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Review Article

Nutrient management in wheat: current scenario, improved strategies and future research needs in India

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Abstract

Wheat (*Triticum aestivum* L) is the second most important staple food and meets about 61% of the protein requirement of the India. The introduction of new high yielding varieties coupled with chemical fertilizer use and creation of irrigation infrastructure have led to green revolution during mid 1960's due to which India became second largest producer (~90 Mt) next to China, contributing about 35% in cereal basket of country. However, during recent past, the yield plateau in most productive wheat ecologies (north-west India) and large management yield gaps (~50%) in eastern India, the heart lands of wheat are major concerns for future food security. In addition to natural resource depletion and biotic-abiotic stresses, the multiple nutrient deficiencies are the key factors that contribute not only to yield plateaus but also to declining factor productivity, shrinking profits and environmental footprints. In the conventional approaches of fertilizer nutrient management practices (blanket and adhoc), the very basic principle of replenishing the soil nutrients reserves at the rates they are removed in annual production systems are lacking. This can be done through all available nutrient sources, inorganic and organic, but the bottom line is that any mismatch between nutrient input and output that depletes the soil or creates imbalance will adversely affect production potential. Though significant efforts have been made on designing improved nutrient management practices but these approaches for fixed-rate, fixed-time fertilizer recommendations made for large areas and cannot be successful as they do not capture the existence of large variability in soil nutrient supply and crop response to nutrients. Recent approaches like site-specific nutrient management (SSNM) provides an approach to "feeding crops" with nutrients as and when they are needed and hence making synergy for nutrient demand and supply under a certain production system. However, such an approach along with careful management of other crop production factors, allowed reaching yield targets and efficiency factors that are far higher than the current levels. But, soil testing has remained the major bottleneck to realize potential benefits of these new and improved approaches. We therefore attempted to develop a decision support system (DSS), based on the principles of SSNM (Nutrient Expert for wheat) that provides flexibility of using SSNM principles with and without soil testing and reaching large number of farmers. In this paper we therefore present the pros and cons of conventional as well as modern tools and techniques of nutrient management and comparing with Nutrient Expert (NE) results validated in Haryana and Punjab and provide alternate solution to soil test based nutrient management while capturing the variability. The Decision support systems (DSS) are now progressively used to facilitate application of improved nutrient management practices in farmers' fields. Therefore, the recently developed Nutrient Expert for Wheat was validated under on-farm research in conventional and conservation agriculture to establish simple delivery system that enables wheat farmers to rapidly implement SSNM for their individual fields. The DSS developed in 2010-11 is an easy-to-use, interactive computer-based decision tool that can rapidly provide nutrient recommendation for individual farmers' field in presence or absence of soil testing data. The results of farmers' field validation trials of NE based prescriptions in wheat across the Indo-Gangetic Plain region showed that the NE based recommendation significantly improved wheat yield and economics. The results also showed that wheat yield in farmers' plots across sites were higher under conservation tillage practices than conventional tillage and the nutrient requirement was different under the different tillage systems. This suggests that nutrient management strategies need to be different for the contrasting tillage practices.

Key words: nutrient expert decission support system, site-specific nutrient management, wheat systems

Introduction

Attaining Food Security had been a major challenge for the nation since independence. In 2008, world food prices have touched record levels. Stagnant cereal production growth rates, depletion of grain stocks due to production shocks, coupled with increasing demand for food has contributed to dwindling supplies. As a result, physical, economic and ecological access to food still remains our major challenge. India has achieved self-sufficiency in food production at present, but the realistic demand for food has been estimated at 235 million tons for 2015, which will reach 265 million tons by the year 2030. Looking at the rapid growth of population in the country, the slow growth rate in food grain production necessitates special initiatives to meet the increasing demands. Wheat has

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to play an important role in this direction considering the vast scope of increasing productivity of this crop through bridging the management yield gaps by the newly emerging technologies.

