Indian Journal of Fertilisers **16** (10) : 1000-1014, October 2020

Precision Nutrient Management for Higher Nutrient Use Efficiency and Farm Profitability in Irrigated Cereal-based Cropping Systems

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Received : 11/02/2020 Accepted : 12/09/2020

Abstract

In the past, blanket region-based fertilizer recommendations prescribed to farmer's that did not take into account the variations in the indigenous nutrient supply from the specific fields have led to higher production costs, diminishing yield and factor productivity, and increasing greenhouse gas emissions. Therefore, precision fertilizer recommendations that address the need-based crop requirements have been urgently needed. Site-specific nutrient management (SSNM) along with modern agronomic management practices may increase yields and nutrient use efficiency by optimizing the balance between nutrient supply and demand. In recent studies across large numbers of locations in rice/wheat-based systems in the Indo-Gangetic Plains (IGP) of India, SSNM has led to 8-12% increases in grain yields compared to farmers' fertilizer practices/state recommended doses of fertilizers (RDF). The adoption of SSNM significantly increased the net returns by Rs. 2,500-3,200 ha^{-1} over farmers' fertilizer practice by saving money on costly fertilizer inputs. Optical sensor (GreenSeeker)-based SSNM saved 20-30 kg N ha^{-1} without affecting grain yield under conservation agriculture (CA)-based cereal systems compared to recommended dose of fertilizers (RDF). Efficient management of N-fertilizers reduced N_2O emissions by avoiding N losses via volatilization, leaching and denitrification. Site-specific nutrient management provides opportunities for enhancing crop productivity, profitability and nutrient use efficiencies (NUE) across the different ecologies. Drip irrigation system (sub-surface drip irrigation) improved the N-use efficiency by 20% over flood irrigation system in rice/maize-based systems that helped in increasing the farm profitability by saving on N-fertilizer use and water in rice-wheat/ maize-wheat systems.

Key words : Conservation agriculture, fertigation, need-based N management, nutrient use efficiency, sub-surface drip irrigation, site-specific nutrient management.

Introduction

In the years to come, demand of increasing population for enough and high-protein food will require substantial nutrient inputs into different agroecosystems to ensure high production levels with higher profitability in India (Jat et al., 2016b; Parihar et al., 2018; Kakraliya et al., 2018). The estimated population of India is likely to reach 1.7 billion by 2050, requiring around 400 million tonnes (Mt) of food grains. The cultivated area has been static since last 5 decades and there is a very little chance for further expansion. Therefore, increase in food grain production will have to come from higher system productivity with limited natural resource base. Indian agriculture has made spectacular progress on food grain production front during the past half century and achieved food self-sufficiency. However, it is a paradox that though the country enjoys high economic growth and at the same time suffers from the deterioration of its natural resources leading to low factor (nutrient) productivity, yield stagnation, lower water and nutrient use efficiency (NUE), imbalanced and inadequate use of external production inputs, and diminishing farm profits coupled with climate change (Jat et al., 2016b; Parihar et al., 2017; Kakraliya et al., 2018a).

At present, a region-based single fertilizer recommendation is prescribed to farmer's that does not take into account the variations in the indigenous nutrient supply from their specific fields (Singh et al., 2015; Kakraliya et al., 2019). This results in either too little or too much application of nutrients in various parts of the fields. The excessive applications of fertilizer nutrients or inefficient management can cause economic loss to the farmers, ground water contamination and environmental problems (Thind et al., 2010; Sapkota et al., 2015). Too little nutrients reduce yields while too much reduce the NUE. Plant nutrients in balanced proportion are essential for achieving maximum yield, providing sufficient and healthy food for the growing population. Hence these constitute a vital component of sustainable agriculture production (Singh et al., 2015; Kakraliya et al., 2019). Moreover, agricultural intensification

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requires increased flow of plant nutrients to crops from the soil through efficient uptake of nutrients. Improved crop management practices (variety, tillage, crop establishment, best irrigation and fertilizer management practices, integrated pest management, *etc*.) are required to achieve the targeted food grain production in the country to feed the over-exploiting population (Ladha et al., 2003; Jat et al., 2013). In order to reach the required yield levels of any crop, focus on fertilizer use is of utmost importance to improve the farm profitability to target the Government Mission of "*Doubling Farmers' Income by 2022*". The current consumption ratio of nitrogen, phosphorus and potassium (NPK) of 7.0:2.8:1 in the country is highly unbalanced. The environmental damage caused by the inappropriate use of fertilizers is certainly a matter of serious concern in many states.

The challenges for fertilizer/nutrient management are to maintain (and where possible increase) sustainable crop productivity to meet demands for food and raw materials (Jat et al., 2016a,b). The environmental hazards can be minimized by matching plant nutrients with crop requirements (Jat et al., 2013). The high cost of external sources of nutrients and their inadequate availability limit the intensification. Fertilizer use research is required to know how much nutrient should be added and which plant nutrients they should supply to achieve the optimum economic increase in yield without damaging the soil and environmental health (Jat et al., 2013). The escalating prices of chemical fertilizers and soil degradation have increased attention to develop Integrated Plant Nutrition Systems (IPNS) that maintain or enhance the soil productivity through a balanced use of mineral fertilizers combined with organic sources (*e.g.*, crop residues, biomass ashes etc.) of plant nutrients.

Current fertilizer recommendations are based upon crop response data averaged over large geographic areas without considering indigenous nutrient supplying capacity of soils. Such blanket fertilizer application, therefore, results into under-fertilization in some cases and over-fertilization in the others. This leads to low NUE, low profits and increased environmental problems. Nutrient management strategies in cereal-based cropping systems in India will have to be formulated keeping in view the dual challenge of substantially increasing agricultural productivity and sustainability. Conservation agriculture (CA)-based crop management technologies may be the one option to quickly address two critical concerns faced by Indian agriculture today - low farm income and degrading natural resources in north-western (NW) India. Burning of huge quantity of rice residues by the farmer's is a serious issue in North-West India. Burning of crop residues leads to loss of plant nutrients (all amount of C, 80% of N, 25% of P, 50% of S, and 20% of K), and adversely impacts the soil and environment health (Lohan et al., 2018). The efficiency of fertilizer use could be improved through 4R nutrient stewardship (**right** rate, **right** source, **right** timing, and **right** place) and precision nutrient management practices that are specific to field, soil, climate, and crop management (Majumdar et al., 2013). Crop residues as soil cover in CA can help in minimizing adverse impact of burning on air pollution and will lead to improvement in soil health. Precision nutrient management is equally important for increasing NUE in both conventional agriculture and CA systems.

