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Review Article

Enhancing Nutrient Use Efficiency and Productivity of Cereals through Site Specific Nutrient Management

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Abstract

The Green revolution era has been the golden period for boosting food production specifically in South-Asia, but the signs of fatigue in the late 1980s with a sharp decline in factor productivity, stagnation in crop yields with dwindling and marginal farm incomes pose a serious threat to food security, agricultural sustainability, soil and environmental health. In a nutshell, growing concerns related to the decline in soil health, productivity and nutrient-use efficiency (NUE) are compelling farmers to use higher amounts of chemical fertilizers during the last two decades. The low NUE and associated environmental pollution as well as global warming problems have increased serious apprehension about the existing nutrient management practices. As such, it is high time to develop site-specific nutrient management (SSNM) technologies that are able to balance crop and soil nutrient dynamics. The SSNM is need-based feeding of crops with nutrients while acknowledging the inherent spatial variability, which enhances crop productivity, profitability, NUE and avoids nutrient loss. For efficient and effective SSNM, the use of soil and plant nutrient status sensing devices, decision support systems, simulation models, and machines for varying applications of nutrients plays a major role. This paper deals with the SSNM technologies and tools that have the potential to enhance NUE, crop productivity, profitability as well as sustainability.

Keywords: Nutrient use efficiency, productivity, SSNM, sustainability

1. Introduction

World-wide use of various fertilizers has made a remarkable contribution to increasing food production. It has been observed that nutrient inputs are responsible for 30–50% of crop yield (Meena *et al.*, 2020). The recovery efficiency (RE) of Nitrogen, Phosphorus and Potassium fertilizer is about 20–40, 15–20 and 40–50%, for respectively, while for secondary and micronutrients it is considerably lower ranging from 5–12% (Mandal *et al.*, 2022). The important causes of low and declining crop responses to fertilizer nutrients include continuous nutrient mining from the soil due to imbalanced fertilizer use (7:2.8:1::NPK), leading to depletion of some of the major, secondary as well as micro nutrients like N, K, S, Zn, Mn, Fe, B etc (Kadyampakeni and Chinyukwi, 2021; Nadeem and Farooq, 2019). The reduction in use of organic nutrient sources such as FYM, compost and integration of green manures/grain legumes in the cropping systems has led to soil degradation. After several years of intensive research on nutrient management,field-specific fertilizer recommendations have been developed for almost all cultivated crops (Chivenge *et al.*, 2022). The recommendations developed tell us about the amounts of different nutrients needed on a hectare basis and their time of application. Such blanket recommendations, which largely did not take into account the variability in the inherent soil fertility and other edaphic characteristics, resulted in over-application of nutrients in some areas and under-application in others (Seth *et al.*, 2020). This resulted in wastage of nutrients and low NUE. Research conducted in many Asian countries, including North-west India, has depicted the limitations of the conventional approach of fixed-rate, fixed-time (blanket) fertilizer recommendations (Singh *et al.*, 2020). However, recognizing the defect in the blanket recommendations of nutrients, the concept of SSNM of nutrients was developed. The original concept of SSNM to manage farm nutrient variability was first developed in Asia for rice (Arouna *et al.*, 2021).

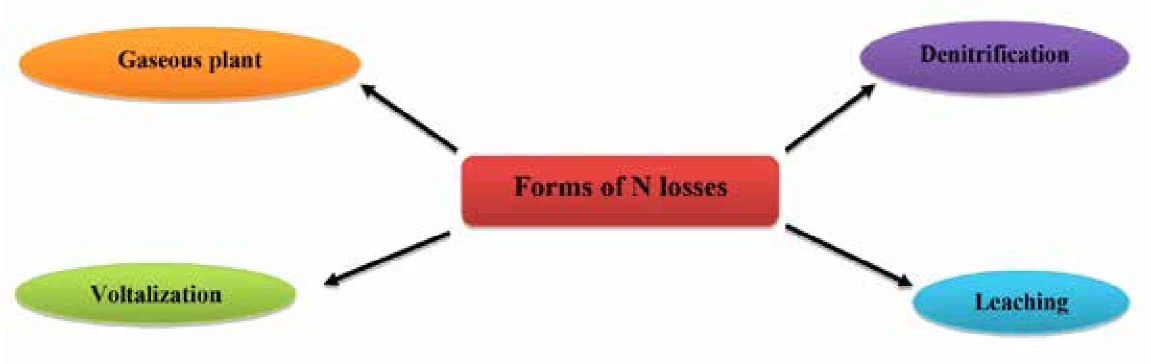

Fig 1: Different forms of nitrogen losses

2. Site-specific nutrient management (SSNM)

Many of the nutrients required by crops come from the soil. But the supply of nutrients is usually insufficient to meet the nutrient requirements for achieving high crop yields. The use of fertilizers is therefore, essential to fill the above gap between the crop nutrient needs and the supply of nutrients from soil and available organic inputs (Vanlauwe and Dobermann, 2020). The SSNM helps in enhancing nutrient use efficiency as it provides an approach for feeding crops like rice, maize, wheat, etc. with nutrients as and when needed. The major advantage for farmers from an improved nutrient management strategy is an increase in the profitability. The SSNM avoid the wastage of fertilizers by preventing excessive rates of fertilization and by eliminating fertilizer application when the crop does not require nutrient inputs (Majumdar *et al.*, 2012). It also ensures that N, P, and K are applied in the ratio required by the crop, optimal use of existing indigenous nutrient sources such as crop residues and measures and application of N, P and K fertilizers is adjusted to the location and season specific needs of the crop. The SSNM approach, which aims to synchronize