Cereals, especially wheat, constitute the staple food in India and meet about 61% of the protein requirement of the country. The current wheat production of India is about 80 million tons and the country has to produce 105 Mt by 2025, demanding an average growth rate of 4% per annum (Prasad, 2011). Expansion of the area sown to wheat has long ceased to be a major source of increased wheat output and most of the increase in production has to result from greater yield per hectare. As we look at further opportunities to improve production, it becomes evident that there still exist substantial yield gaps within wheat growing regions of the country, as well as between on-station and on-farm yields. Inappropriate nutrient management is one of the major factors causing such yield gaps (Majumdar *et al.*, 2012; Nagarajan *et al.*, 2005). The current paper aims to analyze the nutrient management related constraints for such yields gaps and possible ways of improving productivity through appropriate nutrient management strategies.

Wheat production scenario in India

Wheat (*Triticum aestivum* L) is the most important cereal crop in the World and stands next to rice in India. The share of wheat to total food grain production in India is around 37% and occupies about 24% of the total area under food grains (Table 1). Wheat is grown in India over an area of about 29 million hectares (M ha). Nearly 82-85% of the wheat grown in India is under irrigated conditions while the rest is grown under rain-fed ecology. Nearly 90% of the wheat growing area is in the North Western Plain Zone (NWPZ), North Eastern Plain Zone (NEPZ) and Central Zone (CZ). At the current production level, NWPZ alone produces over 50% of the total wheat followed by NEPZ (less than half of NWPZ) and Central zone. The average productivity of wheat in the country is 2839 kg ha^{-1} with the highest yield recorded in Punjab (4307 kg ha^{-1}) followed by Haryana (4213 kg ha^{-1}), Rajasthan (3133 kg ha^{-1}), Uttar Pradesh (2846 kg ha^{-1}), West Bengal (2680 kg ha^{-1}) and Bihar (2084 kg ha^{-1}) indicating wide yield differences between the major wheat growing states of the country (Fertilizer Statistics, 2010-11).

Table 1. Importance of wheat in food grain production scenario

	Normal Area (million ha) and % of Total Area (In parentheses)	Normal Production (million tons) and % share of Production (In parentheses)
Rice	42 (35)	89 (41)
Wheat	29 (24)	80 (37)
Total food grains	121	218

Source: Fertilizer Statistics (2010-11)

It is quite clear that sustaining wheat productivity is essential to food security in India. However, the production data for wheat in India (1990-2007) shows no significant increase in productivity over the last ten years (Figure 1). The projected demand for wheat by the year 2025 will be high for an estimated population of 1.25 billion. Estimated 20-30 Mt of extra production has to come from a practically stabilized acreage under wheat in the next 15 years. Therefore, new technological advancements in all the areas of crop management, with particular emphasis on nutrient management, will be required to achieve the estimated yield targets.

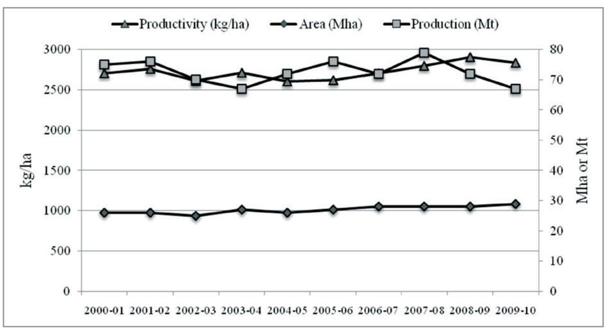

Fig. 1. Area, production and productivity trend of wheat in India Source: Fertilizer Statistics (2010-11)

Yield gaps

Review of current statistics shows that there are considerable yield gaps between the major wheat growing states in the country (Fertilizer Statistics, 2010-11). For example, productivity in Bihar and Madhya Pradesh are less than 50% of Punjab. Similarly, Uttar Pradesh, with the highest acreage among the states (9.7 M ha), has a productivity of 2846 kg ha^{-1}, which is about 65% of Punjab. Such yield gaps can be partially related to the nutrient ($N+P_2O_5+K_2O$) consumption per unit of gross cropped area in a particular state. The productivity data of seven major wheat producing states (Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, Jharkhand and

Madhya Pradesh) were correlated with the latest nutrient consumption data for these states and has revealed a good linear correlation (R^2=0.78) (Figure 2). It must be understood, however, that besides nutrient use, there are several other important factors, including climate and management issues that influence yield gap between these states.

