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Precision nutrient management in agriculture for sustaining crop productivity

U. Bagavathi Ammal[1*], and R. Rajakumar[2]

Department of Soil Science and Agricultural Chemistry, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal 609 603, UT of Puducherry, India
**Corresponding author Email: pancham112@gmail.com*

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ABSTRACT

Precision agriculture (PA) is the science of applying the 'right input' at the 'right time' in the 'right-amount' at the 'right place' and in 'right-manner' to improve productivity. The key component of PA is precision nutrient management (PNM). PNM is the science of using advanced, innovative, site-specific technologies to manage spatial and temporal variability in inherent nutrient supply from soil to increase agricultural production systems' productivity, efficiency, and profitability. It requires a proper understanding of the spatial variability in soil, which is the combined effect of soil's chemical, physical, and biological properties and landscape attributes, including slope, elevation, environmental factors, and management practices. Soil test-based nutrient management recommendations have improved food grain production but have not improved the efficiency of nutrient use beyond a certain limit. Researchers have appropriately shifted to an approach of feeding the crops rather than feeding the soil. The current research is oriented more toward synchronizing nutrient supply with plant needs. Assessing plant nutrient demand from plants is a more efficient strategy as plant growth at any given time integrates the effect of nutrient supply from all the sources and is thus a reliable indicator of its availability. The development of tools such as chlorophyll meters, leaf colour chart, and optical sensors provide facilitates instant nutrient management decisions. Recent advances show that need-based nutrient management in crop fields can be established through geospatial technologies such as GIS, GPS, remote sensing, and real-time and variable rate applications. The need-based variable-rate fertilizer application strategy can enhance fertilizer use efficiency by overcoming the problem of over- and under-fertilization.

Keywords: Precision agriculture, Precision nutrient management, optical sensors, LCC, STCR, SSNM, VRT

INTRODUCTION

India's Green Revolution during the 1960s was the main cause of the surplus production of grains. Food grain production has increased more than three-fold in the past few decades. This is possible only because of the adoption of high-yielding fertilizer-responsive varieties and hybrids, fertilizers, irrigation, pesticides, and farm mechanization. Among these, nutrient management has played a crucial role in achieving self-sufficiency in food grain production. As indicated in the FAO's 2008 report, India has 142 Mha of arable land and has tremendous growth potential for food grain production (FAOSTAT, 2009). However, to harness this potential, we need to achieve an Evergreen Revolution, which means harvesting maximum yield from the available arable land and water resources at the same time without causing any ecological or social damage. It is the need of the hour as India has to meet its projected requirement of 252 Mt of food grains by the year 2030. Precision agricultural techniques and technologies can go a long way in achieving this projected goal. To our understanding, it can be better interpreted as 5-R definition. Accordingly, precision agriculture is defined as the science of applying 'right-input' at 'right-time' in 'right-amount' at 'right-place' and in 'right-manner' to improve productivity, conserve natural resources, and avoid any ecological or social tribulations.

Researchers have realized the importance of feeding the crops rather than feeding the soil. The current research is focused more on synchronizing nutrient supply with plant needs. Precision agriculture has already achieved an unmatched growth in the developed countries. Developing countries in Asia have been comparatively slow in understanding, developing, and adopting precision agriculture practices. Moreover, precision agriculture is often misunderstood as a complex technological intervention for large crop fields in the developed world. Such a perception about precision agriculture is a myth; no data about the 'scale' or 'size' requirement for precision farming is available.

Precision agriculture is made possible by new technologies, *viz.,* geographic positioning systems (GPS), sensors, geographic information systems (GIS), advanced software, and precision application equipment. It aims to spatially and temporally manipulate inputs such as fertilizer, irrigation, and seed rate spatially and temporally at the sub-paddock scale for cost efficiencies, productivity, and environmental gains. Globally, the affordability and accessibility of these technologies helped precision agriculture emerge as a research discipline in the 1980s, and a strong focus has always been on enhancing nutrient use efficiency by matching inputs to site-specific field conditions. This paper deals with the various tools and techniques aiming at precision nutrient management for efficient nutrient management.

Precision nutrient management - definition and concept

Precision nutrient management is the science of using advanced, innovative, site-specific technologies to manage spatial and temporal variability in inherent nutrient supply from soil to increase agricultural production systems' productivity, efficiency, and profitability. It requires a proper understanding of the spatial variability in soil, which is the combined effect of chemical, physical as well as biological properties of soil, landscape attributes including slope, elevation, environmental factors as well as management practices (Wang *et al*., 2009). Traditionally, the spatial and temporal variability of soil nutrients is assessed based on a rigorous field sampling followed by soil testing, leading to more time and energy requirements. The development of tools such as chlorophyll meters, leaf colour chart and optical sensors facilitates instant nutrient management decisions.

Recent advances show that need-based nutrient management in crop fields can be established through geospatial technologies such as GIS, GPS, remote sensing, real-time and variable rate applications (VRA). The need-based variable-rate fertilizer application strategy can enhance fertilizer use efficiency by overcoming the problem of over- and under-fertilisation. The most widely and indiscriminately used nutrient in crop production is nitrogen. The dynamics of N supply to plants govern the chlorophyll content in plants, and thus, spectral properties of plant leaves can be used as an index to coin precision N management strategies. As the plant demand for nutrients other than N cannot be easily accessed from the spectral properties of the leaves, other techniques are being employed for making precision nutrient management decisions while considering spatial and temporal variability in nutrient supply from the inherent sources.

PRECISION NUTRIENT MANAGEMENT - TOOLS AND TECHNIQUES

Optical Sensors

Optical sensors assess visible and near-infrared (NIR) spectral response from plant canopies to detect nitrogen stress (Ma *et al*., 1996). Chlorophyll contained in the palisade layer of the leaf governs much of the visible light (400-720 nm) reflectance, although reflectance of the NIR electromagnetic spectrum (720- 1300 nm) depends on the structure of the mesophyll tissues. Spectral vegetation indices such as the normalized-difference vegetation index (NDVI) provide details about photosynthetic efficiency, productivity potential, and potential yield (Peñuelas *et al*., 1994; Raun *et al*., 2001; Bronson *et al*., 2011). There are several types of optical sensors, including multispectral and hyperspectral sensors.