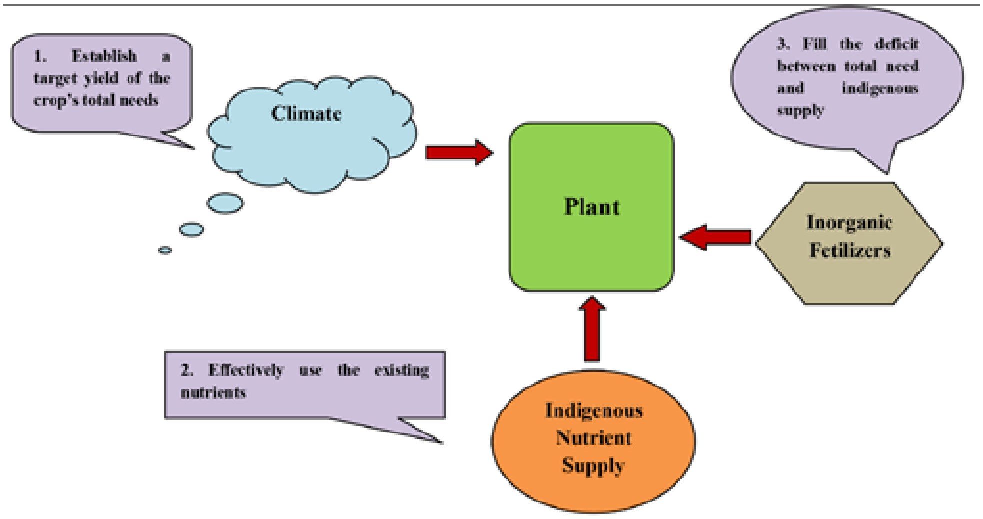

Fig 2: Characteristics of SSNM

nutrient supply and demand in accordance with variations in crop requirements, indigenous nutrient supply and nutrient recovery from fertilizer and other sources is a dynamic, plant-based, field- and season-specific approach to nutrient management. With SSNM, the amount of fertilizer needed for a particular field is determined by subtracting the indigenous nutrient supply, which represents the amount of a specific nutrient (N, P, or K) available from the soil, crop residues, irrigation water, or biological nitrogen fixation during a growing cycle of crop, from the total amount of nutrients needed by the crop to achieve a given target yield (Figure 2). Leaf color chart (LCC) ensures that nitrogen is applied at the right time and in the amount needed by the crop in order to prevent nutrient losses. Nitrogen omission plots to determine the amount of P and K fertilizers needed to meet the crop needs. This ensures that P and K are applied in the ratio required by the crop. Local randomization for application of Zn, S and micronutrients and integration with other integrated crop management (ICM) practices such as the use of quality seeds, optimum plant density, integrated pest management and good water management (Kumar *et al.,* 2019; Saito *et al.*, 2019). On the other hand,the use of technologies like Nutrient Expert (NE), Green Seeker are some of the important features of SSNM.

3. The 4Rs of fertilizer management in SSNM

In SSNM, supplying required nutrients for crop production includes attention to four major fertilization factors (better known as the 4Rs) that are right source, right rate, right place and right timing. Consideration of these factors will provide adequate nutrition for crop production while reducing the risk of loss of nutrients to the environment (Niag *et al.*, 2017). These are important components of nutrient best management practices. Moreover, the four 'rights' offer a simple checklist to evaluate whether aspecific crop has been fertilized properly (Figure 3).