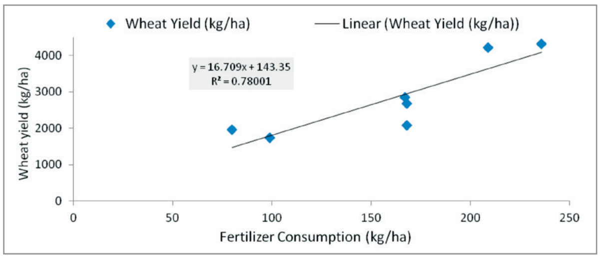

Fig. 2. Correlation between nutrient consumption per unit of gross cropped area and wheat yield in major wheat growing states, Data used for Punjab, Haryana, Uttar Pradesh, Bihar, Jharkhand, West Bengal and Madhya Pradesh; Source: Fertilizer Statistics (2010-11)

Yield gap analysis considering potential, on-station and on-farm yields by several authors (Tiwari, 2006; Ladha *et al*., 2003; Aggarwal *et al*., 2000) revealed a large gap between potential and on-farm yields in different parts of the country and yields under least constrained on-station situations never reached beyond 70% of potential yield (Table 2).Similar but less pronounced yield gaps were also recorded between on-station and on-farm situations and varied genotypes, soil, climate, availability of inputs, nutrient and water management etc. were the factors that affected the realization of production potential at the on-farm situation.

Pathak *et al.* (2005) while working on on-farm situation also observed large yield gaps between potential and farmers' field yield of wheat in the Trans-Gangetic alluvial tract of Delhi. They attributed such yield gaps to a large extent to inappropriate nutrient management. Recently, Gupta *et al*., (2010) suggested that the management yield gaps in wheat in Punjab, Haryana, Eastern UP and Bihar were 17, 14, 47 and 48 %, respectively. However, existence of such yield gaps are also opportunities in disguise as bridging these gaps provides the avenues for future food security in the country. It is interesting to note that an average wheat yield increase of 1 t ha^{-1} in Bihar and Uttar Pradesh can increase the national production by more than 11 million tons annually. Such yield increase is not unrealistic if we consider the existing yield gap between Punjab and these states.

Table 2. Potential, on-station and on-farm yields (t ha^{-1}) and yield gaps of wheat

Site	Yield of wheat (t ha^{-1})			Yield gap (%)	
	Potential (A)	On-station(B)	On-farm(C)	(A-B)/A*100	(A-C)/A*100
Ludhiana	7.9	4.7	4.3	41	46
Karnal	7.3	4.6	3.6	37	51
Kanpur	7.0	4.6	2.8	35	60
Pantnagar	6.5	3.9	4.2	40	35
Varanasi	7.0	3.8	3.2	46	54
Faizabad	6.7	3.4	2.8	49	58
Dinajpur	5.4	3.8	2.3	31	57
24-Parganas	5.2	3.0	2.8	43	45

Source: Tiwari (2006)

Nutrient related constraints

Since the mid-1980s, wheat yield in India has either declined or stagnated (Sinha *et al*., 1998; Duxbury *et al*., 2000). One of the main reasons is conventional blanket fertilizer recommendation, leading to imbalanced use of fertilizers and lower fertilizer use efficiency. Agricultural holdings in India are highly fragmented with variable nutrient supplying capacity both at the spatial and temporal scale. A recent on-farm study (Majumdar *et al*., 2012), using the omission plot studies in the Indo-Gangetic Plains, showed that wheat yield response ranged from 500-4750 kg ha^{-1}, 67 - 2806 kg $ha^{-1}$and 0–2222 kg ha^{-1} for N, P and K respectively, which is related to the soil nutrient supplying capacity. Khurana *et al.* (2008) working on irrigated wheat at 56 sites in six main wheat producing regions of Punjab also highlighted the variability in soil fertility across farmers' field sites. However, the nutrient management and fertilizer recommendation processes in India are based upon response data averaged over large geographic areas and does not take into account the short-range variability in indigenous nutrient supply in soils. More often than not, such generalized nutrient recommendation over large areas of small-scale farming systems fails to meet the nutrient requirement of crops. Due to high field to field variability, the possibility of over or under-application of nutrients are very high with its economic and environmental consequences. This leads to inefficient use of added nutrients, as application rates do not consider the spatial variability in nutrient requirements among the fields (Buresh *et al.*, 2010).

