Nutrient Management Strategies for Enhancing Maize Productivity in India: An Overview

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Abstract

Maize (*Zea mays* L.) is one of the most versatile crop next to rice and wheat. It can be grown over diverse agro-climatic conditions. It has immense potential and is therefore regarded as “Queen of the cereals”. Globally, maize is grown on an area about 196 million hectares, yielding approximately 1110 million metric tons annually, with the United States leading in production as well as productivity (FAOSTAT, 2021-22). In India, maize cultivation covers an area of about 9.20 million hectares, producing 27.23 million metric tons of grains annually (MOA&FW, 2021-22). However, productivity in India starts decreasing below the global average due to several challenges, including deficiencies in quality seed production, limited adoption of technology and small landholdings, which hinder growth. Moreover, improper fertilizer usage and unpredictable weather patterns exacerbate yield limitations. To Overcome these challenges necessitates ensuring consistent nutrient supply throughout the season which is vital for maintaining balanced crop nutrition. However, 4R approach—utilizing the right source, at the right time, in the right place, and with the right method—plays pivotal role in maize nutrient management strategies. Meeting maize's micronutrient needs during key growth stages is imperative for achieving higher productivity and promoting environmental sustainability. Strategies such as balanced fertilization, micronutrient application, integrated nutrient management, incorporating legumes, and precision practices are essential for maximizing production and productivity. Keeping the above points in view, significance of nutrient management in enhancing maize productivity while promoting sustainable agricultural practices has been reviewed

Abbreviations

CAGR: compound Annual Growth Rate
FYM: farmyard manure
INM: integrated nutrient management
LCC: leaf colour chart
LER: land Equivalent Ratio
MCS: maize-chickpea-sesbania
MMS: maize-maize-sesbania
MMuMb: maize-mustard-mungbean
MWMb: maize-wheat-mungbean
NPK: nitrogen, phosphorus and potassium
NUE: nitrogen use efficiency
S: sulfur
SSNM-NE: site-specific nutrient management with nutrient expert
VRT: variable Rate Technology
Yac: actual yield
Yat: attainable yield
Yp: yield potential
Zn: zinc

Introduction

Maize (*Zea mays* L.) is one of the most versatile crops and can be grown over diverse agro-climatic conditions. It has immense potential and is therefore regarded as “Queen of cereals”. Its significance extends beyond basic nutrition, encompassing crucial roles in livestock feed, fodder production and serving as a fundamental resource for many industries including textiles, pharmaceuticals and cosmetics. In India, maize cultivation involves approximately 15 million farmers, offering employment opportunities to over 650 million individuals within the agricultural sector (FICCI & PWC, 2018). With involvement in over 3000 products, maize occupy central position including distinct varieties like quality protein maize, sweet corn, baby corn, and waxy corn. As the third most prominent cereal crop globally and within India, maize owes its importance to its diverse uses, catering to both direct human consumption and high-quality animal feed. Its processing through dry or wet milling techniques enables segregation into different food and industrial constituent. Maize starch, a core component of the kernel is used in food and industrial products. Moreover, maize-derived starch can be fermented into ethanol, suitable for fuel or beverage manufacturing. Maize grain possesses significant nutritional value, to meet out the dietary requirements of both human and animal populations (Table 1).

Table 1 - Nutritional value of Maize

Content	Percentage (dry matter basis)
Starch	71-72
Protein	9-10
Fat	4-45
Fibre	9-10
Sugar	2-3
Ash	1.4

Maize Production in the World

Globally, maize is cultivated on an area of about 196 million hectares with production and productivity of 110 million metric tons and 5.66 tons per hectare (FAOSTAT, 2021-22). Since 2005, there has been a consistent Compound Annual Growth Rate (CAGR) of about 3% in global maize production, with the cultivated area expanding at CAGR of 1.8% and yield increasing at a CAGR of 1.2% (NCoMM Report, 2021). United States of America leads the global maize production, contributing around 375 million metric tons, which accounts for 36% of the total global output. USA has highest productivity worldwide, with an average yield of approximately 10.5 tons per hectare, nearly twice the global average. Other maize-growing countries include China, Brazil, Mexico, Argentina and India. India ranks sixth in production and contributing 2.5% to the global maize output.

Maize Production in India

In India, maize occupies an area of about 9.20 million hectares and yielding around 27.23 million metric tons with an average productivity of 2.95 tons per hectare. Maize exhibits an annual growth rate of about 3-4% (MOA&FW, 2021-22). India's maize production represents about 2.5% of the world's total maize production. Karnataka is leading maize producer in India, contributing approximately 16% of the nation's total maize output, followed by Telangana and Bihar, jointly contributing 20% to India's maize production. Other maize-producing states include Maharashtra, Madhya Pradesh, Tamil Nadu, Andhra Pradesh, Rajasthan, and Uttar Pradesh. Approximately 71% of maize in India is cultivated during the summer season,with Karnataka leading the production. Bihar, Andhra Pradesh, and

