Journal of Advances in Biology & Biotechnology

Volume 27, Issue 8, Page 211-222, 2024; Article no.JABB.120058
ISSN: 2394-1081

Site Specific Nutrient Management (SSNM): Principles, Key Features and its Potential Role in Soil, Crop Ecosystem and Climate Resilience Farming

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jabb/2024/v27i81133

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/120058

Review Article

Received: 11/05/2024
Accepted: 13/07/2024
Published: 16/07/2024

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Cite as: *Sarma, Hridesh Harsha, Santanu Kaushik Borah, Rajesh Chintey, Hrishikesh Nath, and Nilabh Talukdar. 2024. "Site Specific Nutrient Management (SSNM): Principles, Key Features and Its Potential Role in Soil, Crop Ecosystem and Climate Resilience Farming". Journal of Advances in Biology & Biotechnology 27 (8):211-22. https://doi.org/10.9734/jabb/2024/v27i81133.*

ABSTRACT

As the world population expands, farming practices have intensified to meet increased food demand. Modern crop varieties now require higher levels of fertilization compared to traditional organic methods, which are insufficient to meet these new demands. However, inefficient nutrient management and imbalances in field nutrient levels have led to various crop issues. To achieve higher agricultural output and productivity, there has been a notable increase in the application of chemical fertilizers, which unfortunately contributes to soil and water pollution, degradation of soil fertility, and nutrient imbalances. In response, modern technologies are being leveraged to promote sustainable food production and foster balanced agricultural development. Site specific nutrient management (SSNM) aims to empower farmers to adjust fertilizer application dynamically to meet the nutrient requirements of high-yielding crops, bridging the gap between natural nutrient sources like soil, crop residues, manure, and irrigation water. It is based on the principles of 4Rs: right product, right dose, right time and right place. Modern technologies like Optical sensors, Crop Manager, Remote Sensing, Nutrient Expert®, fertility mapping, Active Canopy Sensors, Variable rate technologies etc. are used to enhance the potential of SSNM to higher level. The focus is on optimizing nutrient application timing and rates to maximize crop yield and nutrient efficiency, thereby enhancing the economic value of harvest per unit of fertilizer used, rather than simply increasing or decreasing fertilizer use.

Keywords: Active canopy sensors; fertility mapping; optical sensors; right dose; right time.

1. INTRODUCTION

The anticipated global population growth is expected to decelerate by 2030, yet it will still lead to approximately 1.3 billion additional individuals, marking a 19 percent rise. This demographic shift will generate a substantial surge in demand, posing an increasingly formidable challenge for food provision over the next twenty years [1]. To meet the food demands of a growing population, India must enhance agricultural productivity while using land more efficiently. Achieving sustainable agriculture involves balancing nutrient levels to ensure increased food and fibre production, profitability, efficient input utilization, and environmental stewardship. Over the past four decades, India's agricultural practices have increasingly relied on external inputs, with fertilizers playing a crucial role in boosting crop yields. During the period from 1969 to 2007, food grain production more than doubled, reaching a peak of 212 million tonnes in 2001-2002, while fertilizer use skyrocketed from 1.95 million tonnes to over 23 million tonnes in 2007-08 [2]. Throughout India, soil deficiencies in nitrogen (N), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), and boron (B) have become a significant concern. Nitrogen deficiency is prevalent across the expansive plains of India. The fertility of potassium in soils is not only disregarded but also under considerable pressure due to the current situation where the removal of potassium exceeds its input. With limited opportunities to expand cultivation beyond 142 million hectares, the focus on increasing food grain production must largely rely on enhancing yields per unit of land. This is particularly crucial for major staple crops such as rice, wheat, and maize, which significantly benefited from the adoption of Green Revolution technologies and now contribute over 80% of total food grain production [3].

