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REVIEW ARTICLE



## Cereal production trends, nutrient use efficiency and its management practices in agriculture: A review

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### ABSTRACT

Boosting global food production to meet the escalating demand without distressing the environment is a major challenge of our time. In the present review study, a-59 years global cereal production and fertilizer use trends, nutrients use efficiency (NUE) and some of its management approaches in agriculture were evaluated. Accordingly, the world cereal production increased by 3.4-fold (876.9 to 2979 Mt) from 1961 to 2019, whereas the area of production increased moderately by 1.11 folds. The chemical N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O fertilizer consumption in cereal crop production were increased by 9.45 folds (from 6.9 to 65.2 Mt), 4-fold (from 6.6 to 26.3 Mt), and 4.34-fold (from 5.2 to 22.6 Mt), respectively. The estimated world cereal N, P, and K use efficiency is 33%, 16%, and 19%, respectively. The unaccounted 65% of N, 84% of P and 81% of K fertilizer was either remained in the soil or lost to the environment through volatilization, leaching, and run-offs leading to higher environmental and economic costs. Therefore, improving NUE is a crucial step to enhance crop yields, tackle environmental pollution, reduce production costs. Several NUE management approaches were identified such as soil management (use of organic inputs, 4R nutrient stewardship, adoption of modified fertilizer, root-zone nutrient management, etc.), plant management (growing nutrient use efficient cultivars, crop rotation, and so on), integrated soil-crop system management (ISSM), and application of precision agriculture. However, no single management approach solely resulted in higher NUE but rather the combination. Hence this could be applied in agricultural production to improve yield and NUE while minimizing environmental degradation.

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### INTRODUCTION

Feeding the ever-increasing world population by providing sufficient, safe, and healthy food without threatening the ecosystem is the most important challenge of our time (Timsina, 2018). World food production needs to double by 2050 to meet the escalating demand posed by population growth, a shift of diet, and increasing demand for biofuels (Ray *et al.*, 2012; Tilman *et al.*, 2011). The current forecast reveals that the global demand

for food will rise by 100% to 110% from 2005 to 2050 (Tilman *et al.*, 2011). Since Borlaug's green revolution, food production has increased to feed the world population (Liu *et al.*, 2015). Dhillon *et al.*, (2019) reported that the world cereal production increased by 3.2-fold from 1961 to 2015. The increase in food production was attributed to the intensified use of chemical fertilizer, adoption of high yielding varieties, pesticide use, and irrigation (Jiao *et al.*, 2016; Liu *et al.*, 2015). Nitrogen, phosphorous, and potassium fertilizers are the three most commonly

required and widely used soil nutrients. In the year 2014/15, the total world fertilizer consumption reached about 181.9 Mt, with N accounting for 102.5 Mt, P<sub>2</sub>O<sub>5</sub>, 45.9 Mt, and K<sub>2</sub>O, 33.5 Mt as of 2014/15 (Heffer et al., 2009). Cereals consume nearly half (49.3%) of the total world fertilizers; specifically, maize (16.2%), wheat (15.3%), and rice (13.7%), and the remaining cereals consume 4% of the world fertilizer. It was reported that global N-fertilizer consumption increased by 20-fold in the past five decades (Dobermann, 2005; Tolera et al., 2019). However, fertilizer use per hectare of arable land varies with location and it is about 154.8 kg ha<sup>-1</sup> (European union), 125.4 kg ha<sup>-1</sup> (North America), 293.5 kg ha<sup>-1</sup> (East Asia and Pacific), and 20 kg ha<sup>-1</sup> (sub-Saharan Africa/SSA), while the world average is about 136.8 kg ha<sup>-1</sup> (World Bank, 2021b).

Nitrogen is an important yield-limiting nutrient in agriculture that is highly mobile and easily soluble (Tufa et al., 2020). The plants require comparatively higher nitrogen than any other soil nutrients. It is essential for the growth of the plant and also acts as a building block for protein (Zhang et al., 2012). Effective management of nitrogen in the soil-plant system is challenging due to its mobile nature and propensity for loss. Also, its manufacturing process consumes about 10 times higher energy than that of phosphorous and potassium fertilizers (Fageria et al., 2015). Phosphorous is the second most limiting nutrient after N, which is important for the growth and formation of roots, supports cell division, hastens maturity, and makes plants more tolerant to drought and pests (Singh et al., 2018). Due to the finite and non-renewable nature of phosphorous, proper use and management is crucial through adopting science-based recommendations. Potassium is the third important soil nutrient that helps to enhance crops' yield and overall quality. However, the consumption of these nutrients in agriculture are increasing unprecedentedly recently. Despite their vital role in food production, overapplication of these soil nutrients beyond the crop's demand results in yield stagnation, low NUE, and various environmental problems (Zhang et al., 2011; Jiao et al., 2016; Tilman et al., 2011; Raun and Johnson, 1999).