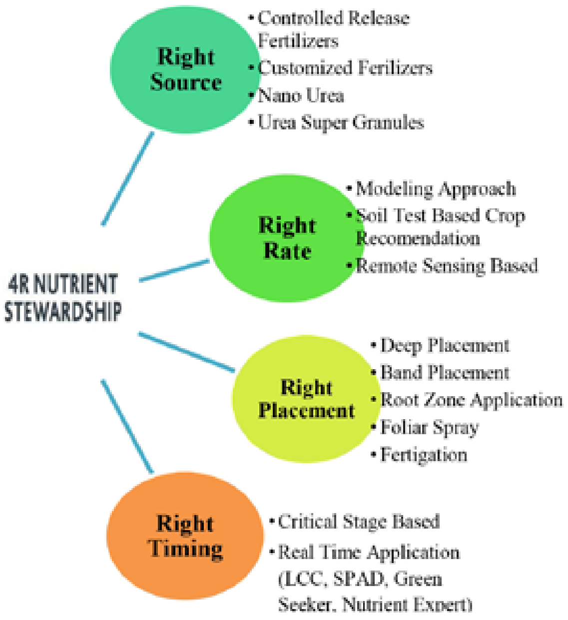

Fig 3: Framework of 4R Nutrient Stewardship

3.1 Right source

The application of fertilizer from the correct or right sources is crucial for achieving an optimum yield. The correct source can be decided based on the cost of source of nutrient(s), organic source of nutrient, type of fertilizer to be used and right source of controlled-release fertilizer. The right source regularly includes the simplicity of use of a supplement and the cost for every unit of addition (Asai *et al.*, 2021). Nitrification and urease inhibitors are examples of Enhanced Efficiency Compounds (EECs) that can delay nitrogen transformations and lower the possibility for soil nitrogen loss (Yang *et al.*, 2016). For example, a controlled-discharge nitrogen source might be preferred to provide limited quantities of supplements throughout the developing season, rather than large quantities of nitrogen conveyed in a couple of side-dressings from a solvent source.

3.2 Right rate

It might be difficult and elusive to calculate the ideal nutrient application rate for a specific production location (field, zone, etc.) at the optimum time to achieve the desired yield (Shivay *et al.*, 2016). Optimal nutrient rates depend on a variety of controlling parameters, including soil texture, weather, N mineralization rates, past and present nutrient losses, organic inputs and yield potential, and they differ from field to field and season to season (Verma *et al.*, 2020). It refers to the amount of fertilizer required for a crop season and is based on extensive research across locations, crops, varieties and years. It also refers to 'how much' i.e.the quantity of fertilizer applied at one time in the growing season. At times, the right rate to apply at any one time is related to the nutrient involved. For example, in plasticulture vegetables, all of the phosphorus may be applied to the soil during the bed preparation. Similarly, a portion of the nitrogen and potassium may be applied during the preparation of the bed and the remaining amount may be applied through the drip irrigation system. However, the proper nutrient rate cannot be separated from judgments on the other 3Rs since they have an impact on the dynamic transformations and losses. The amount of nutrient applied is intimately related to the timing of applications as well as the form and placement of the N applied (Singh, 2017).

3.3 Right placement

For maximum nutrient efficiency, nutrients need to be placed where there is maximum availability of them (Ibrahim *et al.*, 2021). For optimum yield, the right position is in the root zone or only in front of the propelling root structure. Most of the addition takeup happens through the root framework, so putting the supplements in the root zone increases the chance of assimilation by the plant. Band placement and broadcasting are two common ways to deal with supplement positions (Das and Dash, 2019). The decision regarding whether to utilize band placement or broadcasting depends upon the kind of harvest and the spread of the root framework. The right placement can also be related to the form of the nutrient source like urea nitrogen. Nitrogen from urea may be subjected to loss by volatilization when the urea is applied to the surface of soil with a high pH. Incorporating the urea or applying a small amount of irrigation to move the urea into the soil helps in reducing volatilization losses (Patra *et al.*, 2016).

3.4 Right timing

In general, it is difficult for farmers to comprehend the field and climate circumstances that are advantageous for adjusting the timing of nutrient application in the context of logistical and financial considerations. The right time of supplements is decided on the basis of the development yield and regular changes in nutrient requirements during the season (Chen *et al.*, 2021). Timing should be taken into account in relation to rainfall or soil moisture, as dissolved N loss from tile drainage was higher in wetter conditions than it was in drier ones (Christianson and Harmel, 2015). The right planning is interrelated with the right rate as well as position. Major portions of nutrient are applied at or just before when the vegetative development rate is maximal and natural products are being created (Westerschulte *et al.*, 2017). In a multiyear simulation research with 19 locations in the Midwest, split applications that apply the majority of the nitrogen during the growing season needed, on average, 50% and 40% less nitrogen than fall and spring preplant N applications, respectively (McLellan *et al.*, 2018).

4. Principles of SSNM

4.1 Estimation of Indigenous Nutrient Supplies

Indigenous nutrient supply (INS) can be defined as the total amount of a particular nutrient that is available to the crop from the soil throughout the cropping cycle, when other nutrients are non-limiting. The INS is derived from soil incorporated crop residues, water and atmospheric deposition (Zhang *et al.*, 2000). It is estimated by measuring plant nutrient uptake in an omission plot embedded in the farmers' field, where all other nutrients except the one (N, P or K) in question are applied in sufficient amounts.