Fertilizer application guidelines typically rely on crop response data averaged across extensive regions, yet individual farm fields exhibit significant variability in nutrient-supplying capabilities and crop responses. This variability often results in blanket fertilizer recommendations that may lead to over-application in certain areas, under-application in others, or an incorrect nutrient balance for specific soils or crops. Farmers often find that soil alone cannot provide sufficient nutrients to achieve high and profitable yields, necessitating the use of fertilizers. The nutrient requirements of crops vary significantly across fields, seasons, and years due to differences in growing conditions, soil management practices, and climate. Therefore, effective nutrient management demands an adaptable approach that allows for tailored applications of nitrogen (N), phosphorus (P), and potassium (K) to meet specific crop needs. Site-Specific Nutrient Management (SSNM) offers tailored recommendations suited to individual farm conditions. SSNM aims to sustain or improve crop yields while helping farmers save costs through optimized fertilizer use. It offers farmers guidelines, tools, and strategies to accurately determine when and how much nutrients should be applied to fields based on current growing conditions in a particular season and location. It also involves recognizing variations in nutrient levels within fields and adapting nutrient applications accordingly. This involves employing field diagnostics like intensive soil sampling, soil sensing, aerial imagery, and yield mapping to tailor nutrient application to specific locations or soil conditions. By reducing excessive fertilizer application, SSNM also contributes to lowering greenhouse gas emissions, potentially by as much as 50% in certain instances [4].

2. PRINCIPLES OF SITE-SPECIFIC NUTRIENT MANAGEMENT (SSNM)

Site-Specific Nutrient Management (SSNM) strives to effectively manage soil nutrient supply across different periods and locations to align with crop needs. This approach is guided by four fundamental principles, commonly referred to as the "4 Rs", which have been recognized since at least 1988 and are credited to the International Plant Nutrition Institute [5].

They are as follows:

1. **Right product:** Selecting the appropriate fertilizer product or nutrient source tailored to crop and soil requirements ensures a balanced supply of nutrients.
2. **Right rate**: Adjusting the amount of fertilizer applied to match crop nutrient needs while considering existing soil nutrient levels is crucial. Excessive fertilizer can lead to environmental losses like runoff, leaching, and emissions, as well as unnecessary costs, while insufficient fertilizer can deplete soils and cause degradation.
3. **Right time:** Timing nutrient applications to coincide with crop nutrient demands ensures effective utilization. This may involve staggered applications of mineral fertilizers or integrating organic and mineral sources for sustained nutrient release.
4. **Right place:** Placing nutrients at optimal distances from crops and within the right soil depth enhances nutrient uptake and minimizes losses. Incorporating nutrients into the soil is generally preferable to surface application, with the method chosen based on soil characteristics, crop type, tillage practices, and fertilizer type.

3. STRATEGIES INVOLVED IN SSNM

The foundation of the SSNM approach rests on the QUEFTS model (Quantitative Evaluation of the Fertility of Tropical Soils), developed by Janssen et al. (1990) [6]. This model operates through four main stages: (i) establishing the connection between macronutrients present in above-ground plant dry matter at physiological maturity, (ii) assessing potential nutrient contributions from both indigenous sources and fertilizer applications, (iii) predicting grain yield, and (iv) determining plant nutrient accumulation while accounting for interactions among NPK (major nutrients) [7]. It has been extensively used to estimate how crops respond to fertilizer inputs and to ascertain the optimal fertilizer quantities needed to achieve desired yields in rice, wheat, and maize. The model's principles can potentially be extended to other crops once the fundamental relationships between grain yield and nutrient supply are understood. It is executed in the following steps:

3.1 Defining the Target Grain Yield

The targeted grain yield for a specific location and season is determined by the crop's potential under optimal management conditions without nutrient constraints, taking into account factors such as climate, crop variety, and agricultural practices. This yield goal serves as an indicator of the total nutrient uptake required by the crop.

3.2 Estimating NPK Requirements for Target Yield

The nutrient requirements for achieving the target grain yield are calculated based on the crop's optimal internal efficiencies under balanced nutrition conditions. As the target yield approaches the maximum potential yield, the relationship between grain yield and nutrient uptake becomes nonlinear, with internal efficiencies deviating from standard optimal values.

3.3 Assessing Indigenous Nutrient Supply

Indigenous nutrient supply refers to the nutrients sourced from the soil, organic amendments, crop residues, manure, and irrigation water, excluding synthetic fertilizers. The uptake of nutrients from indigenous sources can be estimated by comparing the grain yield from nutrient-limited plots (where a specific nutrient is omitted) to fertilized plots containing other nutrients.