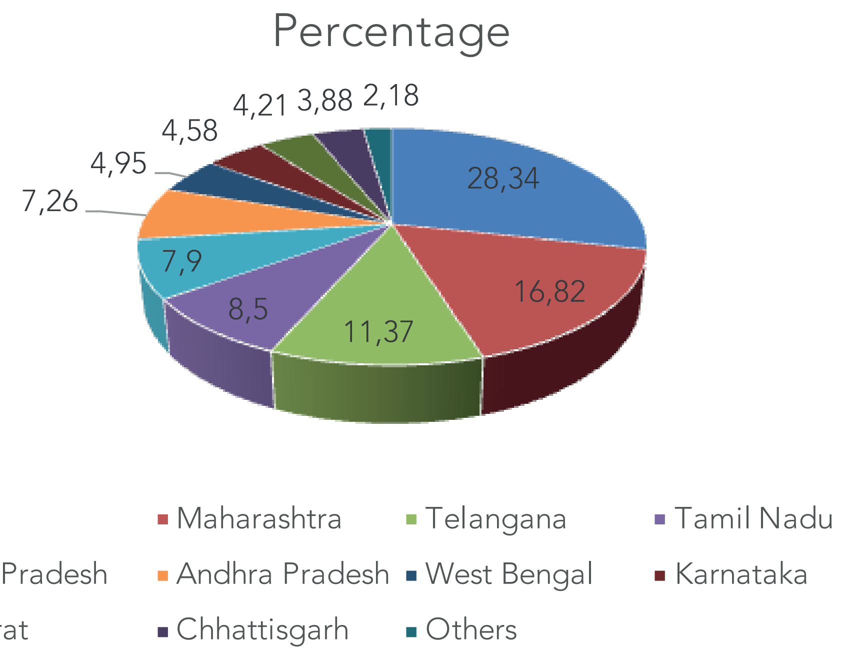

Fig. 1 -Distribution of maize production (%) in India (FAOSTAT, 2023)

Table 2 - Comparison of Maize productivity in India to world and other countries

Country	Productivity (kg/ha)
World	5815
USA	10761
China	6318
Brazil	5695
Argentina	7554
India	3006

Source: MoA&FW (2022)

Tamil Nadu are states known for their winter maize cultivation, being the primary crop in Bihar and Andhra Pradesh. (Fig.1).

Maize Consumption in India

In India, maize consumption is broadly divided into three segments viz food, feed and industrial products, primarily starch. Approximately 60% of maize is consumed as feed with poultry feed being the primary driver, accounting for 47% of total maize consumption, which is followed by livestock feed at 13%. Food consumption of maize in India accounts for 20% with direct consumption accounting for13% and 7%for processed foods. Remaining 20% of maize is consumed as industrial products, with starch being the most important contributor at 14%. Remaining 7% maize is exported and other industrial non-food products, including the utilization of maize as a feedstock for ethanol fuel production (ICAR, 2018).

In comparison to global standards, India's maize productivity falls significantly below average, standing at approximately half of the world's average. One-fifth of the productivity observed in United States and less than half of that in China (Table 2).

Decrease in productivity of maize can be attributed to several factors which are as follows:

(a) Climatic Challenges - Varied climatic conditions of India result possess major constraints like droughts or excess rainfall, leading to increased disease and pest pressure.

(b) Reliance on Rainfed Cultivation - Maize cultivation predominantly occurs in rainfed conditions on marginal lands with insufficient irrigation facilities. Although the area under irrigation with respect to maize in India has increased yet area it is under 30% (Table 3.)

Table 3 - Percentage of area under irrigation in India

Year	Area under irrigation (%)
2014-2015	27.39
2015-2016	27.29
2016-2017	26.96
2017-2018	28.95
2018-2019	26.92
2019-2020	29.30

(c) Limited Hybrid Adoption - Only about 30% of maize cultivation in India utilizes hybrid varieties. The lack of development and adoption of single cross hybrid technology, which is crucial for achieving higher productivity levels as that of the countries like the USA and China, is another important factor contributing to the low productivity of maize in India.

(d) Low Adoption of Improved Technologies - There is limited adoption of innovative and improved production technologies among farmers in India.

(e) Seed Quality and Distribution - Deficiencies exist in the production and distribution system of quality seeds.

(f) Small Land Holdings and Resource Constraints - The small farm holdings and limited resources becomes another important contributor towards low productivity of maize in India

(g) Yield Gap Challenges - There are considerable yield gaps between potential, attainable, and actual yields.

Yield potential (Yp) of any crop for any location and at any given sowing window is the yield which is achieved when that crop is grown in environments to which it has already acclimatized, with nutrients and water non-limiting and pests and diseases effectively controlled. In a study, hybrid maize models, estimated yield potential of four maize hybrids in India that ranged from 7.1 to 19.7 t/ha (Timsina *et al.*, 2010). Attainable yield (Yat), generally set at 80–90% of Yp, is average grain yield in farmers' fields with best possible management practices and without major limitations of water and nutrients. Attainable yield can be limited by variety, planting density, water and nutrient management, soil-related constraints (acidity, alkalinity, salinity, etc.), and other climate-related constraints (flooding, drought, etc.). Actual yield (Yac) is the yield farmers receive with their average management under all possible constraints. Attainable yield of maize in farmers' fields, achieved under optimal conditions, can vary significantly across the agro-ecologies mainly due to genotype x environment interactions but also due to confounding influence of biotic and abiotic stresses and agronomic management. Dass *et al.* (2008) reported Yat and Yac of maize from experiments conducted in 13 representative locations in various agro- environments for 9 years (1995–2003) under the All India Coordinated Research Project (AICRPM) on maize. The selected locations were first divided into two categories: locations having lower productivity than the national average and locations with greater productivity in comparison to national average. Results of the experiment indicated that Yac