It is quite clear that the current approach of fixed-rate, fixed-time fertilizer recommendations made for large areas cannot be successful under intensive cropping mainly because this approach does not take into account the existence of large variability in soil nutrient supply and crop response to nutrients present in our farming system. Several researchers have highlighted falling productivity and nutrient use efficiency, multi-nutrient deficiencies, high extent of nutrient mining and falling farm income as the consequences of generalized recommendation in a highly variable landscape (Ghosh *et al.*, 2004; Tiwari, 2007). Naidu *et al.* (2008) in their recent study observed different potential, limitations and response to management for various crops in different parts of the country, and suggested the necessity of soil-test based nutrient application. They found that following generalized recommendation in wheat caused a misapplication loss of Rs 326 ha^{-1} for N, Rs. 736 ha^{-1} for P and Rs. 333 ha^{-1} for K, as compared to soil-test based nutrient application, in coarse loamy soil of Ludhiana. Nambiar (1994) and Swarup and Wanjari (2000), while summarizing results from long-term experiments, showed the inadequacy of general recommendations and concluded that the application of 150% of the recommended rates consistently improved the yield of wheat in several locations of the country. Another inconsistency in the general recommendation is the absence of recommendations for secondary and micronutrients. It is well recognized now that sulphur (S), zinc (Zn) and boron (B) deficiencies are quite widespread in India. S deficiency is widespread in about 250 districts, whereas 50% of 251873 samples analyzed for Zn were found to be deficient (Tiwari, 2006). Boron was found deficient in 33% of 36800 samples analyzed and deficiency of other micronutrients is reported sporadically from different parts of the country (Tiwari, 2006). Tiwari *et al.* (2006), while analyzing the initial soil samples for their multi-location SSNM trial sites under rice-wheat cropping systems, highlighted the growing importance of secondary and micronutrients as yield limiting factors (Table 3). Recently (Shukla *et al.*, 2012) suggested that Zn fertilization alone contributes to 18.4 Mt (economic value of Rs. 232119 million) of the total food grain production in India. So it is imperative that the balanced fertilization concept must now include all limiting nutrients, including secondary and micronutrients, in a site- specific manner to boost the attainable yields under on-farm situations.

Table 3. Nutrient deficiency status in SSNM experiment (high yield target) under rice-wheat system

Locations	Nutrient deficient							
	P	K	S	Zn	Fe	Mn	Cu	B
PDCSR, Modipuram	-	√	√	√	-	√	√	√
GBPUA&T, Pantnagar	√	√	-	√	-	√	-	√
CSAUA&T, Kanpur	√	√	√	√	-	-	-	-
NDUA&T, Faizabad	√	√	√	√	-	√	-	√
BHU, Varanasi	√	√	√	√	-	√	√	√
RAU, Sabour	√	√	√	-	-	-	-	-
BAU, Ranchi	√	√	√	√	-	-	-	√
HPKV, Palampur	√	√	√	√	-	-	-	√
PAU, Ludhiana	√	√	√	√	√	√	√	√
RS Pura (J & K)	√	√	√	√	-	√	√	-

Source: Tiwari *et al.* (2006)

Besides the above, imbalanced and inadequate nutrient application by farmers is one of the major reasons for wheat yield loss and associated economic and environmental risks. Surveys in the Indo-Gangetic Plains (IGP) revealed that farmers often apply greater than recommended rates of fertilizer N and P, but ignore the sufficient application of other nutrients (Singh *et al.*, 2005). Potassium, sulfur, and micronutrients are not applied in adequate amounts to prevent increasing deficiencies of these nutrients. Sanyal *et al.* (2010) also pointed out the lack of potassium application as one of reasons for yield stagnation in the rice-wheat system in the IGP. The risk of nutrient mining can be particularly serious in highly productive areas and relatively lower levels of input of K, S, and micronutrients (Singh *et al.*, 2008). Such unbalanced and inadequate use of nutrients can decrease the profitability with increased environmental risks associated with loss of excess N from the root zone (Prasad, 2006).