A wide range of optical sensors are available and classified as multispectral and hyperspectral sensors. A multispectral sensor such as Crop Circle

(450-880 nm) and CropScan (440-1750 nm) has wide spectral resolution (10 to 20 nm) with a limited number of wavebands (3 to 16) used to describe N (Roberts *et al.*, 2009), biomass variation, and leaf area index (Darvishzadeh *et al.*, 2006) while hyperspectral sensors such as ASD FieldSpec (350-2500 nm) have fine spectral resolution (1-2 nm) with continuous wavebands (2150) across the EMR which provides detailed biophysical and biochemical information. Univariate and multivariate regression techniques calculated as spectral indices can be used to interpret spectral reflectance data.

Using NDVI measurements of wheat at different times during the crop-growth period, Raun *et al.* (2002) developed concepts of response index and potential yield. These were used to define a fertilizer-N algorithm based on the leaves' expected yields and achievable greenness. The GreenSeeker (GS) canopy sensor (Model 505, NTech Industries, Inc., Ukiah, California, USA) is a commercially available and widely used active optical sensor that emits red (650± 10 nm) and NIR (770±15 nm) wavebands. The sensor has been used in various crops such as wheat (Heege *et al.*, 2008; Bijay-Singh *et al.*, 2013), rice (Bijay- Singh *et al.*, 2015), barley (Soderstron *et al.*, 2010), corn (Tremblay *et al.*, 2009), sugarcane (Singh *et al.*, 2006; Portz *et al.*, 2012), and cotton (Raper *et al.*, 2013). Experiments conducted by Bijay-Singh *et al.* (2011) showed that the optical sensor-guided fertilizer N applications resulted in high yield and N use efficiency. The Yara N-Sensor (Yara International ASA, Oslo, Norway) is a passive multispectral scanner that determines the crop N status and accordingly adjusts the N fertilizer rates (Raper *et al.*, 2013). It is little affected by soil type (Heege *et al.*, 2008) and not sensitive to cultivar type (Portz *et al.*, 2012). The sensor can capture the crop variability with high spatial resolution and perform many readings per unit of time (*i.e.*, 10 readings per second).

The reliability of the NDVI sensor as an important tool for optimizing fertilizer nitrogen in wheat grown under the Eastern plains of India was proved through the study conducted by Mitra *et al.* (2023). A prescriptive dose of 60 kg N ha^{-1} as basal + 60 kg N ha^{-1} at crown root initiation (CRI) stage followed by NDVI sensor-guided N application (at 45 and 65 DAS) brought about a significant improvement in yield performances, N use efficiencies with higher net returns, and benefit-to-cost ratio (Table 1).

Chlorophyll Meters

Chlorophyll meters are reliable alternatives to traditional tissue analysis as plant N nutritional diagnostic tools. Most widely used chlorophyll meter is the hand-held Minolta SPAD-502 (Soil-Plant Analysis Development). It instantly provides an estimate of leaf N status as chlorophyll content (Fiebo *et al.*, 1998; Boggs *et al.*, 2003) by clamping the un-plucked leafy tissue in the meter using two LEDs emitting red (650 nm) and infrared (940 nm) light. The red and infrared radiations are made to pass through the leaf. A portion of light is absorbed and the rest is transmitted through the leaf, and a

Table 1. Grain yield, NUE and production economics of wheat as influenced by various N scheduling

Treatments	Grain yield (t/ha)	Agronomic efficiency (kg grain per kg of N)	Physiological efficiency (kg grain per kg of N uptake)	Gross return (Rs./ha)	B:C ratio
Control	1.353^{d}	-	-	24354^{c}	0.57^{e}
150 kg/ha N (½ basal + ¼ CRI + ¼ AT)	4.720^{ab}	22.45^{ab}	106.9^{b}	84960^{ab}	1.87^{b}
120 kg/ha N (½ basal + ¼ CRI + ¼ AT)	4.098^{c}	22.88^{ab}	119.0^{a}	73764^{b}	1.64^{cd}
150 kg/ha N (½ basal + ½ CRI)	4.700^{ab}	22.31^{b}	112.6^{a}	84600^{ab}	1.86^{b}
120 kg/ha N (½ basal + ½ CRI)	4.125^{c}	23.10^{ab}	119.0^{a}	74250^{b}	1.65^{cd}
30 kg/ha N basal +30 kg/ha N at CRI + NDVI sensor-based N	4.030^{c}	22.69^{ab}	117.4^{a}	72540^{b}	1.62^{d}
30 kg/ha N basal + 60 kg/ha N at CRI + NDVI	4.355^{bc}	22.74^{ab}	120.7^{a}	78390^{b}	1.74^{c}
60 kg/ha N basal + 60 kg/ha N at CRI + NDVI	5.068^{a}	24.44^{a}	110.9^{a}	91224^{a}	2.01^{a}
60 kg/ha N basal + kg/ha N at CRI + NDVI	4.385^{bc}	23.32^{a}	120.3^{a}	78930^{ab}	1.75^{c}
N-rich 225 kg/ha (½ basal + ½ CRI)	4.637^{b}	14.60^{c}	113.8^{a}	83466^{ab}	1.79^{bc}
Significance level	**	**	**	**	**

(Source: Mitra *et al.,* 2023).

silicon photodiode detector converts it into an electrical signal. The amount of light reaching the detector is inversely proportional to the amount of chlorophyll in the path of the light. Leaf chlorophyll content is displayed in arbitrary units (0-99.9) and the meter readings are unitless which need to be calibrated with chlorophyll or N content and leaf greenness. Another type of chlorophyll meter is Field scout CM 1000 chlorophyll meter (Spectrum Technologies, Inc.). It uses point and shoot technology to instantly estimate relative chlorophyll content. There are two approaches used to manage fertilizer N using SPAD meter:

Fixed Threshold Value Approach

Fertilizer-N is applied whenever chlorophyll meter reading is less than the preset threshold value. The SPAD threshold value which represents the limit below which a reduction in yield occurs must be pre-established. Fertilizer-N applications are necessary below this threshold value to avoid yield loss. Peng *et al*. (1996) gave critical SPAD value that farmers could refer to in the rice field. The SPAD values of the index leaf are monitored at 7-10 days' interval starting from 15 days after transplanting till initiation of flowering. In-season top-dressing of 30 kg N ha^{-1} was recommended whenever SPAD value fell below the critical value of 35 for rice cultivar IR72 grown in the dry season in the Philippines. The threshold SPAD value of 35 correlated to 1.4 g N m^{-2} leaf area, a number that was found to be fairly stable for the high-yielding IR72 cultivar during the dry growing season. The use of critical SPAD 35 reading resulted in yields similar to those of less fertilizer N and higher agronomic efficiency compared to fixed split-timing applications (Peng *et al*., 1996). The SPAD value of 35 was also found to be the appropriate threshold value for guiding need-based N management in transplanted rice in South India (IRRI-CREMNET, 1998,2000, 2001). Nevertheless, the SPAD meter threshold value of 35 is not universal and may vary in different rice-growing environments (Table 2).