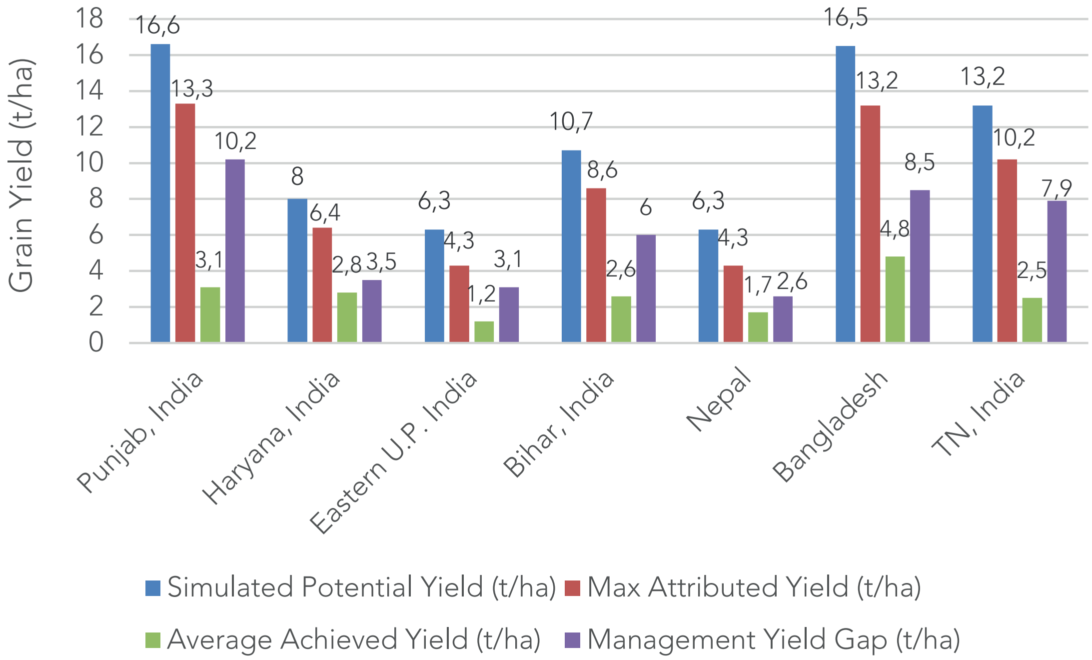

Fig. 2 -Potential, attainable and actual yields and management yield gaps under different ecologies across South Asia

is always less than Yat under all the agro-climatic conditions due to limited availability of agronomic inputs and their inappropriate scheduling. Potential for improving Yat was more at the locations of the first group as compared to the locations of the second group. First group showed the potential for achieving Yat of 4–6 t ha^{-1}, while Yac at all the locations of this group was less than half (1-2 t ha^{-1}) of the Yat. It has also been reported that present average Yac at farmers' fields is only about 50% of the Yat, which could be increased through adoption of improved technology. On the other hand, Yat for most locations was about 4.0 t ha^{-1} in the high productivity group, whereas, Yac at most of the locations of this group was more (1.2–3.4 t ha^{-1}) as compared to the low productivity group. These gaps are ascribed mainly to three major factors, (i) low yielding genotypes, (ii) poor crop establishment due to random broadcasting and (iii) inadequate and inappropriate fertilizer nutrient applications as 15-45% maize acreage remains unfertilised and the rest of the acreage has imbalanced nutrient applications (Fig 2).

Nutrient use in maize

Nutrient depletion far exceeds replenishment in cereal based cropping systems in India which resulted in widespread multi-nutrient deficiencies in soil. Declining soil fertility, coupled with high-yielding maize hybrids has led to variation in nutrient uptake and removal as farmers have not adequately adjusted fertilizer applications. Timsina and Majumdar (2012) noted decline in maize yield in Bangladesh over 5 to 10 years, attributing it to imbalanced and insufficient nutrient application. Maize yielding about 1 t/ha removes approximately 90-100 kg/ha of nutrients. With the adoption of improved cultivars, productivity has risen to 4 t/ha, with nutrient removal at around 220 kg/ha. Introduction of single cross hybrids have further increased productivity to 7.0 t/ha, with total nutrient removal of 420 kg/ha. In many states, particularly hilly regions like the North Eastern Himalayas and rainfed areas such as Madhya Pradesh, substantial maize-growing areas remain untreated with fertilizers, sometimes up to 90% (Nath and Khanna, 2022). Current nutrient use in high-input maize systems reveals imbalanced plant nutrition with excessive nitrogen use and insufficient phosphorus and potassium fertilizers, leading to soil nutrient imbalances, reduced nutrient efficiency, and lower economic returns. This emphasize the need for balanced nutrient application tailored to specific farm conditions and ecosystems and best management practices to enhance nutrient use efficiency

Problems with nutrient management in maize

The cultivation of high-yielding maize hybrids is likely to intensify nutrient deficiencies due to increased nutrient removal and imbalanced application of nitrogen (N), phosphorus (P), potassium (K) and other micronutrients. Hybrids having high biomass production, extract more mineral nutrients from the soil compared to other cereal crops. Despite advancements in breeding and agronomy, guidance on nutrient management for modern maize hybrids remains inadequate. Maize-growing areas in India typically have low soil organic matter and nitrogen as the major limiting nutrient. Nitrogen, phosphorus, and potassium are crucial for increased and sustained maize productivity. While nitrogen fertilization increases maize yield, the agronomic efficiency of nitrogen is low, indicating poor nitrogen use efficiency (NUE) (Bender *et al.*, 2013). Limited awareness of improved nitrogen management strategies, coupled with the relatively lower prices of nitrogen fertilizers, leads to imbalanced nitrogen use by farmers. Therefore, nitrogen management strategies considering yield response, agronomic efficiency, timing, and splitting are crucial for minimizing nitrogen losses and enhancing productivity and profitability. Response of phosphorus varies greatly depending on soil characteristics and growing environments, demanding more application rates based on expected response at specific locations. Application of phosphorus based on yield response may overlook nutrient removal by crops with low or negligible responses, potentially leading to nutrient mining and decline in soil fertility. Maintenance doses replenishing nutrients removed by crops are very essential to maintain soil fertility. Additionally, potassium fertilizer management must account for residues and organic amendments applied to soil. Although, Indian soils have large total potassium content, skipping potassium application results in yield and economic losses, highlighting the seriousness of nutrient imbalances. Improved potassium management holds great potential for enhancing maize productivity in India (Nath and Khanna. 2022).