. Table 1. Illustration of essential scientific principles and corresponding practices of 4R nutrient stewardship

SL. No	SSNM 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) [4]

3.4 Determining Fertilizer (NPK) Application Rates

The fertilizer requirement is calculated based on the difference between the total nutrient demands of the crop (as determined by the target yield) and the nutrient supply from indigenous sources (as determined by the nutrient-limited yield). This calculation ensures that the crop receives adequate nutrients to achieve the desired yield without excessive application that could lead to environmental issues.

3.5 Dynamic adjustment of fertilizer N application

The strategy for managing nitrogen (N) fertilizer evolved based on experience and varied according to factors such as climate, crop variety, duration, establishment method, water management, and potential pest issues. Initially, total N requirements were estimated for achieving target yields under typical seasonal conditions. Plans were then devised to split and time N applications according to crop growth stages.

Key principles included determining the need for pre-plant N application, typically incorporating it when planting density was low or early season soil temperatures were cool. For other sites, pre-plant N was applied only if indigenous N supply was insufficient. The remaining N fertilizer was typically applied in two to three splits during critical growth phases, adjusted based on plant growth, seasonal factors, duration, and variety. A late-season N application was considered to enhance grain filling if crop conditions were favourable and pest pressure was low.

Furthermore, adjustments to N application were informed by actual plant N status assessed using tools like SPAD or Leaf Colour Chart (LCC). Initially, decisions were binary, but they evolved to include more nuanced adjustments based on continuous SPAD readings at critical growth stages [8].

4. CLIMATE RESILIENCE FARMING THROUGH SSNM

The primary focus of research on SSNM has been on enhancing crop productivity, boosting incomes, and reducing environmental impacts. SSNM is pivotal for fostering climate-resilient farming practices. By customizing nutrient applications to suit local soil conditions, crop types, and climate variability, SSNM optimizes nutrient use efficiency and enhances crop resilience. This approach ensures that crops receive adequate nutrition during varying weather patterns, such as droughts or excessive rainfall, minimizing stress and supporting robust growth. Moreover, SSNM promotes soil health and resilience by improving nutrient retention and reducing environmental impacts like nutrient runoff and greenhouse gas emissions from fertilizers. By strengthening plant immunity and pest resistance through balanced nutrient management, SSNM also contributes to sustainable pest and disease control. Ultimately, SSNM not only boosts agricultural productivity and quality but also equips farmers with strategies to adapt to and mitigate the impacts of climate change, fostering long-term economic and environmental sustainability in agriculture.

However, effective nutrient management should also improve crop yields and their ability to withstand challenges, as highlighted by Thornton and Herrero [9]. Moreover, optimizing fertilizer application based on achievable yields in a given year, such as through the use of optical sensors has the potential to save farmers money during adverse weather conditions. As a strategy to mitigate greenhouse gas emissions, SSNM is particularly effective in agricultural systems that currently rely excessively on nitrogen fertilizers. By reducing the amount of nitrogen applied, SSNM helps minimize total reactive nitrogen (Nr: NH_3, NH_4^+, NO_3^-, NO_2^-, NO, N_2O) losses to the environment, including leaching and volatilization, as well as N_2O emissions. Research has shown significant reductions in fertilizer use with SSNM implementation, such as a 30% reduction in rice paddies Wang *et al*., [10] and reduction of N_2O emissions by 50% in wheat Matson *et al*., [11] and leaching losses by 90% Riley *et al*., [12].

The use of slow-release or controlled-release fertilizers also contributes to lower N_2O emissions because they better synchronize nutrient release with plant demand. Additionally, techniques like fertilizer deep placement have shown promise, reducing reactive nitrogen losses by up to 35% [13]. While SSNM may recommend increased nitrogen application in nutrient-depleted soils [14], this does not necessarily lead to increased emissions. Evidence suggests that nitrogen emissions increase exponentially rather than linearly with higher inputs and modest increases in nitrogen rates in low-input systems are unlikely to significantly impact N_2O emissions or lead to nitrogen oversaturation in fields.

Even if there is a slight increase in N_2O emissions, SSNM can still reduce emission intensity, which refers to the amount of greenhouse gases emitted per unit of food produced. For instance, studies in Kenya's highlands have shown that current greenhouse gas emission intensities for upland crops at low input levels are significantly higher than in OECD countries due to low yields [15].