Sufficiency Index Value Approach

Sufficiency index is defined as the SPAD value of the test plot expressed as percentage of the SPAD value of an over-fertilized reference plot or strip. Fertilizer- N is applied as and when sufficiency index value falls below a set value. This approach has the benefit of being self-adjusting for spatial, temporal and varietal variations as SPAD threshold values are established with respect to an over-fertilized reference plot.

Hussain *et al*. (2000) evaluated 0.90 level sufficiency index approach in different varieties *vis-à-vis* blanket N applications. The fertilizer-N was top dressed at the rate of 30 kg N ha^{-1} whenever sufficiency index was less than 90 % up to 50% flowering. Rice grain yields obtained for different cultivars were similar to those obtained in the blanket-N application treatment but with 30 kg less N ha^{-1}. Bijay-Singh *et al*. (2006) followed the criteria of 90 % sufficiency index in direct seeded rice. The approach saved 50 kg N ha^{-1} fertilizer-N in comparison to blanket application of 120 kg N ha^{-1} with no reduction in the grain yield. The fixed and dynamic sufficiency index approaches for need-based fertilizer-N management technologies were compared with farmers' practices, local recommendations, STCR-based recommendations or urea briquette deep placement method at on-farm locations in south Asia (IRRI-CREMNET, 1998; 2000). Using 32 to 65 kg N ha^{-1} less fertilizer produced grain yield equivalent to soil test-based recommendations. The increase in agronomic efficiency ranged from 2.6 to 42.2 kg grain kg^{-1} N.

Table 2. Threshold value of SPAD meter for different crops

Crop	Critical SPAD value	Growing environment/ location	Reference
Rice	32	Wet season	Balasubramanian *et al*., 1999
Rice	37.5	Pakistan	Hussain *et al*., 2003
Rice	35	Bangladesh	Kyaw *et al*., 2003
Rice	37	-	Maiti *et al*., 2004
Wheat	44	-	Bijay-Singh *et al*., 2002
Wheat	42	Bangladesh	Hussain *et al*., 2003
Wheat	37	Eastern Indo-Gangetic plain	Maiti and Das, 2006
Wheat	44	Lower Gangetic plains in Bangladesh	Kyaw, 2003

Leaf Colour Chart

Leaf colour chart is a high-quality plastic strip with different shades of green colour that ranges from light yellowish green to dark green. The use of LCC technology was reported in Japan by Furuya (1987). An improved version of the six-panel LCC was developed through the association of the IRRI with agricultural research systems of several countries in Asia (IRRI, 1996). The LCC score of the first fully exposed leaf is observed at 7-10 days interval starting from 15-20 days after transplanting or sowing till the initiation of flowering. The prescribed amount of fertilizer nitrogen is applied whenever the colour of rice leaves falls below the critical LCC score. The LCC shade 4 is the threshold score for transplanted coarse grain rice varieties widespread in the Indo-Gangetic plains (Hussain *et al.*, 2003). The threshold LCC value was reported to be 3.5 in the lower Gangetic plain in Bangladesh. The critical LCC value (IRRI-LCC, four panel) of 2 and 3.5 was found to be appropriate for scented and aromatic transplanted semi-dwarf indica or transplanted hybrid rice, respectively. The researchers at Zheijiang Agricultural University, China developed ZAU-LCC with scale of eight green colour shades (3, 4, 5, 5.5, 6, 6.5, 7, and 8), and it was calibrated for *Indica, Japonica and Hybrid rice* (Yang *et al.*, 2003). Another eight panel (1 to 8) UCDLCC (University of California, Davis) was developed in USA to define percent leaf N. Later researchers at IRRI further refined the colour panels of the IRRI-LCC and developed a four-panel IRRI-LCC (Fairhurst *et al.*, 2007; Witt *et al.*, 2005). Leaf colour chart may not be as precise as the SPAD meter, but for all practical purposes, it can work like a SPAD meter. Two approaches have been followed for using LCC to synchronize fertilizer- N application with plant needs.

Real-time N Management Approach

In this approach, the LCC score of the first fully exposed leaf is monitored at 7-10 days intervals starting from 15-20 days after transplanting/sowing till initiation of flowering, and the prescribed amount of fertilizer-N is applied whenever the colour of rice leaves falls below the critical LCC score (Fig. 1).