The basic principle of maintaining the fertility status of a soil under high intensity crop production systems is to annually replenish those nutrients that are removed from the field. This can be done through all available nutrient sources, inorganic and organic, but the bottom line is that any mismatch between nutrient input and output that depletes the soil or creates imbalance will adversely affect production potential. It is clear from the above discussion that balanced fertilization under the current Indian context goes well beyond the realm of the three major nutrients or any specific ratio. So the key towards improving wheat yield in India to a large extent will depend on how efficiently we can provide all the limiting nutrients in adequate quantity to the crop, keeping in mind the native nutrient supplying capacity of the soil and the yield target.

Improved nutrient management for wheat

Site-specific nutrient management (SSNM) provides an approach to "feeding" crops with nutrients as and when they are needed. It ensures that all the required nutrients are applied at the proper rate and in proper ratio based on the crop's nutrient needs. The principles of SSNM are well established and have produced yield and quality improvement in wheat across soils and regions. Major research efforts in this line on wheat (Sharma and Tiwari, 2004) showed the advantage of SSNM over the existing practices (Table 4). All the experiments shown here ensured that all limiting nutrients were applied in each location after carefully determining the nutrient supplying capacity of the soil and the nutrient requirement of wheat based on a specified yield target.

Table 4. Effect of site-specific nutrient management on wheat

Site	Yield (kg ha^{-1})	
	SSNM based	State Average
R.S.Pura	4746	1325
Ludhiana	6548	4532
Modipuram	5940	2755
Kanpur	5685	2755
Ranchi	4057	2056

Source: Sharma and Tiwari (2004)

Such an approach of nutrient management, along with careful management of other crop production factors, allowed reaching yield targets that are far higher than the current state averages of wheat yield. IPNI and Project Directorate of Cropping Systems Research (PDCSR) collaborative work on rice-wheat cropping sequence across several states showed that SSNM improved yield of wheat to various extents over state recommendation (SR) and farmers' practice (FP) (Tiwari *et al.*, 2006). Application of SSNM on rice–wheat cropping system in the above study locations increased the system yield to 14-16 tha-1 with subsequent increase in economic return. The extra system net economic return of the SSNM treatments over state recommended practice was between Rs. 1578 ha^{-1} in Ranchi to Rs. 26,224 ha^{-1} in Modipuram. Far higher economic return was obtained through improved nutrient management as compared to the existing farmers' practices that varied between Rs. 5783 ha^{-1} and Rs. 28791 ha^{-1} across the sites. In all the locations, wheat showed variable response to secondary and micronutrients that were applied to rice. The response of S was visible in all the locations and varied between 48-1350 kg grainkg-1nutrient. Average Zn, B, Mn and Cu response across the locations were 313, 382, 231 and 173 kg grain kg^{-1} nutrient, respectively (Sharma and Tiwari, 2004). Shukla *et al.* (2009) later reported similar observations for a wide range of crops including wheat. This showed clearly that application of limiting secondary and micronutrients in a site- specific manner will be necessary to improve yield of wheat. Similar studies conducted in Northern Karnataka (Biradar *et al.*, 2006) revealed that nutrient application on the basis of SSNM principles resulted in significantly higher grain yields over farmer practice (FP) and recommended dose of fertilizers (RDF). Average wheat yield in SSNM practice was 3.7 t ha^{-1}, which was 23% more than the RDF and 39% higher than the FP, with SSNM recorded an additional net income of Rs. 3060 $ha^{-1}$and Rs. 4545 ha^{-1} over RDF and FP, respectively. Maiti *et al.* (2006), using the QUEFTS approach also showed that SSNM significantly improved wheat yield in Eastern India and suggested revision of fertilizer recommendation in West Bengal. Recent studies on SSNM in wheat have looked into the aspect of real time N management for optimizing the efficiency of N. N use efficiency (NUE) in wheat is low and a recent worldwide evaluation showed that N recovery efficiency is about 30% (Krupnik *et al.*, 2004). The main reason of low NUE is inefficient splitting of N applications advocated in the current recommendations, as well as the use of N in excess to the requirements. Such excessive use of N is often associated with wrong perception of farmers, where yellowing of wheat plants due to a different abiotic stress is interpreted as nitrogen deficiency symptoms (Dhadli *et al.*, 2010). On the contrary, optimum use of N can be achieved by matching N supply with crop demand, where appropriate amount of N is applied at the right physiological stage of nutrient demand. A potential solution is to regulate the timing of N application in wheat using a chlorophyll meter (or SPAD meter) or a LCC to determine the plant N needs. Such approach brings in the location specificity in terms of N supplying capacity of the soil and allows varying N application according to crop requirement, as opposed to the standard practice of fixed-time N management. The concept is based on results that show a close link between leaf chlorophyll content and leaf N content.