4.2 Computation of Fertilizer Nutrient Rates

Field-specific fertilizer N, P or K recommendations are calculated on the basis of the above steps and the probable fertilizer recovery efficiency (Kg of fertilizer nutrient taken up by the crop per Kg of the applied nutrient). Studies showed RE values of 40–60% for N, 20–30% for P and 40–50% for K in rice under normal growing conditions, when the nutrients are applied as water- soluble fertilizer sources (Xiang *et al.*, 2008).

4.3 Dynamic Adjustment of N Rates

The basal applications of P and K fertilizer are done at rates as estimated above. Nitrogen application rates and schedules can be further adjusted as per the crop demand using a chlorophyll meter, which is widely known as SPAD or LCC. Recent on-farm studies in India and elsewhere have reported a significant advantage of SPAD or LCC-based N management schedules in rice and wheat in terms of yield grain, N use efficiency and economic returns as compared to the conventionally recommended N application involving 2 or 3 splits during crop growth irrespective of the N supplying capacity of the soils (Pooniya *et al.*, 2015). The highest grain yield (4483 kg ha^{-1}) was obtained when maintaining a SPAD threshold of 40 up to heading stage by topdressing 25 kg N/ha at each time and boosted agronomic N use efficiency by 58.5%, nitrogen RE by 15.1%, and partial factor productivity of applied N by 26.4% compared to traditional fertilizer recommendations (Ghosh *et al.*, 2017).In wheat, timing of N application at SPAD value ≤42 resulted in a 9% higher wheat yield along with a 20 kg/ha N saving, than the recommended soil-based N supply (Shukla *et al.*, 2004).

5. Approaches of Implementation of SSNM

5.1 Plant Analysis Based SSNM

It is considered that the nutrient status of the crop is the best indicator of soil nutrients available as well as the nutrient demand of the crop. Hence, the approach is made around plant analysis. Primarily, SSNM was tried for lowland rice, but then it proved advantageous to various other existing approaches for fertilizer recommendations in rice, wheat and other rice-based production cropping systems prevalent in Asian countries. Witt and Dobermann (2002) suggested five key steps for developing field-specific fertilizer NPK recommendations for rice, though the fundamental principles remain the same for other crops as well.

5.2 Chlorophyll meter

Chlorophyll meter measures the relative difference in crop N status and can detect the onset of an N stress before it is visible to the human eye (Das *et al.*, 2014). Handheld chlorophyll meters provide a fast, easy, on-site and precise way to measure the relative quantity of chlorophyll in rice leaves, better known as SPAD (soil plant analysis development) meter. Research focused on enhancing N use efficiency using SPAD meter can be divided into two broad groups. The first approach is the relationships between SPAD readings and the N content of leaves. In rice, the relationship between SPAD meter reading and N content in leaves has been observed to be non-linear (Esfahani *et al.*, 2008) and suggested adjustment of SPAD readings for specific leaf weight to enhance the prediction of leaf N concentration in rice. Maiti *et al.*(2004) observed a linear correlation between SPAD values and rice leaf nitrogen concentration measured on leaf area basis for entire growth stages and lines tested. The second approach is determining the relationship between SPAD readings and the need for top dress N (Khurana *et al.*, 2005; Singh and Ali; 2020). Two approaches have been used to guide fertilizer N applications to rice:

a) When SPAD value is lower than a predetermined critical reading (Singh *et al.*, 2002; Sarker*et al.*, 2022).

b) In rice, when a sufficiency index that is SPAD value of the plot in question divided by that of a well-fertilized reference plot or strip falls below 0.90 (Hussain *et al.*, 2000).

Chlorophyll-meter based N application (30 Kg basal + 30 Kg N/ha at SPAD value 37.5) saved 30 Kg N/ha and increased rainy season maize grain yield by 10% as compared to soil test-based N application in Semiarid north plain zone of India (Shukla *et al.*, 2004). Moreover, Ghosh *et al.* (2020) found that N topdressing with 25 kg N/ha at SPAD 40 produced higher grain yield (4.48 t/ha) in wheat as compared to the existing fertilizer N recommendation and estimated the optimal SPAD threshold for wheat as 41.8. In spite of, the greater dependence of the sufficiency index or dynamic threshold value approach, the fixed threshold value approach is more practical as it does not need a well-fertilized or N-rich plot.