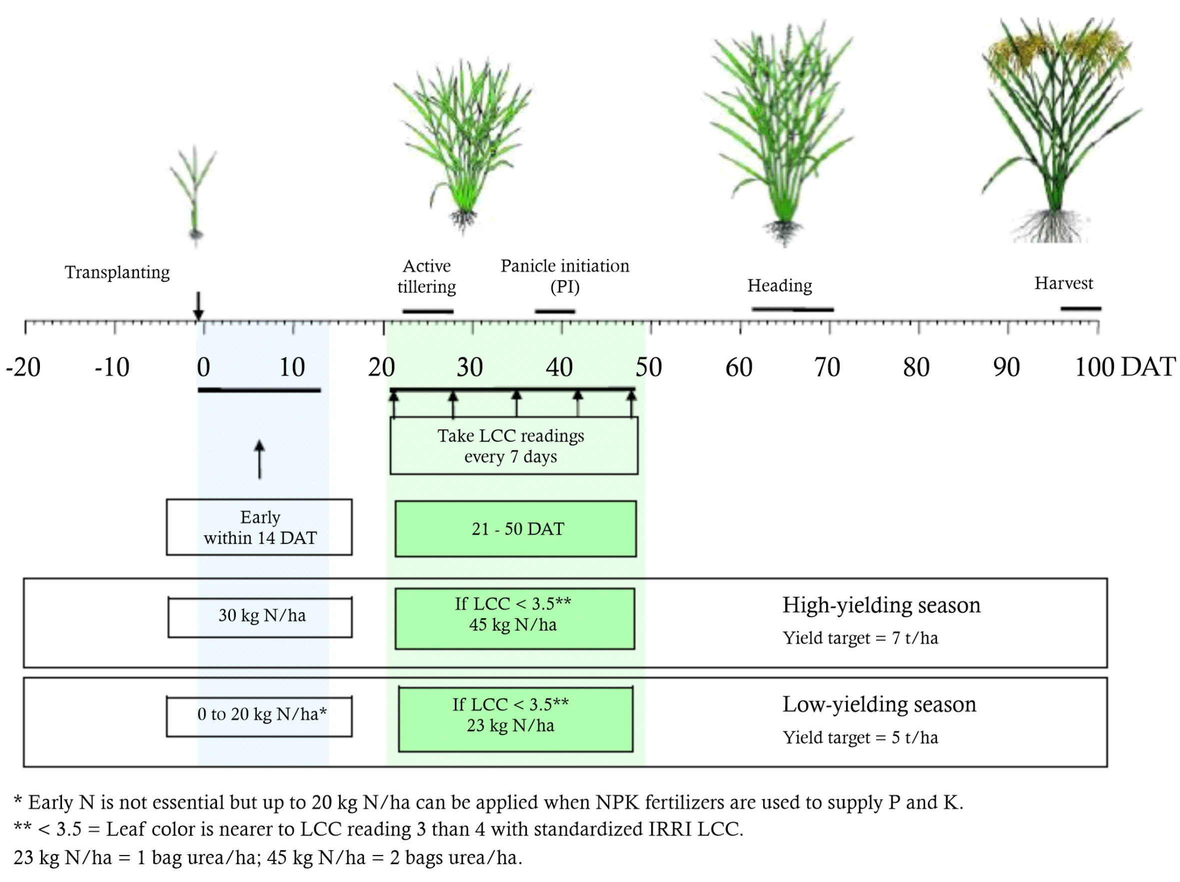
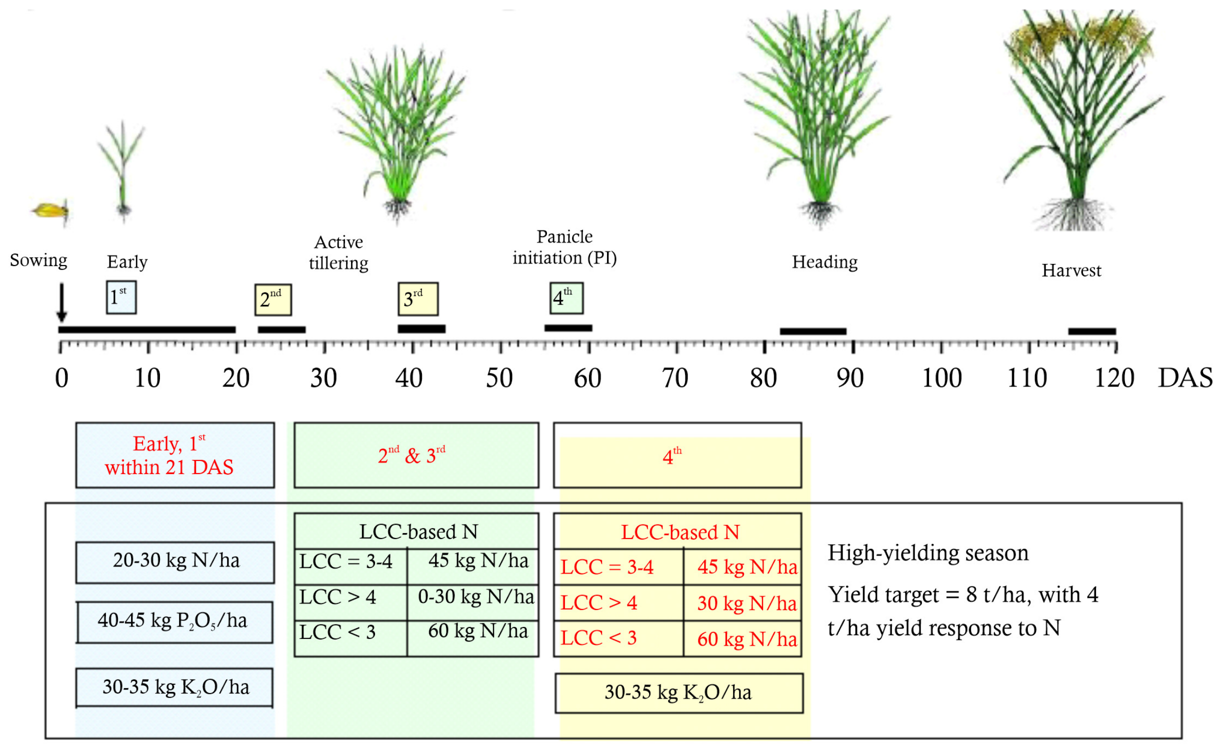


Fig. 1. Synchronizing fertilizer-N application with plant needs through Real-time N Management Approach



* Yield targets depend upon location and can be higher or lower than those in this example.

Fig. 2. Synchronizing fertilizer- N application with plant needs through Fixed-time Variable Rate Dose Approach

Fixed-time Variable Rate Dose Approach

Instead of measuring leaf colour intensity at every 7-10 days interval, LCC can be used to decide variable rate N dose at fixed growth stages in rice (Fig. 2). If the green colour intensity of leaves is higher (for example > LCC 4), apply less fertilizer-N. If the mean leaf colour is lower (for example < LCC 4), apply more fertilizer-N. Such adjustments at active tillering and panicle initiation stages ensure application of more N in fields and years with high plant demand for N and less N in fields and years with low demand for N.

A field study was conducted by Jyothsna *et al.* (2021) at PJTSAU, Telangana, India to study the nutrient management in hybrid maize using simple hand-held decision support tools *viz.*, LCC, SPAD, and Green seeker. Application of N-based on Green Seeker NDVI at threshold 0.8 recorded significantly higher maize grain (8408 kg ha^{-1}). Among different precision N management practices, significantly higher partial factor productivity (57.8 kg kg^{-1}), recovery efficiency (99.7 %), and agronomic efficiency (25.7 kg kg^{-1}) was obtained in N management through SPAD based N at threshold 40 as compared to RDN and absolute control. The study concluded that N management through SPAD based N at threshold 40, Green Seeker based N at NDVI 0.8, and LCC based N at threshold 4 are the best precision N management practices in hybrid maize for achieving higher NUE indices (Table 3).

Omission Plot Technique

The omission plot technique estimates fertilizer requirements for attaining a yield target. All the major nutrients are applied except the nutrient of interest, which is an omitted nutrient. It provides an estimate of the indigenous nutrient supply of the soil. For example, if all the nutrients except P are applied in P omission plot, then the yield will be limited by the indigenous supply of P. The yield gap between the maximum achievable yield and the yield in the omission plot technique is then used to calculate the requirement of fertilizer.