1. Precision Nutrient Management Tools/Software

Nutrient management is the science and practice directed to link soil, crop and weather factors with cultural, irrigation, and soil and water conservation practices to achieve optimal NUE, crop yields, crop quality, and economic returns, while reducing nutrient losses and impact on the environment. It involves matching a specific field, soil, climate, and crop management conditions to rate, source, timing, and place (commonly known as the 4R nutrient stewardship) of nutrient application. Soil test-based fertilizer management recommendations have served the purpose of improving food grain production but have not improved the NUE beyond a certain limit. Strategy for assessing plant nutrient demand is more efficient as plant growth at any given time integrates the effect of nutrient supply from all the sources and thus a reliable indicator of its availability. The availability of quick and non-destructive measures (*e.g.*, optical sensors, chlorophyll meter, leaf color chart, Nutrient Expert) to quantify spectral characteristics of leaves have successfully facilitated the task of making in-season need-based N application and increasing NUE in crops. These tools have provided an excellent opportunity in terms of developing need-based N management strategies for cereal crops. The hand-held model of the optical sensor is now affordable for large scale adoption in Indian agriculture. Nutrient Expert decision support tools have been developed and validated for major cereal-based crops and are freely available for use. These tools enhance the ability to fine-tune nutrient management decisions and develop the site-specific nutrient management (SSNM) plan for each field. Managing the '4R'nutrient stewardship is best accomplished with the right tools for crop-location specific nutrient management practices.

Nutrient management through modern tools and management practices aims to optimize the supply of

Figure 1. Schematic diagramme of 4R plant nutrient management in cereal-based systems (Source: Sapkota et al. 2014).

soil nutrients over time and space to match the requirements of crops based on the '4R' stewardship (**Figure 1**): (a) **Right product**: Match the fertilizer product or nutrient source to crop needs and soil type to ensure balanced supply of nutrients, (b) **Right amount**: Match the quantity of fertilizer applied to crop needs, taking into account the current supply of nutrients in the soil., (c) **Right time**: Ensure nutrients are available when crops need them by assessing crop nutrient dynamics. This may mean using split applications of mineral fertilizers or combining organic and mineral nutrient sources to provide slow-releasing sources of nutrients, and (d) **Right place**: Placing and keeping nutrients at the optimal distance from the crop and soil depth so that crops can use them and is key to minimizing nutrient losses.

The Nutrient Expert® Decision Support Tool

Nutrient Expert® is an easy-to-use, interactive computer-based decision support tool that provides nutrient recommendation for individual farmers' individual fields with or without soil test data. This newly developed Decision Support System (DSS) is being validated as well as promoted for enhanced yield, economic returns and NUE while reducing environmental foot prints (Sapkota et al., 2014; Jat et al., 2013; Majumdar et al., 2012; Satyanarayana et al., 2014). The software estimates the nutrient requirement based on attainable yield by combining information like fertilizer/manure applied, crop residue retained in the previous crop, crop growing conditions, etc. with expected N, P and K responses in target fields to generate location-specific nutrient recommendations for crops (rice, wheat and maize). The software also does a simple profit analysis comparing costs and benefits between farmers' current practice and recommended alternative practices (http://software.ipni.net/article/nutrient-expert).

Crop Manager

Crop Manager is a computer and mobile phone-based application that provides small-scale rice, rice-wheat, and maize farmer's with site and season specific recommendations for fertilizer application. The tool allows farmers to adjust nutrient application to crop needs based on soil characteristics, water management, and crop variety on their farm. Recommendations are based on user-input information about farm location and management, which can be collected by extension workers, crop advisors, and service providers. The software is freely downloadable at http://cropmanager.irri.org/home.

Optical Sensors- GreenSeeker

Farmer's and researchers can use optical sensors to develop SSNM recommendations, particularly for N. Optical sensors measure reflectance from the leaves to generate a vegetative index called Normalized Difference Vegetation Index (NDVI), which measures the nutrient status of the plants based on their size and leaf colour. The original technology was developed for large farms; however, a small handheld version that costs a fraction of the original technology (approximately Rs. 40,000) is now commercially available (www.nue.okstate.edu/Algorithm/Algorithm_Outline.htm.). GreenSeeker is an integrated optical sensing and application system that measures crop status in response to the crop's nitrogen requirements and its application in right amount, in the right place and at the right time in real time (4R-stewardship). A simple farmer-friendly android cell phone application was developed using NDVI value of the GreenSeeker for precisely computing the amount of urea for topdressing for increasing N use efficiency. Snapshot of GreenSeeker-based N application in maize crop and urea calculator is shown in **Figure 2**.

Leaf Color Chart

Leaf color chart (LCC) is a simple, easy-to-use, and inexpensive alternative to chlorophyll meter and is particularly beneficial for individual income-poor farmers. Use of LCC enhances the ability to fine-tune N management decisions and develop the SSNM plan for each field. LCC has provided an excellent opportunity in terms of developing real-time N management strategies for rice.

2. Precision Nutrient Management Under Conventional Agriculture Systems

Recently, Choudhary and Yadvinder-Singh (2019) have provided pertinent information on issues and strategies for enhancing NUE in irrigated agriculture system. This section is mainly focused on precision nutrient management for increasing NUE in cereal crops.

Need-based Fertilizer Nitrogen Management in Transplanted Rice using LCC

Results from several on-farm experiments revealed that using LCC with a threshold value of 4 increased fertilizer N-use efficiency in rice under different rice cultivars (Yadvinder-Singh et al., 2007). Based on 350 on-farm locations in Punjab, reported that following LCC 4 based N-management saved 9.4 to 54.2 kg N ha^{-1}, with an average of about 25% without any reduction in yield as compared to farmers' practice of applying blanket N at fixed time intervals. Application of fertilizer N using LCC increased agronomic N-use efficiency from 48 kg grain kg^{-1} N to 65 kg grain kg^{-1} N.

Bijay-Singh et al. (2012) established another approach known as fixed-time adjustable dose site-specific fertilizer N management using LCC to avoid frequent monitoring of leaf colour. The criteria were developed to apply fertilizer N at critical growth stages of rice but by adjusting the dose of N using LCC. A dose of 30 kg N ha^{-1} at transplanting as prescriptive N management proved to be adequate for achieving high yields of rice. Corrective N management consisting of adjustable N doses was worked out as application of 45, 30 or 0 kg N ha^{-1} depending upon leaf colour to be $<$ LCC shade 4, between LCC shade 4 and 5 or $\geq$ LCC shade 5 both at maximum tillering and panicle initiation stages, and 30 kg N ha^{-1} only if leaf colour is less green than LCC shade 4 at initiation of flowering. A combination of these prescriptive and corrective N management strategies resulted in optimum rice grain yield and high N-use efficiency with less fertilizer N application than the blanket recommendation. Bijay-Singh et al. (2015) found that high N-use efficiency and optimum yield of transplanted rice can be achieved by applying a moderate amount of N fertilizer at transplanting, enough N fertilizer at active tillering, and an optical sensor-guided N fertilizer dose at panicle initiation stage.