5. SOFTWARES, TOOLS AND EQUIPMENT FOR IMPLEMENTING SSNM IN THE FARM

5.1 Optical Sensors

Farmers and extension agents can utilize optical sensors to implement SSNM recommendations, particularly for nitrogen management. Optical sensors measure reflectance from leaves to generate a vegetative index known as NDVI (Normalized Difference Vegetation Index), which assesses plant nutrient status based on their size and colour (green versus yellow). Originally designed for large-scale farms, a compact handheld version is now commercially available at a fraction of the cost (approximately USD 500) [16]. To effectively use optical sensor-based nutrient management, local calibration of the sensor is necessary for specific nutrients, crops, and regions. This calibration establishes a relationship between crop grain yield and NDVI readings. Once calibrated, the process involves: (1) setting up a reference strip in the farmer's field with optimal nitrogen supply, (2) obtaining NDVI readings from both the reference strip and the target field area requiring nitrogen assessment, and (3) entering these NDVI readings along with planting and sensing dates into a region-specific mathematical model. Such models have already been developed for various crops in countries like China, India, Mexico, and Zimbabwe.

5.2 Crop Manager

Crop manager is a digital application accessible via computers and mobile phones, designed to assist small-scale farmers cultivating rice, rice wheat, and maize. it provides tailored recommendations for fertilizer application specific to each site and season. farmers can customize nutrient application based on their farm's soil conditions, water management practices, and crop varieties. These recommendations rely on data inputted by farmers or collected by extension workers, crop advisors, and service providers regarding farm location and management practices.

5.3 Remote Sensing

Remote sensing has become an increasingly valuable tool in precision agriculture, employing scanners aboard aircraft or satellites to monitor changes in light wavelengths reflected from fields and crops. Satellite imagery enhances precise mapping of field boundaries and locations such as tile drainage lines, particularly effective when complemented by ground scouting ("ground truth observations") to understand variability causes. The collected data is mapped and analyzed using GIS tools, generating additional layers for comprehensive analysis and management decisions.

Remote sensing plays a critical role in pinpointing the scope of issues identified during field scouting by identifying recurring patterns. It documents concerns like pest outbreaks, weather impacts, and nutrient management challenges. Although it has taken time to refine remote sensing technology to deliver reliable, cost-effective products promptly, such services are now accessible to assist farmers and advisors in making informed crop management choices.

5.4 Nutrient Expert®

Nutrient Expert® is an interactive, computer-based tool designed to assist smallholder farmers in implementing Site-Specific Nutrient Management (SSNM) effectively in their fields, even in the absence of soil test data. The software predicts achievable yields based on local growing conditions, assesses nutrient balances considering previous fertilizer or manure applications, and incorporates expected responses to nitrogen (N), phosphorus (P), and potassium (K) in target fields to generate personalized nutrient recommendations. Additionally, it conducts a basic cost-benefit analysis comparing current farming practices with recommended alternatives. The algorithm used for calculating fertilizer needs is derived from extensive on-farm research and has been rigorously validated over a five-year period. Currently, the software is available at no cost for wheat and maize systems in South Asia.

5.5 Geographic Information System (GIS) Based Fertility Mapping

Geographic Information Systems (GIS) comprise both data and software tailored for spatial analysis of GPS-referenced information. In agricultural applications, GIS integrates diverse databases such as soil surveys, soil testing results, pest occurrences, yield data, remote sensing images, and other observations tied to their geographic coordinates via GPS. These datasets are utilized to generate maps that visualize spatial variations within fields and augment the overall field database. This approach involves analyzing soil samples for quality and health, integrating their geographic coordinates (latitude/longitude) with corresponding attribute information in a GIS platform. This integration facilitates the creation of continuous surface maps depicting soil attributes through interpolation techniques. The success and accuracy of soil fertility mapping hinge on two critical factors: proper sampling and effective interpolation techniques. Sampling points must be sufficiently dense to capture the variability of soils across the landscape. Grid sampling remains the predominant method for characterizing soil variability. GIS-based decision support tools for soil fertility mapping within specific study areas provide clear visual representations of evolving fertility conditions over time. Implementing such a system offers logistical and economic advantages and can serve as an effective extension tool once established. It enhances farmers' awareness of their fields' soil fertility status relative to the broader landscape, enabling more informed and rational use of fertilizers. Successful dissemination of SSNM is evidenced when numerous farmers promptly adopt science-based Best Management Practices (BMPs) and Recommended Management Practices (RMPs) tailored to their specific fields, crops, and seasons. Beyond mere mapping, the true strength of gis lies in its capability for calculations and analysis of georeferenced datasets. by integrating various spatially variable datasets and employing predictive models, gis can forecast responses to inputs or identify interactions influencing crop yields and production factors. over time, these gis datasets become increasingly valuable as tools for maintaining records and making informed predictions in agriculture.