Moreover, leaf area– based N concentration (Na) varies within a narrow range at different growth stages. Shukla *et al.* (2004) showed a close relationship between N and SPAD or LCC readings in wheat and LCC and SPAD reading were highly correlated (r = 0.91). This allowed the authors to use a single critical value for SPAD or LCC to monitor leaf N status at all growth stages. In wheat, maintenance of LCC ≤ 4 required120 kg Nha^{-1}, which produced higher grain yield, N uptake, and NUE than that of recommended N splits. Chlorophyll meter reading and crop growth rate (gm-2day^{-1}) at 21 days after seeding in wheat were not significantly different with or without basal N application, indicating that basal N application in wheat was not necessary in soils having relatively high indigenous N supply. The authors observed higher net returns of 19 to 31% in LCC-based N management than in fixed time N application for rice–wheat cropping. Results of the above 2-yr rice–wheat system study provided evidence that current fertilizer N recommendations (fixed-time split N) are not adequate for maintaining the high yields and efficient use of N in rice and wheat. The LCC-based N management, that takes into account the inherent variability in N-supplying capacity of soils, assured high yields consistent with efficient N use in both rice and wheat and enhanced rice–wheat systems' total productivity and farmer's profit (Shukla *et al*., 2004). Singh *et al.* (2010) also suggested that fertilizer N use efficiency in wheat in South Asia can be improved by following fertilizer N management strategies responsive to temporal variations in crop N demands and field-to-field variability in soil N supply. The above review showed that improved synchrony between crop N demand and the N supply from soil and/or the applied N fertilizer through a fixed-time/adjustable-dose approach seems to be more promising in wheat. The approach combines preventive (applying fertilizer N as basal or at earlier fixed growth stages to prevent fertilizer N deficiency) fertilizer N application schedule with LCC/SPAD guided corrective N management. Khurana *et al.* (2008) evaluated the performance of SSNM for two wheat crops in several regions of Punjab. The SSNM approach used in this study focused on managing spatial variation in indigenous N, P, and K supplies among individual sites. The approach mainly involved (a) prediction of site specific optimal fertilizer NPK rates using indigenous nutrient supplies and (b) development and implementation of a site-specific N management scheme that accounted for real-time variation in crop N demand at major wheat growth stages. Compared with the current farmers' fertilizer practice (FFP), average grain yield increased from 4.2 to 4.8 t ha^{-1}, while plant N, P, and K accumulations increased by 12–20 % with SSNM. The gross return above fertilizer cost (GRF) was about 13% greater with SSNM than with FFP. Improved timing and/or splitting of fertilizer N increased N recovery efficiency from 0.17 kg^{-1} in FFP plots to 0.27 kg^{-1} in SSNM plots in the above study. The agronomic N use efficiency was 63 % greater with SSNM than with FFP.