Precision N Management in Direct Seeded Rice

Dry direct-seeded aerobic rice (DSR) is an emerging attractive alternative to traditional puddled transplanted rice (PTR) production system for

Figure 2. GreenSeeker-based N application in maize crop (Source: CA Research Platform, Karnal)

reducing labour and irrigation water requirements in the Indo-Gangetic Plains (IGP). In a 3-year study, critical LCC and SPAD meter values for fertilizer N application were worked out to be 4 and 37, respectively. Real-time fertilizer N management strategy based on applying 30 kg N ha^{-1} whenever SPAD meter or LCC readings fall below the critical values maintained optimum rice yields along with higher N-use efficiency than that observed by following blanket recommendation for fertilizer N in the region. The fixed-time variable-dose strategy consisted of applying prescriptive doses of 20 kg N ha^{-1} at 14 days after seeding (DAS) and 30 kg N ha^{-1} at 28 DAS and corrective doses at 49 and 70 DAS depending upon LCC shade and SPAD meter readings. This strategy resulted in optimal rice yield along with higher N-use efficiency as compared to the blanket recommendation (Ali et al., 2015). Results from another 3-year study showed that basal N application in DSR was not necessary and might lead to reduced N-use efficiency. Highest mean grain yield of 6.6 t ha^{-1} was obtained when N was applied in three equal split doses at 14, 35 and 63 DAS which was about 8.5% higher compared with N applied in four equal split doses at 14, 28, 49 and 70 DAS. Under the best N application schedule, the agronomic use efficiency and recovery efficiency of applied N were 26 kg grain kg^{-1} N and 49%, respectively (Thind et al., 2017).

Need-based Fertilizer N Management in Wheat

Bijay-Singh et al. (2011) developed a robust relationship between in-season GreenSeeker optical sensor-based estimates of yield at Feekes 5-6 and 7-8 growth stages and actual wheat yields. Prescriptive N management in the form of applying different amounts of fertilizer N at planting and the crown root initiation stage of wheat, and whether optical sensor-guided N dose applied at either Feekes 5-6 or Feekes 7-8 stage, influenced the amount of fertilizer N to be applied following the N fertilizer optimization algorithm. Study showed that the optical sensor-guided fertilizer N applications resulted in high yield levels and high N-use efficiency. A simple farmer friendly android cell phone application was developed using NDVI value of the GreenSeeker for precisely computing the amount of urea for topdressing for increasing the N use efficiency in wheat.

Need-based Fertilizer N Management using LCC in Maize

Field experiments were conducted to evaluate the threshold LCC guided need-based fertilizer N management in maize (Varinderpal-Singh et al., 2011). Results indicated that LCC shade 5 during vegetative growth stages and LCC shade 5.5 at silking stage (R1) could guide crop demand-driven N applications in maize. Evaluation of the established threshold leaf greenness revealed that fertilizer N management using LCC 5 starting from sixth leaf (V6) stage to before R1 stage improved N-use efficiency in different maize genotypes. Using threshold LCC shade 5 saved 25 to 50% of fertilizer-N. On an average, the LCC-based fertilizer-N management produced grain yield equivalent or more than the blanket N recommendation with less (20 kg N ha^{-1}) fertilizer.

Integrated Plant Nutrient Management (IPNM)

The high fertilizer cost and low purchasing power of the farming community have made it necessary to rethink on alternative sources of nutrients. Diverse nutrient sources can be used in an integrated manner to meet the external nutrient supplies of any cropping system. Integrated plant nutrient management (IPNM) that takes advantage of the recycling of nutrients in manures and crop residues, supplementing them with commercial fertilizers offers great possibilities for saving resources, protecting the environment and promoting more economical cropping. What the country needs today is the conjunctive use of organic and inorganic sources of plant nutrients for sustainable crop productivity. The total nutrient (NPK) potential of various organic resources was estimated at 14.85 Mt in 2000, which will be around 32.41 Mt by 2025. The amount of NPK contained in rice and wheat residues produced in the country is nearly 4.1 Mt. In addition, approximately 25 Mt of rice husk and about 4.5 Mt of rice husk ash are produced in India. In fact, when the application rates of manure are calculated on the N crop requirement, the amount of P added often exceeds the plant P requirement, resulting in soil P accumulation, *e.g.* high P content in press mud cake (PMC). Improved synchronization between N net mineralization from organic material and plant N demand has been advocated as a means for improving the N-use efficiency, especially in the tropical cropping systems. It is essential that adequate amounts of N are present during plant N uptake periods, whereas minimal amounts of N should be present during periods of no N uptake and when there is a high risk of leaching.

A three-year study showed that application of poultry manure (5 t ha^{-1} on dry weight basis) along with 60 kg fertilizer N ha^{-1} produced rice grain yield equivalent to that produced in the recommended fertilizer treatment of 120 kg N ha^{-1} (Yadvinder-Singh et al., 2009). The residual effect of poultry manure in the following wheat was equivalent to 30 kg N and 30 kg P_2O_5 ha^{-1}. Application of poultry manure for 3 years resulted in significant increase in the organic C, and available P and K contents of soil (Yadvinder-Singh et al., 2009).

About 9.0 Mt of PMC is produced annually from the

Table 1. Effect of press mud cake (5 t ha^{-1} on dry weight basis), and fertilizer N and P on grain yield and organic carbon and available P content of soil in rice-wheat rotation (Yadvinder-Singh et al., 2008)

Fertilizer doses		Average grain yield (t ha^{-1})		Organic C (%)	Available P (mg kg^{-1})
Rice	Wheat	Rice	Wheat		
120 kg N ha^{-1}	120 kg N + 60 kg P_2O_5 ha^{-1}	5.6	5.3	0.32	4.9
PMC + 60 kg N ha^{-1}	80 kg N + 30 kg P_2O_5 ha^{-1}	5.6	5.2	0.39	12.1
PMC + 60 kg N ha^{-1}	80 kg N + 60 kg P_2O_5 ha^{-1}	5.5	5.3	0.38	13.6
PMC + 60 kg N ha^{-1}	120 kg N + 30 kg P_2O_5 ha^{-1}	5.5	5.4	0.40	12.3
PMC + 60 kg N ha^{-1}	120 kg N + 60 kg P_2O_5 ha^{-1}	5.6	5.3	0.38	14.0

sugar industries in India. The PMC produced from the sugar industries contains about 1.8-2.25% N, 0.8-1.2% P, 0.4-0.6% K, in addition to significant amounts of micronutrients. Experiments conducted at PAU, Ludhiana showed that application of PMC (5 t ha^{-1}, dry weight basis) along with 60 kg fertilizer N ha^{-1} produced rice grain yield equivalent to that produced in the recommended fertilizer treatment of 120 kg N ha^{-1} (**Table 1**). Application of 80 kg N + 30 kg P_2O_5 ha^{-1} on PMC plots produced wheat yield equivalent to 120 kg N + 60 kg P_2O_5 ha^{-1} on non-amended plots. Residual effect of PMC in the following wheat was thus equivalent to 40 kg N + 30 kg P_2O_5 ha^{-1}. Application of PMC for 4 years caused significant increase in organic carbon and available P content of the soil. The sharp increase in P availability in PMC plots and maintaining it at high levels over long periods will be beneficial in meeting the P requirement of crops.