5.6 Real-Time Kinematic System (RTK)

GPS technology is utilized across various levels of precision depending on the application and data availability, with the Real-Time Kinematic (RTK) system being the most precise in crop production. RTK guidance systems offer high accuracy, which helps minimize costly errors such as skips and overlaps, thereby reducing input costs for seeds, fertilizers, and pesticides. Additionally, they alleviate operator stress and fatigue, providing significant additional benefits.

In an RTK system, a base station transmits its precise location to a rover GPS receiver mounted on the equipment. This receiver corrects the roving unit's position based on the known location of the fixed base station. RTK systems typically achieve accuracy within 1 to 2 cm, ensuring precise row-to-row positioning and enhancing the accuracy of harvest monitoring data over time. RTK technology is also employed to achieve similar precision for multiple operations, such as applying starter fertilizer in the fall and seeding in the spring.

5.7 Active Canopy Sensors (ACS)

Active canopy sensors are advanced tools positioned above crop canopies to detect nitrogen (n) stress and facilitate variable-rate n application decisions in real time. Unlike passive sensors that rely on reflected sunlight, active sensors emit their own light and instantly measure reflectance at the canopy level. However, using active sensors effectively for n application adjustments requires understanding conditions where factors like poor stand, excess water, or other nutrient deficiencies may limit growth.

These sensors collect visible (VIS) and near-infrared (NIR) light reflectance, enabling calculation of various canopy indices such as the normalized difference vegetative index (NDVI) and chlorophyll index (CI). These indices highlight different plant characteristics crucial for identifying N stress, such as canopy biomass and plant coloration.

Two main strategies can be employed with active sensors. One involves conducting canopy sensing annually, applying a reduced N rate before planting, at planting, or early during side dressing, followed by mid-vegetative growth sensing to determine additional N needs. The second approach responds to changes in crop requirements or N loss after primary application, allowing adjustments to be made accordingly throughout the season.

While the second approach maintains flexibility with normal preplant or early side dress N management, it may overlook scenarios where less N than typically recommended could optimize yield. Moreover, similar to canopy monitoring, there's a risk of missing season-long N deficiencies if the initial N application suffices until the time of sensing.

5.8 Variable Rate Technologies (VRT)

Variable-rate technology (VRT) is utilized to adjust agricultural inputs based on specific requirements across different sections of a field. For large-scale operations, this involves employing machinery capable of variable-rate application. On smaller farms, inputs may be manually applied. Successful implementation of VRT relies on: a) accurate field positioning, b) precise location-specific data, and c) farm equipment equipped with VRT controllers, typically featuring a DGPS receiver to pinpoint exact spatial variability within the field. These controllers automatically adjust application rates according to pre-established input maps. VRT technology finds extensive application in managing site-specific cropping systems. It is widely adopted, with approximately 1,600 flotation fertilizer-application systems, map-driven VRT systems, and sensor-equipped tractor-based application systems sold to date.

5.9 Global Positioning System (GPS)

The majority of precision agriculture tools rely on data collection or control systems that utilize the global positioning system (gps). each dataset collected is linked to specific geographic coordinates such as latitude, longitude, and elevation. this enables a precise understanding of the relationships between different layers of data, resulting in yield information, and other measurements. analyzing these layers allows for informed recommendations to be made for future agricultural decisions.