An experiment on the omission plot technique conducted by Sahu *et al.* (2018) revealed that grain and straw yields of rice were significantly reduced with the omission of N, P, and S compared to the treatment receiving all the nutrients (Table 4). Higher grain and straw yields were observed in the treatment, which received all the nutrients. The yield

Table 3. Grain yield and nutrient use efficiency indices as influenced by precision nitrogen management through decision support tools in maize

Treatments	Saving in N fertilizer over RDF	Grain yield (kg/ha)	PFP (kg grain per kg N)	AE (kg increase in grain/ kg N)	RE (% increase in N uptake/ kg N)	PNBN (kg N uptake per kg N)
RDN (200 kg ha^{-1} in 3 splits)	0	7361	36.8	15.1	41.1	0.8
LCC based N at threshold 3	65	7020	51.9	19.8	58.6	1.1
LCC based N at threshold 4	65	7401	54.8	22.6	94.1	1.5
SPAD based N at threshold 35	65	7051	52.2	20.0	76.1	1.2
SPAD based N at threshold 40	65	7809	57.8	25.7	99.7	1.6
Green seeker based N at NDVI 0.6	55	7783	53.7	23.7	86.2	1.3
Green seeker based N at NDVI 0.8	35	8408	50.9	25.4	90.3	1.4
Control (no N) only P & K	0	4343	0	0	0	0
CD (5 %)	-	329	7.1	7.0	10.4	0.09

(Source: Jyothsna *et al.*, 2021)

Table 4. Grain and straw yield of rice under omission plot treatments

Treatments	Grain yield (g/pot)	Straw yield (g/pot)
All	32.80 ^{ab}	34.94 ^{a}
All – N	18.99 ^{c}	24.20 ^{c}
All – P	22.97 ^{c}	29.26 ^{b}
All – K	31.52 ^{ab}	33.79 ^{a}
All – S	28.34 ^{b}	29.24 ^{b}
All – Ca	33.09 ^{ab}	34.96 ^{a}
All – Mg	31.72 ^{ab}	34.51 ^{a}
All – Cu	31.40 ^{ab}	34.48 ^{a}
All – Zn	32.18 ^{ab}	34.80 ^{a}
All – B	34.90 ^{a}	37.62 ^{a}
All – Mo	31.92 ^{ab}	34.96 ^{a}
CD (5 %)	4.45	4.48

(Source: Sahu *et al.*, 2018)

reductions were more pronounced with N and P omission as 42, and 29.97 %, respectively. Based on the performance of rice crop during *Kharif* season, the yield-limiting nutrients identified were in the order of N > P > S. These limiting nutrients were tested on farmer's fields with wheat crop during R*abi* season, 2015-16 where bulk soil samples were collected for pot culture study. The limiting nutrients applied in optimum doses as N - 150, P_2O_5 - 100, K_2O - 80, S - 45. The wheat yield was recorded 25% higher as compared to the farmer's fertilizer practice (80:58:38 kg N: P_2O_5: K_2O).

Nutrient Management Models

Nutrient Expert (NE) and QUEFTS model are basically used computer-based systems for precision nutrient management in crop production. The models are designed to consider spatial and temporal variability in nutrient supply and ensure need-based nutrient management. The NE develops farmers-specific fertilizer recommendations based on the yield of previous 3 to 5 years, organic and inorganic fertilizers applied, achievable yield, soil fertility indicators, residue content. It takes care of the availability of resources to evaluate their yield target. The algorithm for estimating fertilizer requirements in NE is developed from a set of on-farm trial data using the SSNM guidelines. It is a highly interactive computer-based tool that quickly discusses a particular field's fertilizer requirement.

An agronomic field experiment involving nutrient expert-based recommendation + green seaker was conducted at ICAR–IARI New Delhi, India by Shyam *et al.* (2021). The grain yield was improved under precision nutrient management practices of NE+GS7T, NE6T, NE7T, and NE+GS 6T. Maximum net return was in NE7T (Rs. 75194/ ha), and least was in N omission (Rs. 12992 to 20451/ha) (Table 5).

Sapkota *et al.* (2014) conducted on-farm experiments in seven districts of Haryana to evaluate the performance of NE- and NE+GreenSeeker-based nutrient management against current state recommendations and farmers' practices in wheat. Grain yield, NUE, PFP, and net return were higher under NE-based nutrient management strategies than state recommendations and farmers' practices. On average, NE-based strategies increased grain yield and biomass yield by 14% and 9%, respectively over farmers' practice and by 5% and 3%, respectively over state recommendation. Banerjee *et al.* (2014) experimented on precision nutrient management in maize using NE as a decision support system. It was found that NE

Table 5. Yield, harvest index and economics of maize under different precision nutrient management

Treatment	Grain yield (kg/ha)	Harvest index	Net return (Rs./ha)	Added return (Rs./ha)	B:C ratio
Blanket recommendation 150-80-60 kg/ha	5415.2	34.6	59916	0	2.86
NE recommendation for 6t/ha	5741.3	35.6	67643	7726	3.26
NE recommendation for 7t/ha	6217.7	37.2	75194	15278	3.47
NE recommendation with Green seeker for second split for 6 t/ha	5538.3	34.8	64486	4570	3.17
NE recommendation with Green seeker for second split for 7 t/ha	5960.9	36.9	71284	11368	3.37
Blanket recommendation with green seeker for second split	5152.9	34.7	55616	-4300	2.74
Blanket recommendation without N	2525.3	26.6	12992	-46925	1.43
NE recommendation for 6t/ha without N	2621.8	28.2	16848	-43068	1.61
NE recommendation for 7t/ha without N	2849.3	29.2	20451	-39465	1.73
CD (5 %)	479.4	1.0	8150	-	0.28

(Source: Shyam *et al.*, 2021)

recommendation gave highest yield, agronomic efficiency (52.51 and 84.01 %), physiological efficiency (30.04 and 44.56 %), and recovery efficiency (17.28 and 27.17%) over state recommendation and farmers' practice.