Applying rice husk ash (RHA) and bagasse ash (BA) on agricultural land improves yield, nutrient uptake and chemical fertility of soil with special reference to available P and K. Application of fertilizer P increased the wheat grain yield up to 60 kg P_2O_5 ha^{-1} in the un-amended control treatment. However, significant response of wheat to fertilizer P was observed up to 30 kg P_2O_5 ha^{-1} in the presence of BA and RHA, thereby incurring 50% saving on fertilizer P. Both RHA and BA increased the wheat productivity by 12% and 16% over un-amended control, respectively. Subsequent rice crop also produced 14% higher paddy yield, when these ashes were applied along with 30 kg P_2O_5 ha^{-1} to previous wheat. These increases in grain yield were accompanied by significant increases in the Olsen P content in soil. The application of recommended P without biomass ash resulted in negative P balance of 21 kg P_2O_5 ha^{-1}. On the other hand, application of BA alone and RHA along with 30 kg P_2O_5 ha^{-1} resulted in neutral or positive P balance. Thus, it can be concluded from this study that the recycling of biomass ashes with reduced application of fertilizer P, improves the system productivity and economic returns and will go a long way to reduce the environmental pollution.

Green Manuring and Crop Residue Management in Rice-Wheat System

A 4-year field study evaluated the effects of green manure (GM), crop residue and tillage on crop yields, economic profitability and soil fertility in a rice-wheat (RW) system (Thind et al., 2019). The results showed that rice yield was significantly higher by 8% with 50% less fertilizer N application in GM compared with conventional puddled transplanted rice (PTR) with no GM. The ZT (zero tillage) wheat sown into rice residue produced significantly higher mean wheat grain yield by 7.3 and 17.5% compared with CT and ZT wheat with no residue, respectively. System productivity was 11.5% higher in PTR with wheat stubble. GM followed by ZT wheat + residue compared with the conventional RW system gave Rs. 24,075 ha^{-1} more profit. Significant increases in soil organic carbon, available P and available K contents were recorded under ZT wheat + residue compared to CT wheat. Recycling rice and wheat stubble in the field in RWS is also environment-friendly as it avoids ill-effects of straw burning.

3. Precision Nutrient Management in Conservation Agriculture (CA) System

Adoption of CA-based management practices under different production systems and ecologies can address the emerging challenges of natural resource degradation, labour crises, instability in crop yields, high production costs, low input-use efficiency and adverse effects of climate change. The contrasting tillage management practices (intensive and zero/minimum) will have implications on nutrient response and economic profitability through changing soil moisture regime and nutrient dynamics. In CA, use of crop residues as biological mulch immobilizes a portion of applied N in the initial years

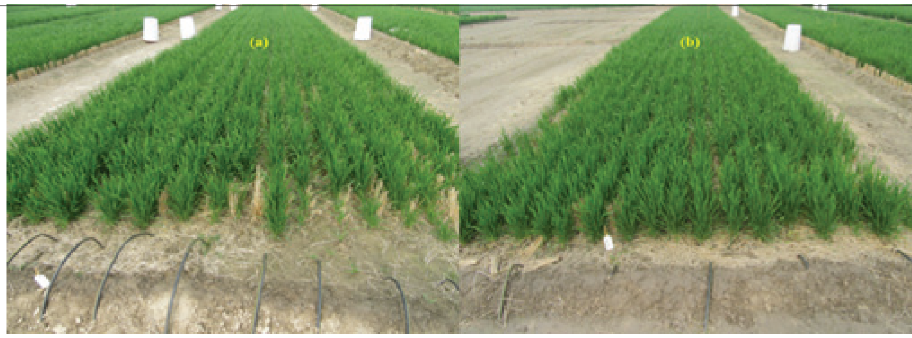

Figure 3. Sub-surface drip irrigation (fertigation) system in wheat in CA-based rice-wheat system (Source: Borlaug Institute for South Asia, Ladhowal, Punjab)

but supplies additional N through mineralization in subsequent years, which needs to be factored out while designing nutrient management practices in CA. Zero tillage and residue retention in CA substantially influence the nutrient dynamics in soil; thus precise management requires special attention. Experiences showed that current fertilizer application practices under CA need to be revised to improve NUE and crop productivity. Therefore, there is a need to develop nutrient and irrigation management options suited for CA-based cropping systems that can be adopted at the farmers' level with minimum use of input to sustain crop productivity while addressing environment and health related issues.

Fertigation using Sub-surface Drip Irrigation (SDI)

Fertigation is a method of fertilizer application in which fertilizer is applied with irrigation water (**Figure 3**). In this method liquid fertilizer as well as water soluble fertilizers are used. Fertigation under sub-surface drip leads to less loss of nutrients resulting into higher NUE and lesser environmental foot prints. In SDI system, water and nutrients are supplied near the active root zone which results in higher nutrient and water use efficiencies by higher absorption with less energy. Thus, proper delivery of fertilizer (both in horizontal and vertical dimension) is very crucial to ensure that plant roots can absorb required nutrient during the growing period and thereby increase the NUE in the cropping systems.

4. Evidences from the Fertilizer Use Research in Cereal-based Systems of IGP

Effect of CA and Precision Nutrient Management on Crop Yields and Profitability

Nutrient Expert® (NE) based nutrient management in maize, rice, and wheat increased the crop productivity by 10-12, 5-8, and 12-15% compared with farmers' fertilizer practice (FP), respectively (**Table 2**). Higher yields of cereal crops are facilitated due to balanced fertilization and better synchronization of nutrient as per plant needs. Higher net returns were associated with NE than FP due to higher crop yields (**Table 2**). Result revealed that GreenSeeker (GS)-guided real time N supply with moderate amount of N fertilizer application to meet

Table 2. Effect of conservation agriculture and precision nutrient management on crop productivity and profitability in wheat-based systems