GPS systems are integral in planting equipment for capturing geo-referenced data during planting, starter fertilizer application, and other inputs. Incorporating appropriate controllers enables variable-rate application of inputs to be integrated into management strategies. these capabilities can be progressively added over time, enhancing the initial investment's value. As advancements in military technology become accessible for civilian use and new supporting technologies for gps evolve, this tool will increasingly benefit farmers in implementing site-specific management practices.

5.10 Green Seeker

The GreenSeeker is a handheld optical sensor developed by Oklahoma State University, utilized primarily for nitrogen management based on the relative greenness of leaves. Manufactured by N-

Tech Industries in Ukiah, CA, it senses a consistent area of 0.6 × 0.01 square meters when positioned approximately 0.6–1.0 meters away from the surface being illuminated. This sensing area remains stable across the sensor's height range.

The GreenSeeker operates by measuring the fraction of emitted light that is reflected back to the sensor from the sensed area. The current algorithm used by N-Tech Industries, named "WheatN1.0," incorporates several distinct components [17,18]. According to Raun et al. [19], these components include predicting mid-season grain yield by dividing the normalized difference vegetative index (NDVI) by the number of days from planting to sensing. Furthermore, the algorithm assesses the temporal responsiveness to applied nitrogen by placing non-N-limiting strips in production fields annually, comparing these to farmers' conventional practices using a fertilizer response index. It also estimates spatial variability within each 0.4 m^2 area by utilizing the coefficient of variation (CV) derived from NDVI readings. The efficiency of nitrogen fertilizer use can be improved by applying an optimized rate determined through soil testing, facilitated by the use of GreenSeeker. This handheld device measures crop reflectance to calculate the normalized difference vegetation index (NDVI), which is crucial for assessing the nitrogen requirements of the crop. NDVI quantifies the ratio of reflected visible red (RED, 650 ± 10 nm) and near-infrared (NIR, 770 ± 15 nm) radiation from the sensed area as the sensor moves above the crop canopy at a height ranging from 0.6 to 1.0 m [20,21]. This method is instrumental in ensuring precise and efficient nitrogen management in fertilizer application

6. YIELD MONITORING AND MAPPING

Yield monitoring and mapping play pivotal roles in site-specific farming, initially emerging as fundamental components of precision agriculture (Heacox, 1998). Yield monitoring provides in-depth insights into the spatial variability of crop yields within farm fields, enabling farmers to evaluate how their management practices and environmental conditions impact crop production [22].

This evaluation offers direct and valuable feedback to farmers, empowering them to enhance management decisions [23]. Such feedback includes real-time documentation of yield and moisture levels, generation of yield and moisture maps, identification of pest occurrences through digital flags, and systematic data organization by year, farm, field, load, and crop type.

Over time, continuous yield monitoring builds a comprehensive GIS database that aids farmers in identifying spatial yield variations within fields, making informed decisions regarding variable-rate applications, and establishing a historical record of field data. This technology is currently under research and development for application in other crops such as potatoes, onions, sugar beets, and tomatoes**.**

7. KEY FEATURES OF SSNM

1. **Precision Agriculture:** SSNM tailors nutrient applications based on site-specific factors such as soil type, crop variety, climate, and growth stage, optimizing resource use. It represents a contemporary method aimed at enhancing crop yields and supporting field management practices through advanced sensor technologies and analytical tools [24].
2. **Soil Testing and Analysis:** This involves comprehensive soil testing and analysis to determine nutrient deficiencies and pH levels, guiding precise fertilizer recommendations.
3. **Crop-Specific Recommendations**: SSNM provides specific nutrient recommendations for different crops to maximize yield potential and quality.
4. **Seasonal Adaptation:** Nutrient management strategies are adjusted seasonally to account for changing climatic conditions and crop growth requirements.
5. **Integrated Approach:** SSNM integrates organic and inorganic nutrient sources, incorporating crop residues, manures, and biofertilizers alongside chemical fertilizers.
6. **Nutrient Balance:** Emphasis is placed on maintaining a balanced nutrient profile to avoid deficiencies or excesses, which can affect crop health and yield.
7. **Optimal Timing of Applications:** Nutrient applications are timed to coincide with critical growth stages of the crop, ensuring nutrients are available when most needed.
8. **Environmental Sustainability:** SSNM aims to minimize environmental impacts such as nutrient leaching, runoff, and greenhouse gas emissions associated with fertilizer use.