Nitrogen, phosphorus, potassium, and zinc are the most limiting nutrients for the growth of maize crop in Jammu and Kashmir. The unbalanced, inadequate or no use of such nutrients drastically reduces the crop yield. Crop responses to applied nutrients vary considerably across fields due to small and marginal landholdings, resulting in high variability in soil nutrient availability over short distances. This emphasises the need for fertilization tools considering spatial and temporal nutrient availability for improved yield and nutrient use efficiencies in maize. Site-specific nutrient management and decision support tools like Nutrient Expert for Hybrid Maize can enhance productivity by providing realistic estimates of indigenous nutrient supply and crop yield requirements customized to individual farmers' fields. Thus, development and adoption of optimal nutrient management strategies is crucial for achieving higher maize productivity.

Nutrient Management Strategies for improving Maize Productivity

Managing nutrients in heavy feeders like maize is very challenging as they remove large amounts of nutrients from the soil, presents a range of challenges. Maize has a season-long uptake of nutrients, with significant absorption of nitrogen (N) and potassium (K) occurring during the vegetative stage, while phosphorus (P), sulfur (S), and zinc (Zn) uptake peak during grain filling. Micronutrients have narrow uptake window compared to macronutrients. Therefore, ensuring a consistent nutrient supply throughout the season is crucial for maintaining balanced crop nutrition. The 4 R approach—utilizing the right source, at the right time, in the right place, and with the right method—is essential in nutrient management strategies for maize. Aligning nutrient supply with plant demands is a key consideration (Li *et al.*, 2015). Optimizing nutrient management necessitates application of fertilizers for uniform and balanced supplementation of nutrients in sync to maize. It is crucial to utilize appropriate fertilizer sources and methods to maximize nutrient use efficiency (NUE). Adoption of methods that minimize nutrient loss while maximizing efficiency is imperative for exhaustive crops like maize. Emphasizing precise nutrient application aligned with target yields, integrating indigenous sources, soil organic matter, farmyard manure (FYM), compost, and crop residues, is key to achieving high yields and NUE. Understanding nutrient uptake rates and timing enables optimization of nutrient application rates, sources and timing Dass *et al.* (2008).

Nutrient management strategies should consider spatial and temporal variations in nutrient availability to maximize effectiveness. When devising fertilizer recommendations for maize, it's crucial to understand two key aspects of plant nutrition essential for managing high-yielding production systems:

1 Total Nutrient Uptake - This refers to the quantity of a specific mineral nutrient required by the plant throughout the growing season for optimal growth and development, encompassing both vegetative and reproductive stages.

2 Nutrient Removal - This denotes the amount of nutrients extracted from the field through harvested grain and straw/stover. Jat *et al.* (2019) concluded that replenishing of exported nutrients with appropriate fertilization practices is vital for sustaining production systems (Table 4).

Aligning nutrient supply with crop demand and replenishing nutrients removed by crop contribute to the sustainability of production systems. Enhancing fertility practices involves synchronizing in-season nutrient uptake with availability, a characteristic of the "right source" principle, which is interlinked with other components of the 4R Principle (Rajendran *et al.*, 2010). During vegetative growth, the majority of nutrients, excluding phosphorus (P), sulfur (S) and zinc (Zn), experience peak uptake rates, aligning with period of greatest dry matter accumulation. Peak accumulation of phosphorus, sulfur and zinc occurs during grain filling necessitates the importance of fertilizer sources that sustenance with maize's nutritional needs to optimize nutrient use efficiencies. Effective management of nutrients further emphasises precise nutrient supplementation of plant as per their requirements, especially in high-yielding conditions (Yadav *et al.*, 2017). For instance, nitrogen (N) and sulfur (S) face similar environmental challenges, but their uptake timings differ notably. N uptake is predominantly concentrated around the VT/R1 physiological stage, whereas S accumulation peaks during grain filling. However, potassium (K) and phosphorus (P) uptake patterns differ, with the majority of P uptake occurring after the VT/R1 stage, highlighting the criticality of season-long P and S supply for maize nutrition. Micronutrients exhibits detailed uptake patterns as compared to macronutrients. Zinc (Zn) and boron (B) uptake commences in early vegetative stages, reaching plateaus around the VT/R1 stage. Subsequently, Zn uptake stabilizes, while B uptake follows a sigmoidal pattern, concluding around the senescence stage. Requirement of micronutrients in maize during key growth stages in high-yielding conditions requires supplying appropriate nutrient sources and rates (Tomar *et al.*, 2017). Therefore, the 4R approach (right source, right time, right amount, and right place) is pivotal not only for achieving higher yields but also for enhancing efficiency, profitability and environmental management.

Major considerations for formulating nutrient management strategies to enhance maize productivity include:

1 Careful application of nutrients for balanced fertilization.

2 Split application of nitrogen with earthing up.

3 Micronutrient application.

4 Legume intercropping.

5 Legume-based crop rotation.

6 Integrated nutrient management (INM).

7 Site-specific nutrient management with nutrient expert (SSNM-NE).

8 Precision and real-time nutrient management practices.

1 Careful application of nutrients for balanced fertilization.

To enhance nitrogen use efficiency (NUE) in maize, it's crucial to carefully apply nutrients, especially nitrogen, due to its susceptibility to various forms of loss such as volatilization, denitrification, nitrate leaching, and surface-applied urea losses. Proper nitrogen scheduling can help minimize these losses and improve NUE. Typically, nitrogen is applied in three splits in maize: 33% basal, 33% at knee-high stage, and 33% at tasseling stage. However, further split nitrogen applications as per crop growth stages to prevent nitrogen deficiency and enhance availability of nutrients for enhanced productivity. Pal and Bhatnagar (2015) reported scheduling of nitrogen 20% basal,25% at four leaf, 30% at 8 leaf,20% at tasseling stage and 5% at early grain filling stage recorded significant higher grain yield, fodder yield and nitrogen use efficiency. Higher-productivity and NUE due to better nitrogen utilization after the grain-filling stage, maintaining plant vigour till harvest. Therefore, balanced fertilization through more split applications of nitrogen proves beneficial in increasing productivity and NUE in maize.