Crop	Technology	Grain yield (t ha^{-1})	Net return (Rs. ha^{-1})	Reference	Experimental Site
Maize	Nutrient Expert	7.5-8.0	91,000-1,04,000	Jat et al. (2018)	Karnal, Haryana
	Farmers' Fertilizer Practice	6.7-7.2	81,250-91,000		
Wheat	Nutrient Expert	5.2-5.4	58,500-68,250	Jat et al. (2018); Sapkota et al. (2014}	Karnal, Haryana
	Farmers' Fertilizer Practice	4.8-5.0	55,250-58,500		
Rice	Nutrient Expert	7.0-7.5	65,000-68,250	Kakraliya et al., (2018, 2019)	Climate Smart Village, Karnal
	Farmers' Fertilizer Practice	7.0-7.2	61,750-65,000		
Rice	Leaf Color Chart	6.68	-	Thind et al. (2010)	Ludhiana, Punjab
	RDF (120 kg N ha^{-1})	6.38	-		
Rice	GreenSeeker	7.2-7.5	61,750-71,500	Singh et al. (2015);	Ludhiana and Karnal
	Farmers' Fertilizer Practice	6.8-7.0	58,500-65,000	Kakraliya et al. (2019)	
Wheat	GreenSeeker	5.8-6.2	66,300-70,200	Singh et al. (2015); Kakraliya et al. (2019)	Ludhiana, Karnal and Modipurm
	Farmers' Fertilizer Practice	5.4-5.6	55,250-61,750		
Maize	GreenSeeker	7.0-7.5	92,300-97,500	Jat et al. (2013);	Karnal, Haryana
	Farmers' Fertilizer Practice	6.8-7.0	78,000-81,250	Jat et al. (2018)	

the N demand during the period between knee high and tasseling stage, resulted not only in higher yields but also in higher net return in irrigated maize crop. Leaf color chart (LCC) improved the rice yield by 1.6 to 2.5 q ha^{-1} compared to farmer practice (**Table 2**) as LCC facilitated the real-time N management based on the crop N demand. In on-farm experiments in India, Kakraliya et al. (2018) observed that GreenSeeker-based N management in rice and wheat crop increased productivity and profitability by 8 and 12% compared to FP, respectively. The data from on-farm sites suggest that farmers are using N fertilizers in rice and wheat very inefficiently and there is a huge scope to improve fertilizer NUE by following optical sensor-based strategies.

Results from 2-year study show that yield of direct seeded rice (DSR) was higher under sub-surface drip irrigation (SDI) by 0.4 t ha^{-1} (2-yr mean) compared to flood irrigation (**Table 3**). Conservation agriculture integrated with SDI (called CA^+) has other advantages like savings in labour, time, water, energy, and cost compared to basin/ flood irrigation (Sidhu et al., 2019). Compared with CA-based DSR, maize recorded higher rice equivalent yield (REY) in both the years (Sc IV and Sc VI). Results from our study showed lower production costs and higher profitability in CA-based scenarios (rice/maize- based systems) compared to business as usual. The higher profitability under CA^+ (Sc V and Sc VI) was mainly due to combined effect of lesser amount of irrigation and fertilizer costs, and partly due to higher crop productivity. The SDI system resulted in incremental trend in yield of maize compared with flood irrigation (**Table 3**).

Bed planting of crops, straw mulching and drip irrigation are known to save precious irrigation water, and improve N-use efficiency and grain yields. Sandhu et al. (2019) studied the effect of surface drip irrigation, residue management, and N application on crop and water productivity in maize-wheat system under permanent raised planting. Yields of maize and wheat under drip irrigation with residue retention system were 13.7 and 23.1% higher compared to furrow irrigation with no residue, respectively. Surface drip irrigation with residue retention saved 88 mm and 168 mm of water and increased water productivity by 66 and 259% in CA-based wheat and maize compared to the conventional furrow irrigation system with residue removal, respectively.

Effect of Band Placement of Fertilizers on Yields and Nutrient Use Efficiency

A saving of 30 kg N ha^{-1} was observed in both maize and wheat by deep placement of 90 kg N ha^{-1} on beds compared to uniform broadcast/ top-dress method

Table 3. Effect of CA-based precision water and nutrient management on grain yield and net returns under different scenarios during years 2016-17 and 2017-18 (Source: Jat et al., 2019)

Scenarios	Grain yield (t ha^{-1})			Net return ($Rs.ha^{-1}$)		
	Rice	Wheat	System	Rice/Maize	Wheat	System
2016-17						
ScI	7.51^{Aa}	5.47^{C}	13.40^{B}	$64,869^{B}$	$54,863^{C}$	$119,732^{C}$
ScII	7.39^{B}	5.72^{BC}	15.08^{A}(0.50)#	$65,200^{B}$	$67,651^{BC}$	$147,429^{B}$
ScIII	5.88^{C}	6.35^{AB}	13.19^{B}(0.15)	$46,713^{C}$	$81,169^{AB}$	$127,551^{C}$
ScIV	7.12^{AB} (7.66)*	6.53^{AB}	14.62^{A}(0.15)	$82,361^{A}$	$82,361^{A}$	$164,457^{A}$
ScV	6.21^{C}	6.79^{A}	14.12^{AB}(0.20)	$56,454^{BC}$	$86,271^{A}$	$144,712^{B}$
ScVI	7.61^{A} (8.20)	6.38^{AB}	15.14^{A}(0.22)	$85,409^{A}$	$80,440^{AB}$	$168,764^{A}$
2017-18						
ScI	6.57^{C}	5.88^{C}	13.33^{C}	$52,677^{B}$	$76,000^{C}$	$128,611^{D}$
ScII	6.85^{BC}	6.06^{BC}	16.19^{AB}(0.74)	$59,965^{B}$	$89,186^{B}$	$170,089^{BC}$
ScIII	5.85^{C}	6.58^{AB}	14.86^{BC}(0.45)	$47,045^{B}$	$98,727^{B}$	$157,566^{C}$
ScIV	7.14^{AB} (7.90)	6.49^{AB}	$16.04^{AB(}$0.45)	$77,458^{A}$	$97,336^{B}$	$186,456^{AB}$
ScV	6.38^{C}	6.61^{AB}	15.61^{AB}(0.51)	$60,098^{B}$	$1,01,179^{A}$	$176,119^{BC}$
ScVI	7.35^{A} (8.13)	6.79^{A}	16.85^{A}(0.53)	$80,771^{A}$	$1,04,293^{A}$	$201,033^{A}$

ScI: conventional-till (CT) rice-CT wheat (farmers' practice); ScII: CT rice-zero tillage (ZT) wheat-ZT mung bean with flood irrigation (partial CA); ScIII: ZT rice-ZT wheat-ZT mung bean with flood irrigation (CA RW); ScIV: ZT maize-ZT wheat-ZT mung bean with flood irrigation (CA MW); ScV: ZT rice-ZT wheat-ZT mung bean with SDI (CA^+ RW); and ScVI: ZT maize-ZT wheat-ZT mungbean with SDI (CA^+ MW)

[a]Means followed by a similar uppercase letter(s) within a column in a given year are not significantly different at 0.05 level of probability using Tukey's HSD test