5.3 Leaf color chart (LCC)

LCC is a high-quality plastic strip on which a series of panels are fixed with colours based on the wavelength characteristics of leaves. The colour ranges from yellowish green to dark green and covers a continuum from leaf N deficiency to excessive leaf N content (Pasuquin *et al.*, 2004). These are simple, easy-to-use and inexpensive alternatives to chlorophyll meters and are visible and subjective measures or indicators of N deficiency. It measures leaf greenness and the related leaf N by visually comparing light reflection from the surface of leaves and with the LCC (Yang *et al.*, 2003). There are two important approaches tothe use of LCC (Witt *et al.*, 2007; Singh *et al.*, 2010). The fixed splitting pattern approach provides a recommendation for the total N fertilizer requirement and a plan for the splitting and timing of applications according to the crop growth stage, cropping season, variety used and crop establishment method. The LCC is used at critical growth stages to choose whether the recommended standard N rate needs to be adjusted up or down depending on leaf colour (Singh *et al.*, 2012). In rice, $LCC < 4$ with 25 kg N/ha in split can save 14.3% nitrogen (Kumari *et al.*, 2022) whereas Ram *et al.* (2022) found that $LCC \geq 4$ saved 15 kg N/ha with a yield penalty of 3.2% as compared to 150 kg N/ha in wheat. In the real-time approach, a recommended amount of fertilizer N is applied whenever the colour of rice leaves falls below a critical LCC value. Local procedures on the LCC's use have now been developed for the major irrigated rice areas. LCC readings are taken at active tillering and panicle initiation and urea is applied accordingly. It may be concluded that if LCC value is more and yield target is also more, than urea requirement is less, as more value of LCC shows more greenness of rice leaf. In the case of wheat, LCC guided N application with zero tillage and residue application recorded a better grain yield (5.39 t/ha) with a B:C ratio of 2.20 (Sudarshan *et al.*, 2022).

5.4 Optical sensors

Chlorophyll meter and LCC do not take into account the photosynthetic rates or biomass production and the expected yields for estimating fertilizer N requirements. Optical sensors measure visible and near-infrared (NIR) spectral responses from plant canopies to detect N stress (Xiang *et al.*, 2008). Chlorophyll contained in the palisade layer of the leaf controls much of the visible light (400-720 nm) reflectance as it absorbs 60% of the entire incident light in the red wavelength bands (Singh and Ali, 2020). Spectral vegetation indices, such as the normalized-difference vegetation index (NDVI) which can be defined as: $(F_{NIR} - F_{Red})/(F_{NIR} + F_{Red)}$, where F_{NIR} and F_{Red} arethe fractions of emitted NIR and red radiation reflected back from the sensed area, respectively. It has proved helpful for indirectly obtaining information such as photosynthetic efficiency, productivity potential and potential yield and has been found sensitive to leaf area index, green biomass and photosynthetic efficiency (Shyam *et al.*, 2021). Based on target yield and split fertilization approach, Xue *et al.* (2014)used Green seeker optical sensor for top dressing of nitrogen at panicle initiation stage of rice. Recently, Singh *et al.* (2015)found that high yields along with high N use efficiency in transplanted rice can be obtained by applying a moderate amount of fertilizer N at transplanting and enough fertilizer N to meet the high N demand during the period between active tillering and panicle initiation before application of an optical sensor-guided fertilizer N dose at the panicle initiation stage of rice.

5.5 Soil-cum-Plant Analysis Based SSNM

In this case, nutrient availability in the soil, plant nutrient demands for a higher target yield that is not less than 80% of $Y_{max,}$ and RE of applied nutrients are considered for developing a fertilizer use schedule to obtain the maximum economic yield of a crop variety. In order to determine desired crop growth, not limited by apparent or hidden hunger of nutrients, soil is analyzed for all macro and micronutrients well before sowing or planting. Total nutrient requirement for the targeted yield and RE are estimated with the use of information available for similar crop growing environments. Field-specific fertilizer rates are then recommended to meet the nutrient demand of the crop,excluding depletion of soil reserves. These soil–test crop response-based recommendations(STCR) are now in practice to achieve desired yield targets in many field crops (Pasuquin *et al.*, 2004). Moharana *et al.* (2017) revealed that higher values of accessible zinc (1.54 mg kg^{-1}) and iron (5.68 mg kg^{-1}) were sustained after integrating FYM and NPK fertilizer using an STCR-based targeted yield method in pearl millet-wheat cropping system for six years. Hence, recent studies with intensive cropping systems have shown that fertilizer recommendations with the above approach offer greater economic gains in comparison to NPK fertilizer schedules, which are traditionally prescribed by soil testing laboratories (Singh *et al.*, 2012).According to Singh *et al.* (2021), the highest economic efficiency was recorded with STCR with target yield level of 5.0 Mg ha^{-1}(₹ 285 ha^{-1} d^{-1}) and in case of direct seeded rice, it was enhanced by ₹ 91 ha^{-1} $d^{-1}$to INR 143 $ha^{-1}d^{-1}$due to the STCR-target yield based nutrient recommendation as compared to general recommended fertilizer dose. Moreover, the wheat growth indices, including plant height (104 cm), dry-matter accumulation (803 g m^{-2}), LAI (5.66), and tillers per m^2 (479) were significantly higher by STCR-based nutrient management among various precision nitrogen management approaches. Additionally, it produced higher grain yield than SPAD and control by 13.86 and 33.83% respectively (Mohanty *et al.*, 2015).