2 Split application of nitrogen with earthing up

Earthing up is an important operation in maize cultivation to prevent lodging and improve standability by providing anchorage to lower adventitious roots above

Table 4 - Major nutrient removal from the soil by the maize plant

Plant part	Yield(t/ha)	Nutrient extraction(kg/ha)					Total
Traditional cultivars	**N**	**P**	**K**	**Ca**	**Mg**	**Zn**	
Grain yield	1.0	25	15	3.0	2.0	0.023	51.0
Stover	1.5	15	18	4.5	3.0	0.040	43.5
Total	2.5	40	33	7.5	5.0	0.063	94.5
Improved cultivars							
Grain yield	4.0	63	30	8.0	6.0	0.093	119.1
Stover	4.0	37	38	10.0	8.0	0.108	99.1
Total	8.0	100	68	18.0	14.0	0.201	218.2
Hybrid cultivars							
Grain yield	7.0	128	37	14.0	11.0	0.163	210.2
Stover	7.0	72	93	17.0	13.0	0.189	209.2
Total	14.0	200	130	31.0	24.0	0.352	419.4

*Source: Jat *et al.* (2019)

the soil surface which function as absorbing roots. Thakur *et al.* (2013) reported significant increase in grain and straw yield due to earthing up as it facilitates better aeration and reduces irrigation water requirements. However, the conventional method of top-dressing of fertilizer, especially nitrogen, through manual broadcasting results in low fertilizer use efficiency and various losses, such as volatilization and fixation issues. To address these challenges, split application of nitrogen with earthing up has been proposed as a solution. Singh *et al.* (2013) emphasized the importance of regular and adequate nitrogen supply for maximizing maize productivity. Broadcasting urea on the soil surface is commonly practiced by farmers led to poor nitrogen

Fig. 3 - Pant fertilizer band placement cum earthing machine

Fig. 4 - Field condition during operation of machine in maize

use efficiency (Jat *et al.*, 2016). Placement of urea below the soil surface could enhance nitrogen use efficiency and decrease nitrogen doses (Jat *et al.*, 2014). Earthing up not only improves aeration and soil tilth but also creates favourable conditions for root development, resulting in increased water and nutrient uptake from the soil and promoting shoot growth. Bhatnagar and Kumar (2017) conducted a field experiment to study the effects of mechanized earthing and nitrogen dose on maize productivity and profitability. The experiment included four earthing treatments and four nitrogen levels, with the use of a specially designed Pant fertilizer band placement-cum-earthing machine. This machine performed soil loosening, weed cutting, fertilizer placement, and earthing-up simultaneously which resulted significantly higher productivity and monetary benefits. The enhanced availability of nutrients throughout the crop growth period contributed to higher nitrogen use efficiency and productivity in maize. Thus, the combination of split application of nitrogen along with earthing up, especially with the use of mechanized equipment, offers promising benefits in terms of improved nitrogen use efficiency, enhanced productivity, and profitability in maize cultivation (Fig 3. and 4.).

3 Micronutrient application

Micronutrients are essential trace elements play vital roles in various metabolic functions of maize crop. Their deficiency can lead to reduction in crop yield. Application of micronutrients either before planting or directly to the crop enhances maize productivity. Adhikari *et al.* (2010) reported maize crop supplied with micronutrients (B, Zn, S, Mn and Mo) in combination with NPK fertilizers at 120:60:40 kg ha^{-1}which produced almost 171 per cent higher grain yield than those with control plot (2.21 t ha^{-1}) and 3.78 t ha^{-1} of additional grains over NPK treated crop. Similarly. Paramasivan *et al.* (2010) reported significant increases in grain yield with the application of NPK fertilizers combined with zinc. Archana *et al.* (2012) found that foliar sprays of iron sulfate resulted in higher grain yields as compared to untreated plots. Borase *et al.* (2018) also observed increased grain yields with the application of micronutrients, particularly zinc sulfate, iron sulfate, and borax. Therefore, for achieving maximum grain yield, maize should be supplied with the recommended doses of NPK fertilizers along with specific micronutrients such as zinc sulfate, iron sulfate, and borax. These findings emphasise the importance of micronutrient management in optimizing maize productivity.

4 Intercropping with Legumes

Intercropping offers a strategic approach to maximize total productivity per unit area and time while ensuring equitable land resource and farming input utilization, including labour, and providing insurance against crop failure. Maize sown at wider row spacing and inter-row spaces can be utilized for profitable economic returns. Although intercropping is a traditional practice, its global recognition is owing to its yield advantages. One of the primary reasons for increased yields in intercropping is the complementary use of growth resources by component crops. When grown as intercrops, these crops utilize resources more efficiently, leading to better overall resource utilization compared to monoculture systems (Jat *et al.*, 2014). Intercropping of legumes not only contribute nitrogen to associated crops but also enhance soil humus levels through crop residue decomposition. Contrary to any adverse effects, legumes as intercrops with maize can actually improve maize yields, resulting in higher total yields and economic benefits. Bhatnagar and Pal (2014) revealed that maize crop intercropped with urdbean in row ratio (1+1) was found to be beneficial as compared to sole maize cropping and yielding higher maize equivalent yield, land equivalent ratio (LER), and net returns. Thus, maize intercropped with legumes in an additive series proves advantageous due to balanced competition and the additional yield income from the intercrop