Figures in parenthesis are actual yield of maize* and mung bean#

Table 4. Effect of residue and N management on grain yield and recovery efficiency of N (RE_N) in maize-wheat system (2-year mean) (Sandhu et al., 2020)

Levels and methods of N application	Wheat		Maize	
	Grain yield (t ha^{-1})	RE_N (%)	Grain yield	RE_N (%)
N_0	2.26^e	-	3.06^g	-
N_{90}-Broadcast	4.22^d	52.6^c	4.97^f	55.0^e
N_{90}-Deep placement on beds	4.49^{bc}	66.6^{ab}	5.67^d	88.0^b
N_{120}–Broadcast	4.57^b	61.1^{bc}	5.98^c	74.4^{cd}
N_{120}-Deep placement on beds	4.89^a	72.8^a	6.63^a	98.5^a

[b]Means followed by a similar uppercase letter(s) within a column in a given year are not significantly different at 0.05 level of probability.

with 120 kg N ha^{-1} to obtain similar yields. Deep placement of fertilizers increased the maize and wheat yields by 10.9 and 7% compared to uniform broadcast, respectively (Sandhu et al., 2020). At 120 kg N ha^{-1}, NUE of 61 and 74% with broadcast application increased to 73 and 98% with deep placement in wheat and maize, respectively (**Table 4**).This is ascribed to the fact that the placement of fertilizer near the seed-row may increase access of crops to the nutrient early in the growing season and provide a 'starter' effect that improves early growth. Applying nutrient at the right place (both in horizontal and vertical dimension) in the soil ensures that the plant roots can absorb higher amount of each plant nutrient compared to broadcast application during the crop growing season.

Effect of CA on Fertilizer Saving

Results from a long-term study on CA based practices in rice-wheat (RW) and maize-wheat (MW) systems showed that wheat after 4 years of continuous CA required 30% less N and 50% less K fertilizer compared to conventional-till (CT) RW system with similar yields at same management practices (**Table 5**). This might be due to the addition of nutrients through residues which leads to improved physical environment and microbial activity that helped in higher mineralization resulting in the enhanced availability of nutrients to crops and thus increased the N-factor productivity under these CA based practices (Singh et al., 2015; Kakraliya et al., 2019).

Fertilizer Management in Zero-till Wheat with Straw Mulch in Rice-Wheat System

A 2-year study highlighted that on medium-textured soil (loam), drilling 50 or 75% of recommended fertilizer N at sowing significantly increased grain yield by about 10% in comparison with drilling 20% at sowing with the remainder applied in two equal splits before the first and second irrigations in wheat sown into rice residue (Yadvinder-Singh et al., 2015). On a coarse-textured soil (sandy loam), drilling more than 50% of the recommended fertilizer N at sowing significantly reduced grain yield and RE_N, and the reduction in yield with 100% of the N drilled at sowing was much greater on the sandy loam than on the loam. Results from another study by Yadvinder-Singh et al. (2015) showed that drilling of 24 kg N ha^{-1} as di-ammonium phosphate at seeding stage using Happy Seeder followed by 2-top dressings of 48 kg N ha^{-1} each just prior to first and second irrigations resulted in significant increases in

Table 5. Response of wheat (t ha^{-1}) to N and K in CA plots under rice-wheat and maize-wheat cropping systems (Jat et al., 2018)

Treatment	CT-RW	CA-RW	CA-MW
N (% of 160 kg N ha^{-1})			
100	5.33a	4.99bc	5.30ab
85	5.12a	5.48a	5.42a
70	4.63b	5.32ab	5.16b
55	3.56c	4.62c	4.98c
0	2.41d	3.83d	3.68d
K (% of 60 kg K_2O ha^{-1})			
100	5.00a	5.01a	5.35a
50	4.52b	5.06a	5.40a
0	4.36c	4.50b	5.05b

Where; CT-Conventional till, CA- Conservation agriculture, RW- Rice-Wheat, MW- Maize-Wheat
Values with-in the same column differ significantly at P = 0.05 when not followed by the same small letter (s) according to Duncan Multiple Range Test for separation of mean.

Table 6. Effect of method and time of N fertilizer application on yield and recovery efficiency of N (RE_N) of wheat sown into rice residue using Happy Seeder (Yadvinder-Singh et al., 2015).

Treatment (N applied at sowing —before 1st irrigation—2nd irrigation) (total N applied is 120 kg ha^{-1})	Grain yield (t ha^{-1})	RE_N (%)
25D*+35B**—0—0	4.42b	45.0b
25D+35B—30—30	4.29bc	44.1bc
25D+65B**—0—30	4.27bc	41.9bc
25D+95B—0—0	4.02c	39.1c
25D*+35B—48—48	4.79a	59.7a
25D +-35PSI***—60—0	4.37b	47.8b
25D*+35PSI—30—30	4.36b	49.4b

*D- Drilling, **B-Broadcast, ***PSI- Pre-sowing irrigation
Values in a column not followed by same letter differ significantly.

grain yield and N-use efficiency in zero till wheat with rice residue as mulch compared to currently followed practice of applying fertilizer N in two equal split doses at sowing and with first irrigation (**Table 6**).

SSNM for Increasing N Use Efficiency under CA

Nutrient Expert ® (NE), DSS modules for wheat and hybrid maize for South Asia were developed by IPNI and CIMMYT and released in 2013 for public use (http:/ / blog.cimmyt.org/tag/nutrient- expert/). The SSNM aims to supply crop's nutrient requirements tailored to determine the nutrient balance in the cropping system based on yield and fertiliser/manure applied and residue retained 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 crops (rice, wheat, maize, etc.). The NE- maize tool was able to capture the inherent differences between conventional and CA practices of crop management, and the NE-based fertilizer recommendations generated on the principles of SSNM performed better than FP and state fertilizer recommendation for maize. Better efficiency of nutrients applied according to NE recommendations than in farmers' practice indicates that location-specific nutrient application rate and better timing of nutrient application (*i.e.,* increased number of splits and matching physiological demand of the crops) reduced N losses and enhanced the efficiency of nutrient utilization. The NE-based applications of P resulted into higher partial factor productivity (PFP) than the application based on state recommendation (SR) and farmers' practice. Partial factor productivity of N (PFP_N) based on NE was significantly different from farmers' practice but not from that of state recommendation under both the tillage methods (Sapkota et al., 2014). Declining factor productivity in wheat production is now a serious issue in India and the current results clearly show that the ZT system of wheat production and SSNM could significantly improve the PFP of applied nutrients.

At Pusa, Bihar, farmers' fertilization practices (FFP), ad-hoc state recommendation, Nutrient Expert ® and GreenSeeker™-based nutrient prescription with different combinations of fertilizer application methods were tested in wheat to decide on the optimum nutrition of crop in CA. The ad-hoc recommendation for state was 150, 60 and 40 kg N, P_2O_5 and K_2O ha^{-1}, respectively. Results showed that drilling of the fertilizer nutrients improved NUE, crop productivity and profitability of wheat (**Table 7**). Under CA practices, drilling of same amount of nutrient increased the grain yield by 430 kg ha^{-1}.