9. **Data-driven decision-making:** It relies on data from soil tests, crop growth monitoring, and nutrient status assessments (e.g., SPAD readings) to make informed decisions about nutrient management.
10. **Adaptability and Flexibility:** SSNM practices evolve over time based on local agronomic research, farmer feedback, and changing environmental conditions, ensuring continuous improvement in nutrient management strategies.

8. IMPACT OF SSNM ON SOIL

Degraded soil quality is significantly reducing crop productivity due to excessive nutrient depletion and imbalanced use of fertilizers and plant growth promoters (PGPs). This poses a threat to sustainable soil management in India, where soil fertility is declining rapidly due to an imbalance in nutrient levels. If current practices of indiscriminate fertilizer application continue, it could irreversibly damage the nutrient supply system. Improved management practices (IMPs) are crucial to address these challenges by shifting from generalized approaches to more nuanced strategies that consider individual farm diversity and crop yield potential. Over time, the effectiveness of fertilization has declined from approximately 17 kilograms of grain per kilogram of nutrient in 1951 to around 6 kilograms per kilogram of fertilizer in recent years (2013-2014). Ideally, this ratio should range between 18 to 25 kilograms of grain per kilogram of nutrient. The diminishing response to applied nutrients, coupled with decreasing levels of soil organic carbon (SOC) and overall soil quality, underscores the urgent need for Best Management Practices (BMPs) to enhance productivity factors and sustain soil health over the long term for future generations [25]. Recent research conducted across various Asian countries, including Northwest India, highlighted shortcomings in the conventional practice of applying fertilizers at fixed rates and times across large agricultural areas [26]. This approach has been found to contribute to poor Nutrient Use Efficiency (NUE), as nitrogen, phosphorus, and potassium fertilizers are often applied without considering crop-specific requirements and other essential nutrients. Consequently, this imbalance leads to suboptimal profitability in farming practices [27].

Recently, Site-Specific Nutrient Management (SSNM) has gained favor over blanket Recommended Management Practices (RMPs) due to its ability to adapt to site-specific conditions, seasonal variations, and crop growth dynamics, thus promoting sustainable soil management. SSNM aims to optimize nutrient utilization from various sources including soil, irrigation water, biological nitrogen fixation, organic matter, and fertilizers, enabling farmers to apply nutrients precisely when crops require them the most. This tailored approach aligns nutrient applications with crop needs, reducing the risk of excessive fertilizer use. Furthermore, SSNM emphasizes balanced nutrient application to sustain long-term soil productivity and quality, as highlighted by Singh in [28,29]. Site-Specific Nutrient Management (SSNM) represents an advanced approach leveraging geo-informatics technologies such as remote sensing (RS), global positioning systems (GPS), geographic information systems (GIS), and sensors. This stands in contrast to Recommended Management Practices (RMPs), which are applied uniformly across large areas regardless of soil types, crops, or cropping sequences. SSNM incorporates spatial variations in soil nutrient levels, ensuring precise application of inputs to avoid both excessive and insufficient use of costly resources. Furthermore, SSNM adopts a systems approach, facilitated by Decision Support Systems (DSS) equipped with sophisticated analytical frameworks, databases, and simulation models, which continually enhance its effectiveness and adaptability. The foundation of Site-Specific Nutrient Management (SSNM) hinges on the utilization of GPS and GIS technologies to map soil properties, particularly soil nutrients. This process enables the assessment of soil fertility dynamics across various crop types and cropping sequences within diverse agricultural environments. It facilitates continuous monitoring and updating of databases to maintain accuracy. Activities include geo-referenced soil sampling, laboratory analysis to generate reliable data, and structuring databases within GIS or Decision Support Systems (DSS) environments. Site-specific nutrient management (SSNM) plays a critical role in managing and improving soil health through targeted and precise application of nutrients. By utilizing technologies such as GPS and GIS for soil mapping and nutrient analysis, SSNM ensures that fertilizers are applied according to the specific requirements of different soil types, crop varieties, and cropping sequences. This approach minimizes the risk of over-application, which can lead to nutrient imbalances and soil degradation, while also preventing under-application that could limit crop productivity. SSNM promotes balanced fertilization practices that support optimal nutrient levels in the soil, enhancing its fertility and overall health. Moreover, by minimizing nutrient losses through strategic timing of fertilizer applications and appropriate management practices, SSNM helps preserve soil structure, reduce erosion, and maintain water quality. By supporting the accumulation of soil organic matter through practices like crop residue incorporation and conservation tillage, SSNM further contributes to soil health by improving soil structure, water retention, and nutrient cycling. Ultimately, SSNM promotes sustainable agricultural practices that safeguard soil health and productivity, ensuring the long-term viability of agricultural lands amidst evolving environmental challenges.