5 Legume-based crop rotation

The practice of continuous cereal cropping combined with intensive tillage practices has led to a decline in factor productivity (Dwivedi *et al.*, 2003), resulting in stagnant crop yields and decreased farm income. With the increasing demand for pulses, farmers are now adopting legume-based crop rotations with maize. Yadav *et al.* (2017) evaluated long-term effects of legume-intensified maize-based crop rotations. The experiment included four crop rotations as subplot treatments: MWMb: Maize-Wheat-Mungbean, MCS: Maize-Chickpea-Sesbania, MMuMb: Maize-Mustard-Mungbean, MMS: Maize-Maize-Sesbania. Experimental results revealed that maize grain and stover yields were consistently higher in Maize-Chickpea-Sesbania and Maize-Wheat-Mungbean systems as compared to Maize-Mustard-Mungbean and Maize-Maize-Sesbania rotations. The increased maize yield in Maize-Chickpea-Sesbania system due to inclusion of two legumes (one winter and another in summer) as compared to only one summer legume in other cropping systems. The incorporation of legumes improved soil fertility, particularly nitrogen (N) availability, thereby enhancing the growth and yields of maize. Maximum nitrogen (N), phosphorus (P), and potassium (K) content in maize stover was observed in Maize-Chickpea-Sesbania sequence plots among other cropping sequences. Inclusion of deep-rooted legumes alongside shallow-rooted

Table 5 - Effect of integrated nutrient management on yield and nutrient productivity (kg/ha) of quality protein maize in different agro-ecologies (pooled data of 7 locations across different ecologies in India)

Treatment	Yield(kg/ha)		Nutrient productivity (kg grain/kg Nutrient applied)	
	2007	2008	2007	2008
O_0N_1	4226^{f}	4395^{f}	28.1^{a}	26.1^{a}
O_0N_2	4735^{e}	4930^{de}	20.8^{b}	20.5^{b}
O_0N_3	5136^{cd}	5173^{cd}	17.7^{bcd}	16.8^{c}
O_0N_4	5482^{b}	5512^{bc}	15.4^{cd}	14.7^{cd}
O_1N_1	4482^{ef}	4766^{ef}	19.9^{bc}	20.1^{b}
O_1N_2	5069^{d}	5333^{c}	16.6^{bcd}	16.6^{c}
O_1N_3	5433^{bc}	5745^{ab}	14.9^{d}	14.6^{cd}
O_1N_4	5839^{a}	6099^{a}	13.5^{d}	13.2^{d}
P value	<.0001	<.0001	<.0001	<.0001

Means with atleast one letter common are not statistically significant using Fisher's Least Significant Difference

*Without organic manure (O_0) and application of FYM @ 6 t/ ha (O_1) with four levels of fertilizer nutrients *i.e.*, 100:40:30 (N_1), 150:60:40 (N_2), 187:75:50 (N_3) and 225:90:60 N: P_2O_5 : K_2O kg/ha (N_4)

Source: Chhonker (2018)

cereals in cropping systems facilitates the extraction of sub-surface nutrients, subsequently increasing nutrient availability in the surface soil layers where maize roots predominantly exist. Thus, enhanced nutrient availability promotes higher uptake of N, P, and K that led to higher nutrient content in maize stover. Earlier studies by Parihar (2014) and Aziz *et al.* (2015) also reported increases in NPK content due to the inclusion of legumes in cropping systems. Overall, legume-intensified maize-based crop rotations offer sustainable approach to enhance soil fertility, improve maize yields and increase farm profitability.

6 Integrated nutrient management (INM)

Chhonkar (2018) reported that unbalanced use of chemical fertilizers has led to soil imbalances, resulted in nutrient deficiencies and decline in soil productivity (Table 6). To address this issue, there is a recognized need for supplementary, cost-effective sources of nutrients, especially in low-fertility situations where the use of non-renewable chemical fertilizers is costly and concerns about environmental degradation are paramount. Vermicompost helps to maintain soil fertility by converting mineral elements into readily available forms for plant uptake, including nitrates, exchangeable phosphorus, soluble potassium, calcium, and manganese. Integrated nutrient management (INM) systems have emerged as a solution, aiming to optimize nutrient benefits from various sources in an integrated manner while improving soil health and sustaining crop productivity. Various INM options for maize include crop residue incorporation, farmyard manure, compost, vermicompost, green manuring, biofertilizers, Nitrogen-fixing bacteria *viz. Azotobacter chroococcum*, Phosphorus-solubilizing bacteria and fungi, Potassium-solubilizing bacteria such as *Bacillus mucilaginous* and plant growth-promoting bacteria like Pseudomonas fluorescence (Table 5.)

Tomar *et al.* (2017) demonstrated that maize can be successfully grown in the Indo-Gangetic plain zone with 100% NPK, 5 t/FYM, *Azotobacter*, and PSB (*Phosphorus-Solubilizing Bacteria*), resulting in maximum productivity, profitability, and improved nitrogen use efficiency. Similar findings were reported by Sharma *et al.* (2013) and Kokani *et al.* (2014). Higher NPK uptake was observed under this combination due to favorable effects of incorporating organic sources along with inorganic nutrients, as reported by Sharma *et al.* (2013).

Source: Chhonker (2018)

Furthermore, the decomposition of organic sources releases CO_2, which forms carbonic acid upon dissolution in water. This acid aids in the decomposition of primary minerals, released nutrients, higher biomass production and nutrient uptake (Chandravanshi, 2014). Thus, integrating organic and inorganic nutrient sources in maize enhance soil fertility, crop productivity, and nutrient use efficiency while addressing environmental concerns associated with excessive chemical fertilizer use.