Increased dose of N and K increased grain yields and net return with drilling. Drilling of same amount of N, P and K improved the NPK use efficiency (kg grain

Table 7. Precision nutrient management in wheat (Source: Jat, R.K., unpublished)

Tillage practice	Nutrient management	Grain yield (t ha^{-1})	Additional cost (Rs. ha^{-1})	Additional income (Rs. ha^{-1})
T1-CT	FFP (BC, BI)	4.26	0	0
T2-CT	FFP (BC, AI)	4.61	0	4,947
T3-PB	Ad-hoc state recommendation (BC)	4.89	0	8,795
T4-PB	Ad-hoc state recommendation (D)	5.31	1,000	12,350
T5-PB	Ad-hoc SR - 80% N in 2 splits, 3rd N split based on GreenSeeker(D)	5.44	1,504	13,588
T6-PB	Nutrient Expert based NPK rates (BC)	4.90	658	8,364
T7-PB	Nutrient Expert based NPK rates (D)	5.52	1,658	16,018
T8-PB	Nutrient Expert based NPK rates - 80% N in 2 splits, 3rd N split based on GreenSeeker (D)	5.56	1,658	16,523

Where; BC- Broadcast; D- Drilling of fertilizer; BI- Before irrigation; AI: After irrigation

Table 8. Interaction effect of tillage and nutrient management practices on grain yield (3 yrs' mean) of maize and wheat

Tillage	Nutrient management			
	*FFP	**GRD	***Nutrient Expert ® (SSNM)	Mean
Maize				
CT	3.62	3.85	4.33	3.93
PB	3.78	4.82	4.90	4.50
ZT	3.94	4.60	4.76	4.43
Mean	3.78	4,42	4.33	
Wheat				
CT	3.65	4.45	4.84	4.31
PB	4.16	5.04	5.32	4.84
ZT	3.91	4.89	5.05	4.62
Mean	3.91	4.79	5.07	

* Fertilizers in the farmers' fertilizer practice (FFP) applied were 110:30:0 and 172:57.5:0 kg ha^{-1} of N: P_2O_5: K_2O for maize and wheat, respectively.

** State general recommended fertilizer doses (RDF) were 150:60:40 kg ha^{-1} and 120:60:40 kg ha^{-1} of N: P_2O_5: K_2O for maize and wheat, respectively.

*** Site-specific nutrient management (SSNM) doses for maize and wheat worked out by Nutrient Expert® were 170:37:44 and 155:63:65 kg ha^{-1} of N: P_2O_5: K_2O (average of 3 years) for maize and wheat, respectively.

kg^{-1} nutrient applied) compared to broadcasting in CA but increased dose of N and K decreased the N and K use efficiency. In a 3-year study (**Table 8**) among tillage practices, ZT and PB practices enhanced grain yield of maize and wheat by 12.7-14.5 and 7.2-12.3% and reduced the system irrigation water requirement by 140–200 mm ha^{-1} and 200–300 mm ha^{-1}, respectively, compared to CT system; it resulted in higher water productivity (WP) by 18.4–39.0% (Jat et al., 2018). Significant interactions between tillage practices and nutrient management strategies were measured with respect to water use, WP and grain yield of maize-wheat (MW) system. Results showed that nutrient application on SSNM basis coupled with CA-based tillage practices (PB) in MW system has complementarity to attain higher system productivity and WP compared to the use of these crop management practices in isolation (Parihar et al., 2017). Combination of PB and SSNM increased the MW productivity by 23.1 and 40.6% compared with CT+RDF and CT+FFP, respectively. The layering of CA-based management practices with precision nutrient prescriptions using SSNM based decision support tools offers a new management paradigm for scaling up of the MW system in North-West IGP and can potentially help in diversifying RW system to address emerging challenges of water scarcity and system sustainability.

The partial factor productivity of N (PFP_N) of rice was significantly influenced with the layering of management practices. Climate smart agriculture practices; CSAPs (mean of S4-S6) improved PFP_N by 34.3 and 34.2% during first and second year, respectively compared to farmer practice (Kakraliya et al., 2018, 2019). This might be due to addition of nutrients through residue, improved physical environment and precision nutrient management (layering of Nutrient Expert + GreenSeeker + *Neem* Coated Urea) that helped in mineralization resulting into better availability of nutrients to crops and thus increased the nitrogen-use efficiency and helped in mitigating GHG emission, especially nitrous oxide (N_2O). Sapkota et al. (2014) conducted on-farm experiments in seven districts of Haryana to evaluate performance of NE- and NE+GreenSeeker-based nutrient management against current state recommendation and farmers' practice in wheat (**Figure 4**). Grain yield, nitrogen-use effciency and net return were higher under NE-based nutrient management strategies as compared to state recommendation and FFP. On an 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 fertilizer recommendation. The GHG emissions were higher with farmers' practice and lower under NE+GreenSeeker N management.

The least PFP_N in wheat was observed under S1 (26.9 kg grain kg^{-1} applied N) during both the years. While, highest PFP_N was recorded with S6 (41.9 kg grain kg^{-1} applied N) and being at par with S5 during first year, it was significantly higher over the rest of scenarios in second year. However, CSAPs improved PFP_N by 59% (2 years' mean) compared to S1 (**Figure 4**). The overall improvement in PFP_N of wheat crop was due to the residual effect of improved practices (layering of Nutrient Expert + GreenSeeker + *Neem* Coated Urea) that could be ascribed to their pivotal role in improving several physiological and bio-chemical processes, *viz*., root development, photosynthesis and energy transformation (ATP and ADP) (Kakraliya et al., 2018).