The above SSNM studies in wheat highlights that a combined approach of real-time N management along with application of nutrients based on indigenous nutrient supply and yield target has the potential to improve productivity of wheat, far beyond achievable by the current general recommendations. Such approaches not only have the capability to reverse the yield stagnation in wheat but also can improve farmers' profit and lessen the environmental impact of imbalanced fertilization promoted by generalized nutrient recommendation.

Decision support systems (DSS) are now progressively used to facilitate application of improved nutrient management practices in farmers' fields. A recently developed DSS, Nutrient Expert for Wheat, synthesized the wheat on-farm research data into a simple delivery system that enables wheat farmers to rapidly implement SSNM for their individual fields. The decision support system developed in 2010-11 is an easy-to-use, interactive computer-based decision tool that can rapidly provide nutrient recommendation for individual farmers' field in presence or absence of soil testing data (Pampolino *et al*., 2012). The tool estimates the attainable yield for a farmer's field based on the growing conditions determines the nutrient balance in the cropping system based on yield and fertilizer/manure applied in the previous crop and combines such information with expected N, P and K response in the concerned field to generate a location specific nutrient recommendation for wheat. It utilizes information provided by a farmer or a local expert to suggest a meaningful yield goal for his location and formulates a fertilizer management strategy required to attain the yield goal. The software also does a simple profit analysis comparing costs and benefits between the farmer's current practice and the recommended alternative improved practice. First year farmers' field validation of Nutrient Expert decision support tool in wheat (Table 5 & 6) across the Indo-Gangetic Plains region showed that the tool-based recommendation significantly improved yield and economics of production. The tool was validated under conventional as well as conservation tillage systems and effectively captured the bio-physical differences between the two tillage systems as evidenced from the yield and economic data. Conservation tillage practices in wheat are now quite popular, particularly in Northern India, and nutrient management DSS tools that can handle contrasting scenarios of tillage will be more acceptable for use. The validation trial results also showed that wheat yield in farmers' plots (Table 5 & 6) across sites were higher under conservation tillage practices and the nutrient requirement was different under the different tillage systems. This suggests that nutrient management strategies need to be different for the two common tillage practices.

Table 5. Yield, fertilizer use and economic comparison between farmers' practice (FP) and Nutrient Expert-based recommendation (NE) in conventionally tilled wheat (n = 46)

Parameter	Unit	FP	NE	NE-FP
Grain yield	kg/ha	3504	4436	932 ***
Fertilizer N	kg/ha	134	141	6 **
Fertilizer P_2O_5	kg/ha	57	54	-2 ns
Fertilizer K_2O	kg/ha	13	76	63 ***
Fertilizer cost	INR/ha	2436	2933	496 ***
1GRF	INR/ha	36804	46742	9938 ***

***, **, *: significant at <0.001, 0.01, and 0.05 level; ns = not significant; 1 GRF = gross return above fertilizer cost; Prices (in INR/kg): wheat = 11.20; N = 10.50; P_2O_5 = 16.22; K_2O = 7.50

Table 6. Yield, fertilizer use and economic comparison between farmers' practice (FP) and Nutrient Expert-based recommendation (NE) in wheat under conservation tillage (n = 27)

Parameter	Unit	FP	NE	NE-FP
Grain yield	kg/ha	4392	5180	788 ***
Fertilizer N	kg/ha	152	161	8 ***
Fertilizer P_2O_5	kg/ha	57	58	1 ns
Fertilizer K_2O	kg/ha	0.5	83	83 ***
Fertilizer cost	INR/ha	2549	3271	723 ***
1GRF	INR/ha	46751	54850	8099 ***

***, **, *: significant at <0.001, 0.01, and 0.05 level; ns = not significant; 1 GRF = gross return above fertilizer cost; Prices (in INR/kg): wheat = 11.20; N = 10.50; P_2O_5 = 16.22; K_2O = 7.50