7 Site-specific nutrient management with nutrient expert (SSNM-NE).

Maize is heavy nutrient and water required crop and it needs intensive management of these inputs. With increasing input costs, especially fertilizers, site-specific nutrient management (SSNM) offers an effective approach for farmers to enhance crop productivity and sustain soil fertility. SSNM aims to supply the required nutrients to a crop based on the specific field or growing environment, utilizing information gathered from various scales to make field-specific nutrient management decisions (Chandravanshi *et al.*, 2014). Various tools are currently employed by farmers to apply required nutrients to targeted crops and fields. One

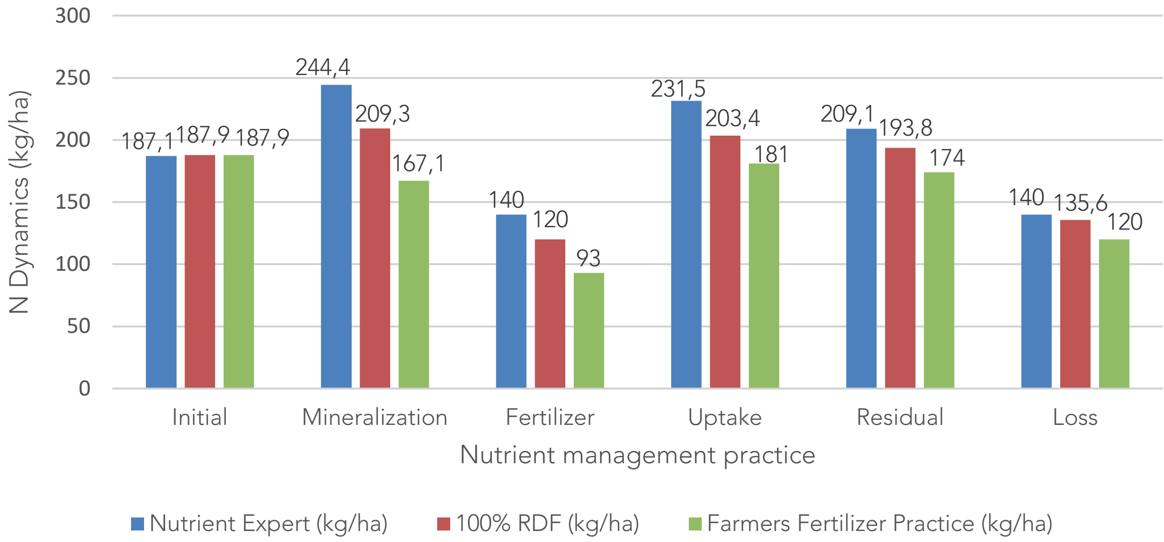

Fig. 5 - Nitrogen dynamics in Nutrient Expert, 100% RDF and Farmer's Fertilizer Practice for the maize crop (Singh *et al.*, 2017)

such tool is the Nutrient Expert (NE), a simple nutrient decision support tool used to develop fertilizer recommendations for farmers' fields. NE for hybrid maize is a computer-based decision support tool developed to assist local experts in formulating fertilizer guidelines for tropical hybrid maize based on SSNM principles. Satyanarayana *et al.* (2013) adopted NE-based field-specific fertilizer recommendations which resulted in increase in fertilizer efficiency and maize productivity (Table 6). Singh *et al.* (2017) evaluated Nutrient Expert (NE) for hybrid maize against farmers' fertilizer practice (FFP) in a three-year maize-wheat rotation. Experimental results revealed that NE-based nutrient management approach led to higher yields, nutrient uptake, profits, and sustained soil properties among other practices of nutrient management (Fig 5). Jat *et al.* (2019) reported, the application of SSNM principles aided with balanced nutrient could prove to be an important strategy to improve nutrient management in maize based systems towards enhancing yield and profitability. Another study conducted on SSNM under AICRIP-Maize in 2 major maize based cropping systems at 11 locations in maize

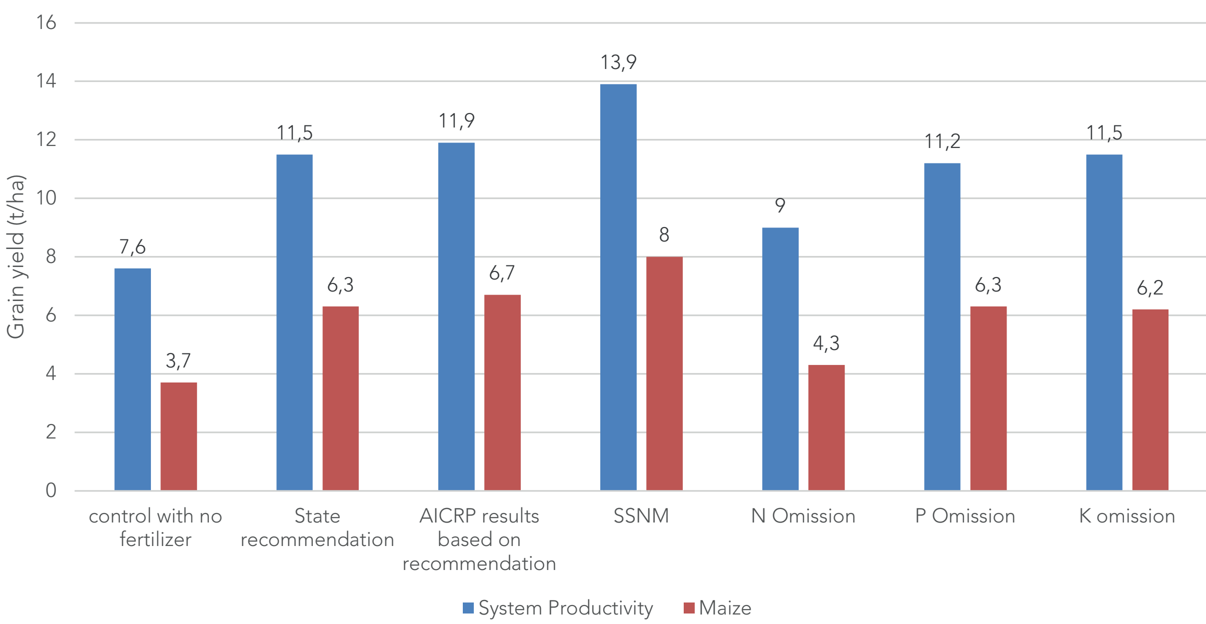

Fig. 6 - Grain yield of maize and system productivity of an SSNM experiment in rice-maize system (Jat *et al.*, 2019)