5.6 Nutrient Expert

Nutrient Expert (NE) is an easy-to-use, interactive, and computer-based decision support tool that can quickly provide nutrient recommendations for aspecific farmer's field in the presence or absence of soil testing data. NE is a nutrient decision support software that uses the principles of SSNM and allows farm advisors to develop fertilizer recommendations adapted to a specific field or growing environment. NE allows users to draw needed information from their own experience, farmers' knowledge of the local region and farmers' practices (Pooniya *et al.*, 2015; Timsina *et al.*, 2021). NE can use experimental data, but it can also calculate the required SSNM parameters using existing site information. The algorithm for estimating fertilizer requirements in NE is determined from a set of on-farm trial data using the SSNM procedure. The parameters needed in SSNM are generally measured in nutrient omission trials conducted in farmers' fields, which need at least one crop season (Dass *et al.*, 2014). NE being statistically at par with green seeker (GS) recorded a significantly higher straw and grain yield than other treatments while a yield enhancement of 19.2% and 14.7% above farmers' practice-based N management (FP) (Mohanta *et al.*, 2021). In comparison to FP; NE, GS, LCC, and state recommendation all were produced more straw with respective increases in yield of 19.19%, 14.94%, 10.40%, and 6.08% (Figure 4).

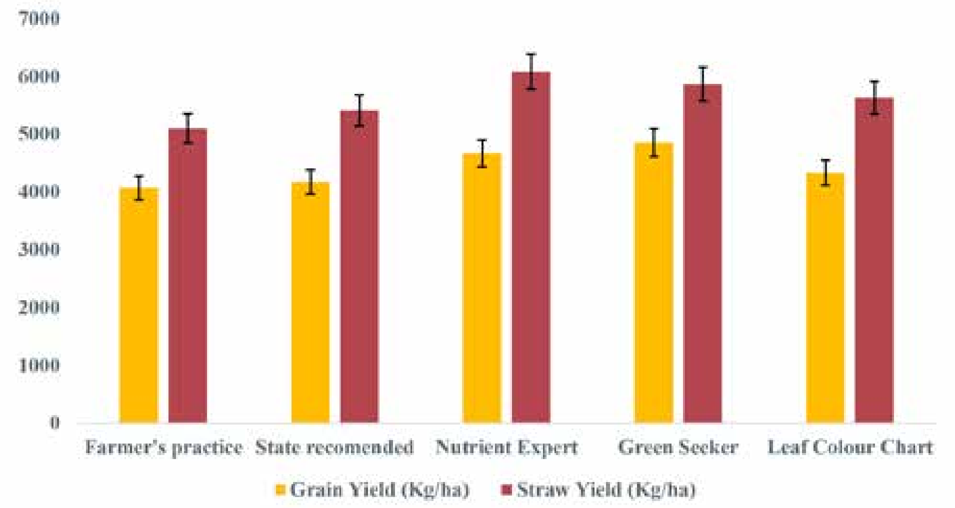

Fig. 4: Influence of nitrogen management on the yield of rice variety "Pratikhya" (Mohanta *et al.,* 2021)

NE assesses the attainable yield and yield response to fertilizer from site information decision rules developed from on-farm trials. Specifically, NE uses distinctiveness of the growing environment such as water availability (irrigated, fully rainfed and rainfed with supplemental irrigation) and any occurrence of flooding or drought; soil fertility indicators- soil texture, soil color and organic matter content, soil test for P or K (if available), historical use of organic materials (if any) and problem soils (if any); crop sequence in farmer's cropping pattern; crop residue management and fertilizer inputs for the previous crop; and farmers' current yields (Pampolino *et al.*, 2012). Data for specific crops and specific geographic regions are needed in developing the decision rules for NE. The datasets must represent diverse conditions in the growing environment, characterized by variations in the amount and distribution of rainfall, crop cultivars and growth durations, soils and cropping systems. Current versions of Nutrient Expert® NE has been developed for specific crops and geographic regions. Nutrient Expert® for Hybrid Maize (NEHM) for favourable tropical environments (e.g., South-East Asia) was developed in late 2009 and underwent field evaluation in Indonesia and the Philippines. Using NEHM as a model, the NE concept has been adapted to other crops in different countries. Sapkota *et al.* (2021) that Nutrient expert-based recommendations reduced N input by 15–35%, increased grain yield by 4–8%, and reduced global warming potential by 2–20%.