9. POLICY ASSOCIATED WITH SSNM

National policies play a crucial role in facilitating practices like Site-Specific Nutrient Management (SSNM) and other soil fertility approaches because the economic viability of these practices is largely determined by fertilizer and crop prices. Many countries utilize fertilizer subsidies to enhance accessibility for farmers, which can help alleviate poverty and increase crop productivity among resource-poor farmers. For instance, Malawi's implementation of vouchers for fertilizer and maize seeds in 2005 drew international attention by significantly boosting national food production and security [30]. However, fertilizer subsidies can also lead to unintended consequences. In China, prolonged periods of artificially low fertilizer prices have resulted in excessive fertilizer use (approximately 550 kg per hectare compared to 100 kg per hectare globally) and subsequent nutrient pollution [31]. Reducing subsidies can incentivize farmers to use fertilizers more efficiently, thereby increasing the demand for SSNM. In China, proposed limits on fertilizer usage have encouraged research and innovation in this area.

While Malawi is less likely to face issues of fertilizer overuse, recommendations for enhancing their program include promoting proper timing, placement, and formulation of fertilizers. Integrating organic inputs like legume seeds into subsidized packages for green manure could further improve soil fertility management (see Integrated Soil Fertility Management practice brief). Linking the adoption of best practices with access to subsidized inputs is also a promising approach [30]. Furthermore, collaboration with fertilizer producers and suppliers is crucial for effective fertilizer use and the development of suitable products such as slow-release and well-balanced NPK fertilizers, as well as large granules for deep placement. Some manufacturers are actively promoting efficient fertilizer use in response to public pressure and environmental concerns. Input suppliers serve as vital channels for disseminating information to farmers, often replacing traditional agricultural extension services in many countries.

9.1 Soil Health Management (SHM) Under National Mission for Sustainable Agriculture (NMSA) in India

The National Mission for Sustainable Agriculture (NMSA) operates under the Sustainable Agriculture Mission, a pivotal component of the National Action Plan on Climate Change (NAPCC). It aims to enhance agricultural sustainability through targeted adaptation measures across ten critical dimensions in Indian agriculture. These include advancing crop seeds, livestock, and fish cultivation; improving water use efficiency; managing pests effectively; adopting better farming practices; managing nutrients wisely; implementing agricultural insurance and credit support; enhancing market access; providing vital information; and diversifying livelihoods. The mission's strategies focus on promoting integrated farming systems tailored to specific locations, conserving natural resources through soil and moisture conservation, and practicing comprehensive soil health management. It emphasizes optimizing water use efficiency to achieve higher crop yields per unit of water, improving agronomic practices for increased productivity and soil health, and utilizing technology like GIS for soil analysis to guide crop management decisions with precision agricultural practices. Furthermore, the mission advocates for integrated nutrient management suited to diverse agro-climatic conditions, engaging knowledge institutions to develop climate-resilient strategies for agriculture.

10. CONCLUSION

In conclusion, Site-Specific Nutrient Management (SSNM) stands as a pivotal approach in modern agriculture, leveraging technological advancements to optimize nutrient application according to specific soil conditions, crop requirements, and environmental factors. By promoting precision in fertilizer use, SSNM not only enhances crop productivity but also contributes to sustainable soil health and environmental stewardship. This tailored approach ensures efficient resource utilization, minimizes nutrient losses, and fosters resilient agricultural systems capable of adapting to diverse climatic challenges. As agriculture continues to evolve, SSNM remains integral to maximizing yields while preserving the long-term viability and productivity of agricultural lands for future generations.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/120058