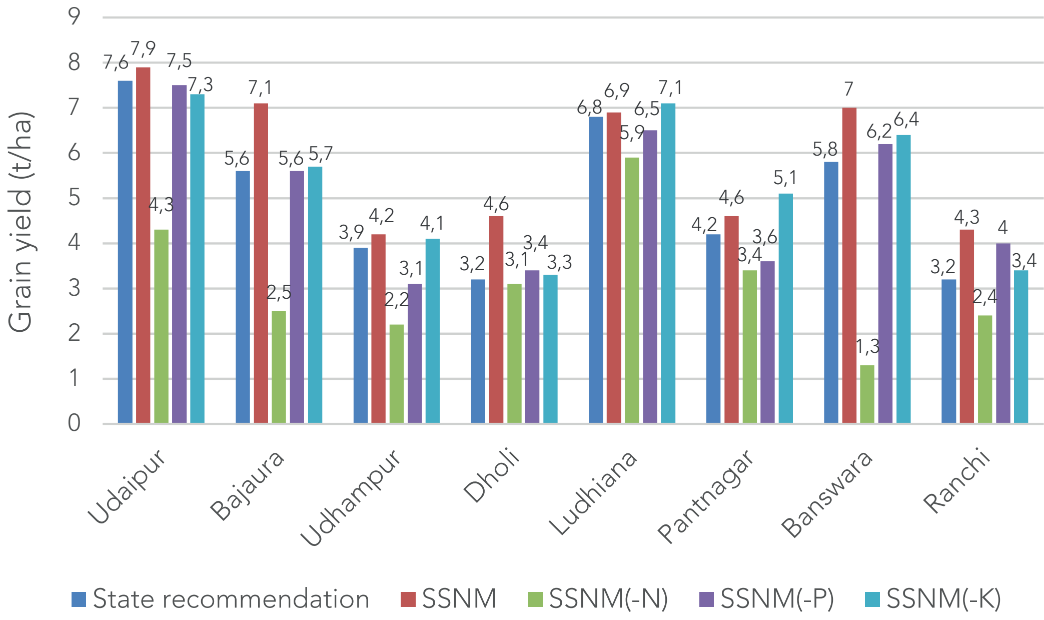

Fig. 7 - Effect of nutrient management practices on grain yield of maize at different locations in India (Jat *et al.* 2019)

based cropping systems indicated significantly higher yield of maize under SSNM compared to state recommendations at most of the locations (Fig 6 and 7). This emphasizes the effectiveness of utilizing decision support systems like NE to optimize nutrient management practices for maize cultivation, contributing to improved productivity and soil health.

8 Precision and real-time nutrient management practices.

Blanket recommendations for applying fertilizer at specific growth stages do not consider dynamic soil nutrient supply and crop nutrient needs, leading to inappropriate timing of nutrient application and potential nutrient losses. Therefore, adopting need-based fertilizer management for maize can improve recovery efficiency and reduce nutrient losses. Adjusting nitrogen (N) application during the maize growing season can be facilitated using various methods, such as leaf color charts (LCC), SPAD meters, and Green-Seeker sensors. Research consistently demonstrates that enhanced N management with LCC leads to higher yields and profitability compared to fixed fertilizer practices (Rajendran *et al.*, 2010). For example maize-wheat farmers of northern Karnataka benefited from applying appropriate N rate (e.g., 240 and 150 kg/ha for maize and wheat, respectively) and using timely N fertilizer application based on real-time N management with LCC (Biradar *et al.*, 2012). Singh *et al.* (2011) assessed different need-based N fertilizer management strategies in maize and found LCC 5 is an effective threshold during vegetative growth stages for improving N recovery efficiency and achieving high yields. They observed no response to N fertilizer application at initial stage based on various LCC threshold values. Additionally, using LCC 5 as the threshold for N application resulted in equivalent grain yields compared to fixed-time applications of 150 kg N/ha, with only 90 kg N/ha applied. This approach increased recovery efficiency by 19.8–22.8% and enhanced grain yield production by 7.1 to 8.5 kg per kg of applied fertilizer N. These findings highlight the efficacy of need-based fertilizer management strategies, particularly when employing tools like LCC, to optimize maize productivity while minimizing environmental impacts associated with excessive fertilizer use.

Conclusions

Maize holds significant importance for food and nutritional security in India. Despite modern high-yielding hybrids with reduced water requirements and strong market demand, the increase in maize production has not been proportional to the rise in cultivation area. This is evident from significant yield gaps observed across maize-growing regions in the country. Maize, being an exhaustive crop, requires ample nitrogen supply for enhanced productivity, and adopting proper fertilizer application methods is crucial to improve nutrient use efficiency and maize yields. Moreover, micronutrients also play an important role in maize growth and should be adequately supplied either before planting or directly applied to the crop to boost productivity. Inclusion of legumes in maize systems as intercrops has been shown to enhance productivity and profitability. Integrated Nutrient Management (INM) options can also be employed to augment maize productivity. Approaches such as leaf-colour charts (LCC), Nutrient Expert (a computer-based decision support tool), Variable Rate Technology (VRT), among others, offers an effective means to enhance fertilizer efficiency and maize yields. Implementation of the 4R Principles—applying the right source of nutrients, at the right rate, at the right time, and at the right place—is expected to enhance nutrient use efficiency, productivity, and profitability in maize production. This approach not only benefits crop production but also promotes better management of nutrients. Adopting 4R Principle-based site-specific nutrient management decision support tools could offer the opportunity for widespread adoption of improved nutrient management practices across various maize ecologies, ultimately contributing to sustainable maize production systems

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