5.7 Customized fertilizer

Customized fertilizer is more than simply a fertilizer. It may also be defined as a multi-nutrient carrier enriched with both macro and micro nutrients and manufactured through a systemic process of granulation with stringent quality checks. The idea behind customized fertilizer is to provide site-specific nutrient management for attaining maximum fertilizer use efficiency for the applied nutrient in a cost-effective manner (Choudhary *et al.*, 2020). A fertilizer is formulated according to specifications that are furnished by or for a consumer prior to mixing, usually on the basis of soil tests. Customized fertilizer manufacture basically involves mixing and crushing of urea, DAP, MOP, ZnS, bentonite sulphur and boron granules to obtain the desired proportion of N, P, K, S and micronutrients. The mixture is exposed to steam injection, drying, sieving and cooling, so as to get a uniform product with every grain having an equal nutrient composition. The sharp rise in fertilizer prices indicates the need for more research to improve the efficiency of fertilizer use. The treatment with 100% RDF along with S, Zn and B had the highest grain production (4.92 t ha^{-1}) and straw yield (6.60 t ha^{-1}) compared to all other treatments (Figure 5). It was 64% higher over the control, followed by a treated plot with customized fertilizer (10:26:17:1.0:0.3) [N: P_2O_5: K_2O: S: Zn] by 49%. Moreover, rice grain yield increased by 41.3%, 46%, and 47.6% over control after applying 25% N through sewage sludge, vermicompost and Sesbania respectively (Kumar *et al.*, 2021).

Crops need almost 17 essential nutrients for normal growth and development, and if the crop is grown continuously for several years on the same piece of land, some of those nutrients will be slowly exhausted from the soil system to a level that can't support crops to give good yields. Hence, crop fertilization becomes more important in order to maintain soil fertility and nutrient supplying capacity (Parvathi *et al.*, 2018). Application of nutrients in the form of fertilizers in right quantities, in the right form, at the right time and right place is one of the good management practices in modern agriculture. As compared to farmer's practice, SSNM in transplanted rice in 40 farms at the old and new Cauvery Deltas of Tamil Nadu, India increased fertilizer N (12–36%), P (8–13%) and K (>100%) use-efficiencies (Yi *et al.*, 2018). Farmers face problems regarding the application of the right dose of required nutrients in the right fertilizer form needed for the crop at the right time and place. In this process, farmers lose precious time and money during the season in search of fertilizers to match the crop's requirements. Sometimes, they apply fertilizers in imbalanced proportions of one or more nutrients and unreasonably spend money on additional doses of nutrients that are not needed and spend less on those fertilizers that are require most.

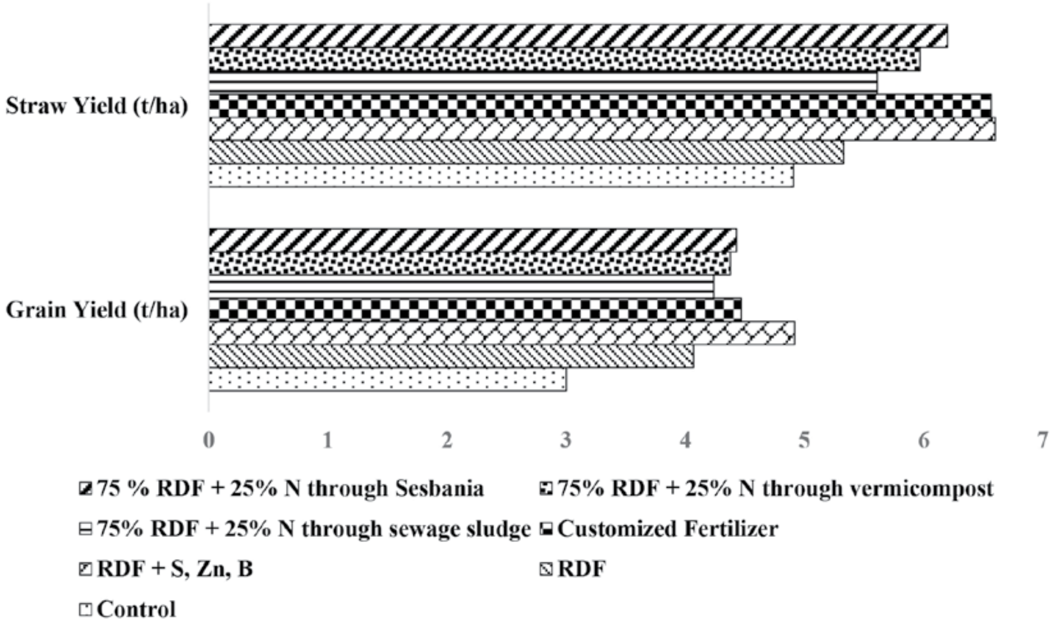

Fig. 5: Effect of organic and inorganic nutrient sources on the grain and straw yield of rice (Kumar *et al.,* 2021)