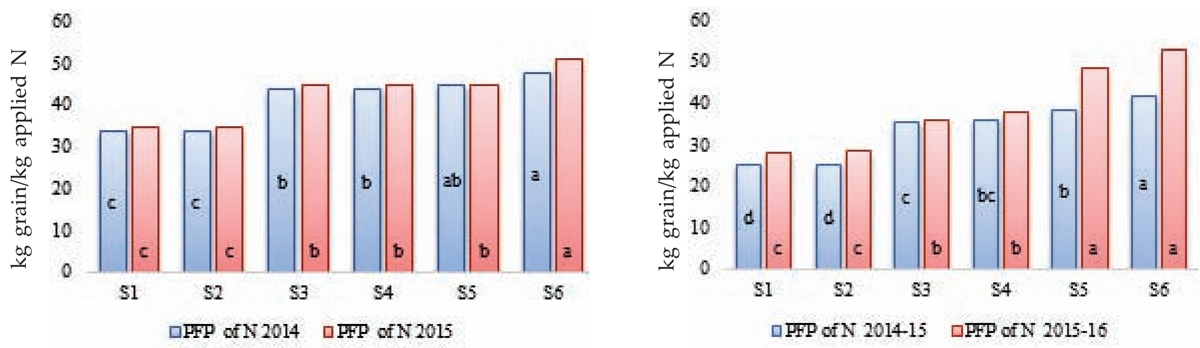

Figure 4. PFP_N of rice (left) and wheat (right) as influenced by different management practices during 2014 and 2015

Effect of Drip Fertigation System on N Use Efficiency

The conservation agriculture + sub-surface drip irrigation (CA^+) practices in rice (ScV) and maize (ScVI) improved the PFP_N by 20 and 33% (2-yr mean) compared to ScI (**Table 9**). Like rice and maize, the PFP_N of wheat was significantly higher with the sub-surface drip irrigation (SDI) compared to the flood irrigation in both partial CA (ScII) and CT (ScI) during both the years. The CA^+ system in wheat improved the PFP_N by 46% compared to the CT in rice (37.8 kg grain kg^{-1} N applied). The CA^+ based RW-mung bean (ScV) and MW-mung bean (ScVI) recorded 45 and 50% higher PFP_N compared to those of ScI and nearly31% higher compared to their respective CA-based systems (ScIII and IV), respectively. SDI layered with CA-based RW and MW systems has potential to save both irrigation water and fertilizer use with significant reduction in GHGs while producing same or even higher yields of major cereals. In another study on CA-based RW system, significantly higher PFP_N was recorded in subsurface drip irrigation compared to flood irrigation (Sidhu et al., 2019).

Table 9. Mean (averaged across 2-yrs) partial factor productivity of nitrogen (PFP_N) under different CA-based maize-wheat and maize-wheat scenarios at CSSRI, Karnal, Haryana (Jat et al., 2019)

Scenarios	PFP_N (kg grain kg^{-1} N applied)		
	Rice/Maize	Wheat	System
ScI	40.2	37.9	41.1
ScII	47.5	39.3	52.1
ScIII	36.7	43.1	45.2
ScIV	40.7	43.4	47.2
ScV	48.4	56.8	59.4
ScVI	53.4	54.9	61.5

Where; ScI: Conventional-till (CT) rice-CT wheat (farmers' practice); ScII: CT rice-Zero tillage (ZT) wheat-ZT mung bean with flood irrigation (partial CA); ScIII: ZT rice-ZT wheat-ZT mung bean with flood irrigation (CA RW); ScIV: ZT maize-ZT wheat-ZT mung bean with flood irrigation (CA MW); ScV: ZT rice-ZT wheat-ZT mung bean with SDI (CA^+ RW); and ScVI: ZT maize-ZT wheat-ZT mung bean with SDI (CA^+ MW)

Results from another study by Sandhu et al. (2019) showed that fertigation using surface drip irrigation system at 10-days' interval with five splits in wheat and sevens splits in maize increased the mean N recovery efficiency by 17% and 29% compared to furrow irrigation in wheat and maize under CA-based permanent raised bed system, respectively.

5. Effect of Conservation Agriculture and Precision Nutrient Management Practices on Soil Quality

The CA-based rice/maize-wheat-mung bean increased soil organic carbon by 65-70% and available N, P, K contents by 50, 30 and 45%, respectively over conventional RW system after 4 years of cultivation, respectively (Jat et al., 2018). Further, authors also reported reduced fertilizer N and K dose by 30 and 50%, respectively in CA wheat with same yield levels (Jat et al., 2018). The CA-based maize-wheat (MW) system improved soil microbial biomass C (MBC), and soil microbial biomass N (MBN), dehydrogenase (DHA), and alkaline phosphatase activity (APA) by 208, 263, 210, and 48%, respectively compared with farmers' practice of RW system (Choudhary et al., 2018a). Similarly, CA- based RW system improved the soil MBC and MBN by around 40% and DHA and APA by about 15% (Jat et al., 2019a). The population of bacteria, fungi, and actinomycetes improved by 30, 50 and 70% in CA-based MW system than conventional RW system, respectively. They identified MBC, bulk density, APA and microarthropod population as key the soil quality indicators under CA-based RW and MW systems (Choudhary et al., 2018a). CA-based MW system recorded highest soil quality index (SQI) of 1.45 followed by 0.58 for CA-based RW system and the lowest score of 0.29 for conventional RW system (Choudhary et al., 2018a). Their studies demonstrated that mung bean integration in CA-based MW cropping system resulted in higher SQI (0.76) than other systems (Choudhary et al., 2018b). Bacterial diversity was found to be highest with conventional till compared to CA- based RW and MW systems. Fungal diversity increased with CA- based management practices, and phylum level, relative abundance of *Ascomycota* ranged from 55% in conventional RW system to 74%, within the CA-based rice/maize systems (Choudhary et al., 2018c).

Conclusions

Imbalanced and inappropriate plant nutrition has already contributed to multiple nutrient deficiencies in IGP. To overcome the limitations of traditional nutrient management practices, scientists are conducting researches to develop precision nutrient management strategies for both conventional till and CA-based cropping systems to improve NUE in crop production and protect environmental quality. Studies have demonstrated that there is a great potential in improving NUE by adopting precision nutrient management strategies. Defining precise recommendation domains for fertilizer best management practices for plant nutrients in cereal systems and their implementation using modern tools, techniques and approaches have to play a major role not only for bridging yield gaps but also for improving NUE, economic profitability and reducing losses and to address climate change issues. The nutrient management for conventional production systems should be revised, and new concepts of SSNM need to be applied. Establishment of need-based fertilizer nitrogen management strategies using simple and inexpensive leaf color chart in rice, wheat and maize is a land mark achievement in the science of natural resource management. It leads to higher profits in terms of saving on nitrogen fertilizers and ensuring minimal leakage of N to the environment. The algorithms developed for optical sensor-based N management in rice, wheat and maize should be further evaluated by the researchers for further downstream research. Research carried out on integrated use of organic manures and chemical fertilizers will reduce fertilizer consumption and thus add to the profitability and sustainability of the agriculture production system. Many of the CA-related soil processes, *e.g*. increased soil organic matter and other soil quality parameters have a significant bearing on nutrient transformations and management. However, systematic research on nutrient dynamics and their nutrient management requirements in CA are very limited. Evidence shows that over long-term adoption of CA systems, fertilizer requirements are likely to be lower and NUE is higher due to increase in microbial activity and efficient recycling of nutrients. Combined use of Nutrient Expert® and GreenSeeker™ minimized the environmental footprint under CA systems in India. Layering CA systems with subsurface drip irrigation has shown great potential in increasing water productivity and NUE in cereal-based systems. There is a strong need for new scientific thinking and research to fill the knowledge gap that currently exists about CA in different environments.

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