Future research needs on nutrient management in wheat systems

Until recent past, the nutrient management research was primarily focused on developing generalized prescriptions for larger domains and for conventional crop management practices. However, in recent past significant attempts have been made to develop precise approaches based on the principles of site-specific nutrient management (SSNM) so as to capture the spatial and temporal variability in soil fertility. This approach (SSNM) has been able to address many of the issues of adhoc nutrient prescriptions. However, large-scale implementation of SSNM in farmers' field still remains a challenge due to the knowledge requirement. Recent development and validation of the Nutrient Expert DSS for wheat provides a great opportunity to easily implement SSNM in farmers' fields. However, there are several other areas of research that has potential to help in implementing improved nutrient management practices at different scales:

- Calibrating sensors for nutrients beyond N (P, K, Zinc, etc.)
- Establish relationships for on-the-go remote sensing sensors and satellite remote sensing for SSNM
- Use of remote sensing and GIS for mapping fertility variability and making nutrient prescriptions at different scales
- Geo-referencing/ mapping of large domains for developing homologous regions for nutrient prescriptions
- Develop, validate, and bring to scale decision support tools (Nutrient Expert) and farmer friendly simple practices for system based SSNM for small holder precision
- Develop and deploy regional recommendations that can be distributed through ICT solutions

During past decade or so, alternate crop establishment techniques, zero tillage with or without surface retention of residues, have emerged as one of the potential alternate to conventional tillage based wheat production. However, most nutrient management research caters to conventional tillage based crop management systems. These two contrasting crop establishment practices (conventional and conservation agriculture) will have implications on soil moisture regime and nutrient dynamics that in turn will influence nutrient response and economic profitability of nutrient application. Therefore, there is a need to develop recommendation and application strategies in line with the 4R principles (right source, right rate, right time and right place) for conservation agriculture systems of wheat cultivation.

- Scientific basis of attainable yield targets need to be established under contrasting management practices for tillage and residues in various cropping systems under diverse ecologies (rainfed, irrigated).
- Crop physiological processes and efficiency under contrasting management practices will be variable that will lead to variable nutrient responses. Basic understanding of such processes will allow designing appropriate nutrient management decision tools/ prescriptions.
- Nutrient availability under enhanced moisture availability under zero-till and residue retention scenarios needs to be understood properly to determine appropriate rate and time of nutrient application.
- Development of appropriate machinery for nutrient application (surface application, drilling, band placement, fertigation) under different management scenarios (no-till with and without surface residues, conventional till with and without residue incorporations) is urgently required.

Repeated foliar application of N:P:K fertilizer grades (19:19:19 or 20:20:20) at flowering is also gaining momentum in farmer fields especially in areas where wheat is subjected to severe incidence of frost damage. Therefore the relationship between foliar feeding of nutrients and crop damage to frost has to be well established and there is a need to quantify the contribution of such foliar application of nutrients to the final crop removal.

Developing Expert Systems/mobile apps for identification of nutrient deficiency symptoms in wheat is a critical area of research. Timely identification of deficiency symptoms and their early rectification can save farmers from major economic losses. A recent publication by IPNI and CIMMYT entitled "A guide to Identifying and Managing Nutrient Deficiencies in Cereal Crops" could provide background information and photographs for development of expert systems or mobile applications for wheat.

Analysis of socio-economic conditions of the farmers and combining socio-economic and bio-physical parameters for targeting nutrient management strategies to farmer groups could assure better adoption. Crop nutrient recommendations are rarely based on resource availability to farmers and adoption of such recommendations is generally poor. Research in this line is urgently required to increase acceptability of recommendations or DSS "tools" among the different farmer groups with different socioeconomic background.

Recent estimates for India suggest that to meet the expected food demand in the next 30 years, we therefore will need to increase average productivity of wheat from its current level of 45–60 % of the attainable yield potential to 70–80 % of the attainable potential. The huge yield gaps existing at several levels give the opportunity to reach the above goals provided we are ready to exploit the existing yield gaps through more knowledge-intensive precision nutrient and crop management practices. The systematic implementation of site-specific systems is probably our best opportunity to develop a truly sustainable agriculture system and restore the momentum to the productivity growth of wheat in the coming decades to maintain the balance between food demand and supply.

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