5.8 Nanofertilizers

Nanofertilizers are nutrient fertilizers composed, in whole or part, of nanostructured 83 formulations that can be delivered to the plants, allowing efficient uptake or slow release of ingredients. Conventional bulk fertilizers have low plant uptake efficiencies, and thus larger amounts are required to be applied. Two major challenges of the low nutrient uptake efficiency for nitrogen and phosphorus-based fertilizers are the rapid changes into chemical forms that the plants do not take up, and runoff, leaching, or atmospheric losses. The resultant effects are emission of harmful greenhouse gases such as certain oxides of nitrogen, and eutrophication, with negative outcomes for soil and environmental health (Dimkpa *et al.*, 2017). Therefore, it is important to develop smart fertilizers that are more readily uptake by the plants. As a result, scientists are working hard to develop a variety of metal and metal oxide nanoparticles for use in plant science and agriculture. Since nanoscale particles are smaller in dimension as compared to bulk particles, the plants can absorb them with various dynamics than bulk particles or ionic salts, which presents an added advantage (Subbaiah *et al.*, 2016). Kumar *et al.* (2020) reported that the highest grain yield of wheat was 4.8 t/ha with an additional increase of 425 ha^{-1} over FFP, giving a 9.76% increase was found under treatment 50% N-FFP with 2 sprays of nano-urea at active tillering and panicle initiation stage. Azan *et al.* (2022) found that foliar application of nanofertilizers with different concentrations increased the plant growth, photosynthetic pigments and antioxidant activity by 59.28, 48.19% and 52.91%, respectively, in maize. Although, environmental health and safety aspects of nanotechnology should also be considered, and it is important to determine the toxicity and biocompatibility of nanofertilizers (Babu *et al.*, 2022).

5.9 Crop simulation models and various decision support systems

To maintain sustainable crop output and to reduce environmental risk, crop simulation models are crucial for maximization of fertilizer use in agriculture. The EPIC models (Sharpley and Williams, 1990) and the DSSAT models are the most well-known individual nutrient response models that encompass a variety of crops (Jones *et al.*, 2003). With a single set of algorithms and different parameter settings for every crop, EPIC can simulate more than 20 different crops. On the other hand, the DSSAT group of models concentrated more on the physiological growth of crops, specifically addressing prospective yields and their reliance on the environment. They encompass more than 16 distinct crops in total, and the majority have been successfully tested in various climate zones (Huffman *et al.*, 2001). Among these models, CERES is mainly used for cereals (Kosamkar, 2019).

The Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model presupposes that fertilizer and soil availability of N, P, and K determine production. A distinction is made in the model between a nutrient's potential supply (the greatest amount that may be provided from soil and fertilizer) and its actual uptake by the crop. The relationship between nutrient absorption and yield is the core of QUEFTS. The computed NPK ratio for producing 1 tonne of grain yield wheat was 4.9:1:8.9. (Maiti *et al.*, 2006). Amaize-N and NuDSS used for forecasting crop yield and site-specific N fertilizer requirements for maize and rice crops respectively (Raja and Balachandra, 2021).

5.10 Advanced technologies of SSNM

The approach of remote sensing based SSNM entails collection and analysis of information for better decision making in order to increase agricultural productivity and product quality. Soil fertility may be predicted using machine learning techniques. Five nutrient components–N, P, K, organic carbon (OC) and B are used to determine the fertility of the soil. The extreme learning machine (ELM) method is used to forecast the quantities of these five nutrients (Suchithra and Pai, 2020). PLS, ANN, and LS-SVM are three techniques that have been used to non-destructively assess the N status in rice utilizing visible and near-infrared reflectance spectroscopy (Shao *et al.*, 2012). As a result of the comparative analysis, it was determined that LS-SVM is a promising substitute for regression analysis in order to quantify the N status in rice.

The vegetation index parameter is used to quantify the crop monitoring application in drone-based monitoring of agricultural fields. The most commonly used vegetation index is the Normalized Difference Vegetation Index (NDVI) (Zhang *et al.*, 2014). It is possible to determine the photosynthetic activity of the plants using the 3D imagery NDVI map, which reveals the location with high cation exchange capacity (CEC). CEC is a tool for measuring soil fertility since it shows how well the soil can hold the nutrients. A drone can spray the exact amount of fertilizer evenly on the desired place in real time by dynamically altering the altitude of flight (Nevavuori *et al.*, 2019) which results in lower labour, chemical cost and time frame.

Conclusion

The declining factor productivity and nutrient use efficiency has resulted in overuse of fertilizers by farmers, which has led to a harmful effect on the chemical and biological properties of soil,and groundwater contamination and environmental pollution as well. These led to compel us to think a new approaches for efficient application of nutrients in agriculture, such as SSNM. The concept of SSNM is fundamental to precision nutrient applications in different crops. SSNM provides an approach for need-based feeding of crops with nutrients while recognizing the inherent spatial variability. This allows the effective utilization of nutrients by crop plants and avoids the wastage of fertilizers. A number of tools such as chlorophyll meter or SPAD meter, LCC, green seeker, nutrient expert etc. are used for application of need based fertilizer doses. SSNM increases the partial factor productivity of nitrogen and decreases the proportion of nitrogen losses from applied fertilizers and thereby increased the NUE. However, increased net benefits are associated with SSNM as it increases the yield while decreasing the cost of cultivation. There is still scope for working on nutrient dynamics, soil organic matter, soil physical and biological activities for the development of more suitable methods for fertilizer recommendations.

Author contributions

All the authors contributed to the article and approved the submitted version.

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Declaration

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