The researchers also worked with another empirical model – QUEFTS (Quantitative Evaluation of Fertility of Tropical Soils) model to predict the effect of fertilizer application on yield, based on soil and plant characteristics. This model provides a generic approach that considers climate-adjusted, season-specific yield potential (Witt and Dobermann 2002). The QUEFTS model consists of four steps: i) Potential indigenous nutrient supply assessment, ii) nutrient uptake assessment, iii) designation of yield range as a function of nutrient uptake, and iv) estimation of final yield. Instead of calculating fertilizer N, P, and K requirements individually, QUEFTS model considers interactions between nutrients to achieve an optimal nutritional balance. Buresh *et al.* (2010) used QUEFTS model to estimate the relation between grain yield and nutrient accumulation in above-ground dry matter at maturity in irrigated rice. The average yield gain obtained for applied nutrients was 12% for K, and 9% for P. Wijayanto and Prastyanto (2011) worked on QUEFTS model to evaluate nutrient management in maize. The QUEFTS model, in comparison to farmers' practice, leads to lower N and P fertilizer and higher K fertilizer applications and increased nutrient use efficiencies

Site specific nutrient management (SSNM)

SSNM provides a method of demand based on the supply of nutritious plants. The SSNM approach aims to increase farmers' profitability by achieving the goal of maximum crop yield. The main features of SSNM are 1. Direct site utilization of nitrogen, phosphorus, and potassium and secondary and micronutrients according to soil test, and 2. Proper utilization of existing nutrients, such as soil, residues, and compost (Fig. 3). SSNM continues to provide guidelines for selecting the most nutritious economic combination and promotes the efficient and effective use of existing indigenous natural resources such as crop residues and fertilizers (Maitra and Zaman, 2017).

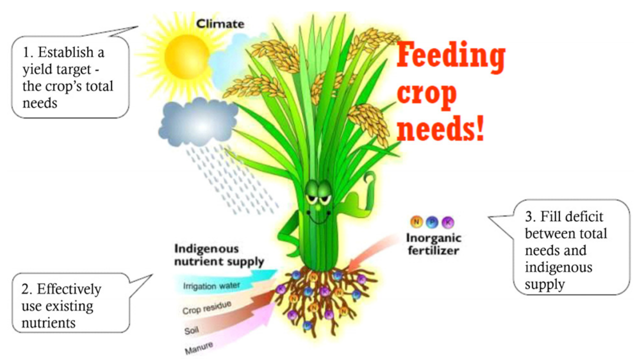


Fig. 3. Pictorial representation of SSNM

The implementation of SSNM strategies should begin with the priority areas that address one or more of the following problems: Areas with insufficient or uneven use of fertilizers with low yields show signs of severe malnutrition. Pest problem areas are linked to nutrient imbalance or overuse of fertilizer, such as N. phosphorus mines and potash reserves of soil. Areas with evidence of multiple nutrient deficiencies, including secondary and nutrient depletion in soil and plants.

Variable Rate Technology

Variable rate technology (VRT) is used to adjust agricultural inputs according to the specific needs of the site in each part of the field. When machines are used, this requires flexible measuring equipment. On small farms, inputs can be used manually. Fixed price requests require (a) Correct field position, (b) Appropriate location information, and (c) Farm equipment is equipped with VRT controls with a DGPS receiver to pinpoint the exact location of the field variance and automatically control the application rate based on pre-obtained input plan maps. The FRT describes any technology that enables the variable application of inputs. Therefore, VRT mounted on equipment permits input application rates to be varied across fields to manage field variability site-specifically. This strategy can reduce input usage and environmental impacts, increase efficiency, and provide economic benefits.

Aerial Imagery and Site Maps

Precision nutrient management plans also use aerial photography, site maps, and soil survey maps. These tools, which include knowledge of prior land use(s), are used to derive decisions for efficient nutrient management. Even with all this information, imagery does not help to explain within-field variations that may be induced by management decisions, climatic conditions, geologic characteristics, and/or other sources of variation. Although some researchers have worked on it, the application of aerial imagery and site maps for precision nutrient management decisions is not yet established.

Magri *et al*. (2005) analyzed geographical information system, spatial data processing, and their correlation. They found that aerial data correlated with soil organic matter, but it did not correlate with soil fertility indicators. Nitrogen fertilization and yield data were variable and strongly affected by seasonal weather conditions. There seems to be a limited scope in using aerial imagery and site maps to improve nutrient use efficiency.

STCR APPROACH FOR PRECISION AGRICULTURE

The STCR (Soil Test Crop Response) approach is a precision agriculture technique that helps to optimize nutrient management and crop yields by using information about soil fertility and plant nutrient requirements. It involves three main components: soil testing, crop response and nutrient management.

Basic concept

A unique field experimental approach (Inductive Methodology) as followed in the All India Coordinated Research Project for Investigation on Soil Test Crop Response Correlation studies, was evolved by creating a macrocosm of soil fertility variability within a microcosm of an experimental field (Ramamoorthy *et al.,* 1967*)* by applying graded doses of fertilizers. The relationship between soil-available nutrients and grain yield was outlined by Troug (1960) and Ramamoorthy *et al. (*1967*)* established the fact that there exists a linear relationship between the nutrients absorbed by the plant and the grain yield or economic produce. This provides a scientific basis for balanced fertilization between fertilizer nutrients and the soil's available nutrients. Since different levels of uncontrolled variables (e.g. Soil fertility) cannot be expected to occur at one place, in the present approach, all the needed variation in soil fertility level is obtained by deliberately creating it in one. The same field experiment to reduce the heterogeneity in the soil population studied, management practices adopted and climatic conditions prevailing.

Experimental Technique

The experimental technique involved in the STCR approach is as follows. A leveled field of about 0.5 ha with low to medium soil fertility and representative of the experimental station or area is to be chosen, and a composite soil sample is collected and analyzed for its initial soil characteristics. The field is divided into three equal strips, and eight pre-sowing soil samples from each strip are collected from 0-15 cm and 15-30 cm depth and analyzed for available N, P, and K status. The first strip receives no fertilizer (NPK), and the second and the third receive one (NPK) and two times (NPK) a standard dose of N, P, and K, respectively. The standard dose of P and K are fixed considering the soil's phosphorous and potassium fixing capacities, and the standard dose of N is fixed per the general recommendation for the gradient crop. An exhaust or gradient crop is grown so the fertilizers transform the soil with plant and microbial agencies. After the harvest of this exhaust crop, twenty-four soil samples one from each plot, are taken and analyzed for available N, P, and K status and compared with pre-sowing results to confirm the creation of soil fertility variations. In the subsequent season, each strip is divided into 24 sub-plots. Twenty-one fertilizer treatments from 4×4×4 levels of N, P_2O_5, and K_2O, in addition to 3 absolute controls, are randomly allotted in each of three strips. Across the strips, three levels of organic manures (0, 1, and 2) are superimposed. The treatments are randomized so that all 24 treatments occur in such a way that all the 24 treatments occur in either direction, and a test crop is grown. Pre-sowing soil samples are collected from each sub-plot and analyzed for available N, P, and K by different soil test methods. The test crop is grown with good agronomic practices and is harvested at maturity. After harvest, grain and haulm yields are recorded, and total nutrient uptake is determined plot-wise. Post-harvest soil samples are collected and analyzed for available N, P, and K status

Calculation of basic parameters

Using the data on the yield of rice, total uptake of N, P, and K, initial soil test values for available N, P, and K, and doses of fertilizer N, P_2O_5, and K_2O applied, the basic parameters *viz.*, nutrient requirement (NR), contribution of nutrients from soil (Cs), fertilizer (Cf) and FYM (Cfym) to be computed. The basic parameters are calculated following the methodology of Ramamoorthy *et al.* (1967) and are furnished below.

