-fertilizer interaction by intensifying crop biological potential, developing new advanced green manufacturing technology which can stimulate the rhizosphere effects in the root zone on crop plants and enhancing the utilization of mineral resources contained in raw materials. Green intelligent fertilizers not only increase yield and improving quality of food, but also serve as an important entry point for integrating the fertilizer industry and agricultural chain via green transformation of the fertilizer production.

Nanotechnology: Nano size fertilizer materials have great advantage for its application to agricultural crops. Reducing the size of fertilizer materials aid to enhance nutrient uptake by crop plants and reducing the loss of fertilizer material from soils. Due to higher reactivity of nano fertilizer material they form complexes with the different material in soil and plant which can also help in controlled release of plant nutrients. Further coating of nano-fertilizers with materials like polymer also act as barrier for controlled release of plant nutrients into the soil. The other liquid nano-fertilizers such as Nano-emulsion is also advantageous in the sense that it allows more nutrients in a single droplet. The use of IT based nano sensors are also recently emerged technology for effective fertilizer management for real-time sensing and managing the fertilizer release from the nano based controlled release fertilizer materials.

Digital soil mapping for parcel specific fertilizer recommendation: Digital Soil Mapping (DSM) is the recently introduced concept for fast mapping of soil resources and its attributes. The DSM is basically the approach of creation of soil information systems by using the mathematical models by considering the interaction between soil attributes and related environmental factors (covariates). It is very useful technique for the prediction of key soil attributes such as soil depth, pH, organic carbon, textural fractions, and soil moisture. Among the different models recently studied, Regression Kriging has been accepted method for mapping of soil nutrients with fairly good accuracy.

IoT-enabled nutrient delivery systems: The Internet of Things (IoT)-enabled nutrient delivery systems represent a modern approach to precision agriculture. In this approach, sensor-based, automated, controlled, and optimized fertilizers are applied by using smart devices. It is a combination of standard protocols of agronomy, automation, and data science that are offering real-time nutrient management, particularly in controlled environments. Application of IoT-based technologies such as sensors, actuators, cloud platforms, and analytics, which are able to monitor and regulate the

nutrient delivery based on real-time crop and weather data. In this system, continuously monitor soil moisture, temperature, soil pH, and nutrient concentration in real time and accordingly regulate the type and amount of nutrients applied to crops. Hence, farmers can make informed decisions and remotely control irrigation and fertilizers by connecting sensor data with cloud-based analytics and mobile applications. Applying IoT-based fertilizers not only improves the NUE and crop yield but also reduces input, minimizes the environmental losses, and ensures sustainable crop production.

SUMMARY

Global food security faces pressures from population growth, climate change, and resource decline, while

in India, low NUE, soil degradation, and shrinking farmland exacerbate concerns. Sustainable Nutrient Management (SNM) aligns with SDGs by promoting cost-effective, resource-efficient practices. Based on 4R stewardship, SNM integrates STCR, IPNS, and SSNM, supported by tools like SPAD meters, LCC, and GreenSeeker for real-time adjustments. It emphasizes organic residue valorization, microbial inoculants, and residue management to restore soil health. Emerging innovations such as green fertilizers, nano-fertilizers, DSM, and IoT-enabled systems enable precision nutrient delivery. Together, SNM strategies enhance yields, improve NUE, reduce losses, and sustain productivity.

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