Nutrient requirement (NR) kg q^{-1}

i) kg N required per quintal of rice grain production

$$= \frac{\text{Total uptake of N (kg ha}^{-1})}{\text{Grain yield (q ha}^{-1})}$$

ii) kg P_2O_5 required per quintal of rice grain production

$$= \frac{\text{Total uptake of } P_2O_5 \text{ (kg ha}^{-1})}{\text{Grain yield (q ha}^{-1})}$$

iii) kg K_2O required per quintal of rice grain production

$$= \frac{\text{Total uptake of } K_2O \text{ (kg ha}^{-1})}{\text{Grain yield (q ha}^{-1})}$$

Percent nutrient contribution of nutrients from soil (Cs) to total nutrient uptake

i) Per cent contribution of N from soil

$$= \frac{\text{Total uptake of N in control plot (kg ha}^{-1})}{\text{Soil test value for available N in control plot (kg ha}^{-1})} \times 100$$

ii) Per cent contribution of P_2O_5 from soil

$$= \frac{\text{Total uptake of } P_2O_5 \text{ in control plot (kg ha}^{-1})}{\text{Soil test value for available } P_2O_5 \text{ in control plot (kg ha}^{-1})} \times 100$$

iii) Per cent contribution of K_2O from soil

$$= \frac{\text{Total uptake of } K_2O \text{ in control plot (kg ha}^{-1})}{\text{Soil test value for available } K_2O \text{ in control plot (kg ha}^{-1})} \times 100$$

Percent nutrient contribution of nutrients from fertilizer to total uptake (Cf)

i) Per cent contribution of N from fertilizer

$$= \frac{\text{Total uptake of N in treated plot (kg ha}^{-1}) - \left(\text{Soil test value for available N in treated plot (kg ha}^{-1}) \times \text{Average Cs}\right)}{\text{Fertilizer N applied (kg ha}^{-1})} \times 100$$

ii) Percent contribution of P_2O_5 (kg ha^{-1}) from fertilizer

$$= \frac{\text{Total uptake of in } P_2O_5 \text{ treated plot (kg ha}^{-1}) - \left(\text{Soil test value for available } P_2O_5 \text{ in treated plot (kg ha}^{-1}) \times \text{Average Cs}\right)}{\text{Fertilizer } P_2O_5 \text{ applied (kg ha}^{-1})} \times 100$$

iii) Per cent contribution of K_2O from fertilizer

$$= \frac{\text{Total uptake of } K_2O \text{ in treated plot (kg ha}^{-1}) - \left(\text{Soil test value for available } K_2O \text{ in treated plot (kg ha}^{-1}) \times \text{Average Cs}\right)}{\text{Fertilizer } K_2O \text{ applied (kg ha}^{-1})} \times 100$$

Percent contribution of nutrients from FYM (Cfym)

$$\text{Cfym} = \frac{\text{Total uptake of N/P/Kin FYM treated plot (kg ha}^{-1}) - \left(\text{Soil test value for available N/P/K in FYM treated plot (kg ha}^{-1}) \times \text{Average Cs}\right)}{\text{Nutrient N/P/K added through FYM (kg ha}^{-1})} \times 100$$

Targeted yield equations

Making use of these parameters, the fertilizer prescription equation (FPEs) are to be developed as detailed below.

Fertilizer nitrogen (FN)

$$\text{FN} = \frac{\text{NR}}{\text{Cf}/100}\,\text{T} - \frac{\text{Cs}}{\text{Cf}}\,\text{SN}$$

$$\text{FN} = \frac{\text{NR}}{\text{Cf}/100}\,\text{T} - \frac{\text{Cs}}{\text{Cf}}\,\text{SN} - \frac{\text{Cfym}}{\text{Cf}}\,\text{ON}$$

Fertilizer phosphorus (FP_2O_5)

$$FP_2O_5 = \frac{\text{NR}}{\text{Cf}/100}\,\text{T} - \frac{\text{Cs}}{\text{Cf}} \times 2.29 \times \text{SP}$$

$$FP_2O_5 = \frac{\text{NR}}{\text{Cf}/100}\,\text{T} - \frac{\text{Cs}}{\text{Cf}} \times 2.29 \times \text{SP} - \frac{\text{Cfym}}{\text{Cf}} \times 2.29 \times \text{OP}$$

Fertilizer potassium (FK_2O)

$$FK_2O = \frac{\text{NR}}{\text{Cf}/100}\,\text{T} - \frac{\text{Cs}}{\text{Cf}} \times 1.21 \times \text{SK}$$

$$FK_2O = \frac{\text{NR}}{\text{Cf}/100}\,\text{T} - \frac{\text{Cs}}{\text{Cf}} \times 1.21 \times \text{SK} - \frac{\text{Cfym}}{\text{Cf}} \times 1.21 \times \text{OK}$$

Where, FN - Fertilizer N (kg ha^{-1}), FP_2O_5 - Fertilizer P_2O_5 (kg ha^{-1}), FK_2O - Fertilizer K_2O (kg ha^{-1}), NR -

Nutrient requirement of N or P_2O_5 or K_2O (kg ha^{-1}), Cs - percent contribution of nutrient from soil, Cf - percent contribution of nutrient from fertilizer, SN - Soil test value for available N (kg ha^{-1}), SP - Soil test value for available P (kg ha^{-1}), SK - Soil test value for available K (kg ha^{-1}), Cfym - percent contribution of nutrients from FYM, ON - Quantity of N applied through FYM (kg ha^{-1}), OP - Quantity of P applied through FYM (kg ha^{-1}), and OK - Quantity of K applied through FYM (kg ha^{-1}).

This approach, coupled with Inductive methodology termed as "inductive cum targeted yield approach," forms the basis for the ICAR-sponsored All India Coordinated Research Project for Soil Test Crop Response Correlation Studies (AICRP-STCR). These fertilizer prescription equations are vigorously tested and evaluated for their predictability through field verification trials in farmer's holding. The equations are valid if 90 percent of the targeted yield was achieved. By substituting the required parameters in the fertilizer prescription equation under IPNS, fertilizer doses are arrived at the desired yield target of crops for a range of soil test values (nomograms).

The fertilizers prescription equation (FPEs) are valid only under the following situations: i) They should be used for the same or allied soil type, ii) The maximum target should be based on the genetic character and the highest yield achieved for that crop in that area, iii) FPEs must be used within the experimental range of soil test values and cannot be extrapolated, iv) Good and recommended agronomic practices are to be followed and v) Other micro and secondary nutrient should not be yield limiting.

The fertilizer prescription equations were developed for cultivating various crops in the soil series of UT of Puducherry by the AICRP-STCR center, Puducherry, and are presented in table 6. Fertilizer saving for crops in different soil series due to the adoption of STCR-IPNS over blanket recommendation on a yield equivalent basis is presented in table 7.

The STCR approach can help farmers reduce fertilizer use and minimize environmental pollution by applying only the nutrients the crops need. It can also increase crop yields and profitability by

Table 6. Fertilizer prescription equation developed for different crops at Puducherry

S. No.	Soil series/ Soil order	Crop	Fertilizer prescription equation
1.	Mannadipet/ Inceptisol	Rice	FN = 4.70 T - 0.59 SN - 0.91 ON FP_2O_5 = 1.61 T - 1.10 SP - 0.86 OP FK_2O = 2.10 T- 0.37 SK - 0.72 OK
2.	Bahour/ Inceptisol	Rice	FN = 3.06 T - 0.33 SN - 0.85 ON FP_2O_5 = 1.63 T - 0.81 SP - 1.02 OP FK_2O = 1.70 T- 0.22 SK - 0.85 OK
3.	Sanyasikuppam/ Inceptisol	Rice	FN = 3.41 T - 0.25 SN - 0.37 ON FP_2O_5 = 1.27 T - 0.79 SP - 0.69 OP FK_2O = 1.65 T - 0.34SK - 0.41 OK
4.	Thirunallar/ Vertisol	Rice	FN = 4.73 T- 0.74 SN - 0.98 ON FP_2O_5 =1.63 T- 0.69 SP - 0.83 OP FK_2O =2.97 T- 0.30 SK - 0.62 OK
5.	Bahour/ Inceptisol	Bhendi	FN = 2.00 T - 0.39 SN - 1.12 ON FP_2O_5 = 1.13 T - 1.05 SP - 0.98 OP FK_2O = 0.93 T - 0.16 SK - 0.64 OK
6.	Bahour/ Inceptisol	Chilli	FN = 1.25 T – 0.42 SN – 0.65 ON FP_2O_5 = 0.84 T – 4.82 SP - 0.84 OP FK_2O = 0.72 T – 0.29 SK – 0.77 OK
7.	Mannadipet/ Inceptisol	Brinjal	FN = 0.74 T - 0.61 SN – 0.74 ON FP_2O_5 = 0.33 T – 0.97 SP - 0.71 OP FK_2O = 0.35 T - 0.33 SK - 0.49 OK
8.	Thirunallar/ Vertisol	Cotton	FN = 0.74 T - 0.61 SN -0.74 ON FP_2O_5 = 0.33 T - 0.97 SP- 0.71 OP FK_2O = 0.35 T - 0.33 SK - 0.49 OK

(Source: Bagavathi-Ammal, 2017, 2019 & 2023)

Table 7. Fertilizer saving for different crops due to STCR-IPNS over blanket recommendation on yield equivalent basis

S. No.	Soil series / soil order	Crop & blanket recommendation	Yield target t/ha	Yield in blanket (t/ha)	STV (kg/ha)			Fertilizer STCR - IPNS(kg/ha)			Fertilizer saving (kg/ha)			Fertilizer saving (kg/ha)		
					SN	SP	SK	N	P	K	N	P	K	Urea	SSP	MOP
1	Mannadipet Inceptisol	Rice 150:50:50	5.0	3.62	196	69	132	75	25	25	75	25	25	163	156	42
2	Bahour Inceptisol	Rice 120:40:40	5.0	4.12	248	56	238	68	20	20	52	20	20	113	125	33
3	Thirunallar Vertisol	Rice 150:50:50	5.0	3.46	228	66.8	272	74	20	35	76	30	15	165	187	25
4	Sanyasikuppam Inceptisol	Rice 120:40:40	5.0	3.61	242	32.4	130	70	20	16	50	20	24	109	125	33
5	Bahour/ Inceptisol	Bhendi-hybrid 200:100:100	16.0	12.3	252	20.6	196	170	86	63	30	14	37	65.1	87.5	59.2
6	Bahour/ Inceptisol	Chilli-hybrid 120:80:80	25.0	20.6	232	24.2	210	100	40	40	20	40	40	44	250	67.0
7	Mannadipet/ Inceptisol	Brinjal 100:50:50	34.0	26.6	278	27.2	276	75	40	35	25	10	15	55	62.5	25.0
8	Thirunallar/ Vertisol	Cotton-hybrid 120:60:60	3.1	2.67	200	69.4	348	100	46	38	20	14	28	44	87.5	47.0

(Source: Bagavathi-Ammal, 2017, 2019 & 2023)

optimizing nutrient management and reducing nutrient deficiencies or excesses. Additionally, using precision agriculture technologies such as variable rate application can further improve the accuracy and efficiency of nutrient management.

CONCLUSION

Precision nutrient management practices include optical sensors, chlorophyll meters, leaf colour charts, omission plot techniques, and crop models for facilitating need-based nutrient applications and thus improving nutrient use efficiencies while achieving high yield. The real-time nitrogen management approach works well in rice and maize. However, a fixed time variable rate approach that combines preventive (applying fertilizer nitrogen as basal or at earlier fixed growth stages to prevent fertilizer nitrogen deficiency) fertilizer nitrogen application schedule with LCC, SPAD or optical sensor-guided corrective nitrogen management seems more effective in wheat. Nutrients other than nitrogen can be managed using the omission plot technique and crop models. Since precision nutrient management focuses on synchronizing the demand and supply of nutrients, its impact on grain quality must be worked out more systematically.

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