Nutrient use efficiency (NUE) is used as an indicator for evaluating a crop's ability to convert available soil nutrients into economic yield. It has environmental, edaphic, and economic implications (Balemi et al., 2019; Jiao, et al., 2016). It shows a reducing trend with an increase in nutrient application rate. Improving NUE is a crucial step to enhancing crop yield, reducing environmental degradation and production cost, and ensuring agricultural sustainable production (Zhang et al., 2015). Also, reducing the gap between actual and attainable NUE is an important step for sustainable food production and maintaining eco-services (Cui et al., 2014). Considering the nature, economic benefits, and environmental impacts of these soil nutrients, it is fathomable that NUE needs to be improved. This study highlights the global cereal production, fertilizer use, and NUE, and its management practices in agriculture.

## LITERATURE SURVEY AND DATA COLLECTION

In the present study, data was collected and computed from

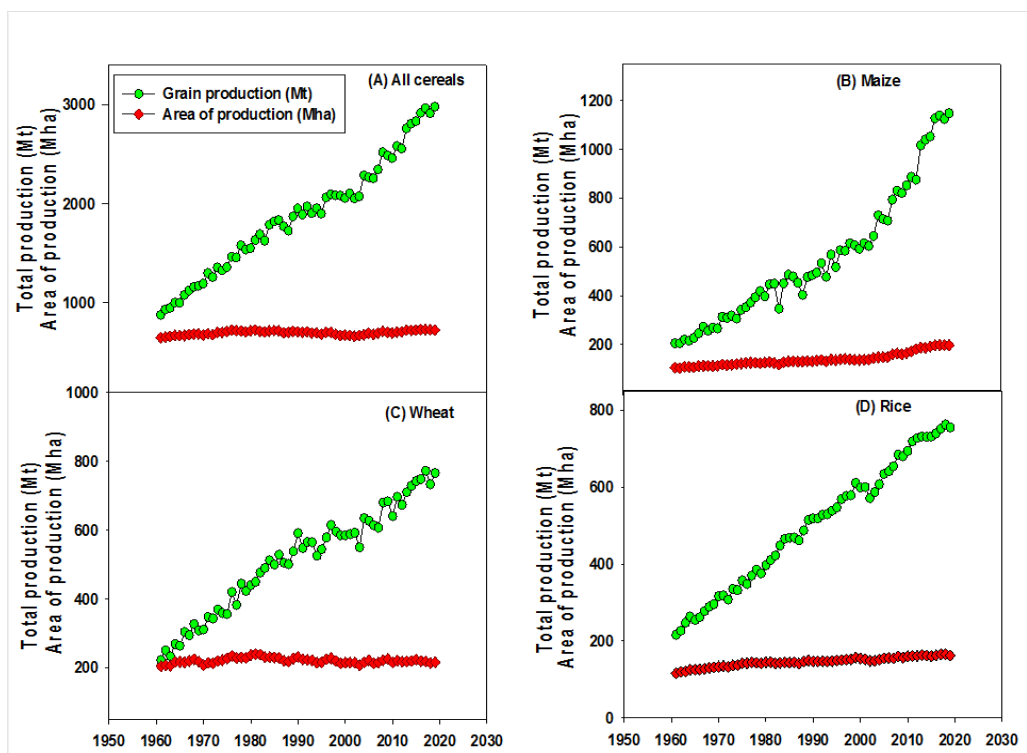
FAOSTAT, the world bank, and different published sources. The area coverage, total production, and productivity of the overall and the three most important cereal crops (maize, wheat, and rice) at a global level were presented below in Figure 1 and Figure 2 (left). The 'overall cereal' crops mentioned in this study includes maize, wheat, rice, sorghum, millet, oats, barley, rye, and other minor cereal crops. The world area under cereal coverage (the ratio of world cereal production area to the world total harvested area) was adopted from the previous reports and we have used the mean value of 60.5%, which is derived from the earlier reports of world cereal area coverage of 61% (Dhillon et al., 2017), and 60% (Dhillon et al., 2019). The amount of nitrogen, phosphorous, and potassium fertilizers used in cereal production was calculated by multiplying the world fertilizer consumptions by area coverage of cereal crops as indicated in the equation below (Eq. (1)).

$$\text{World N/P}_2\text{O}_5\text{/K}_2\text{O fertilizer consumption} * 0.605 \quad (1)$$

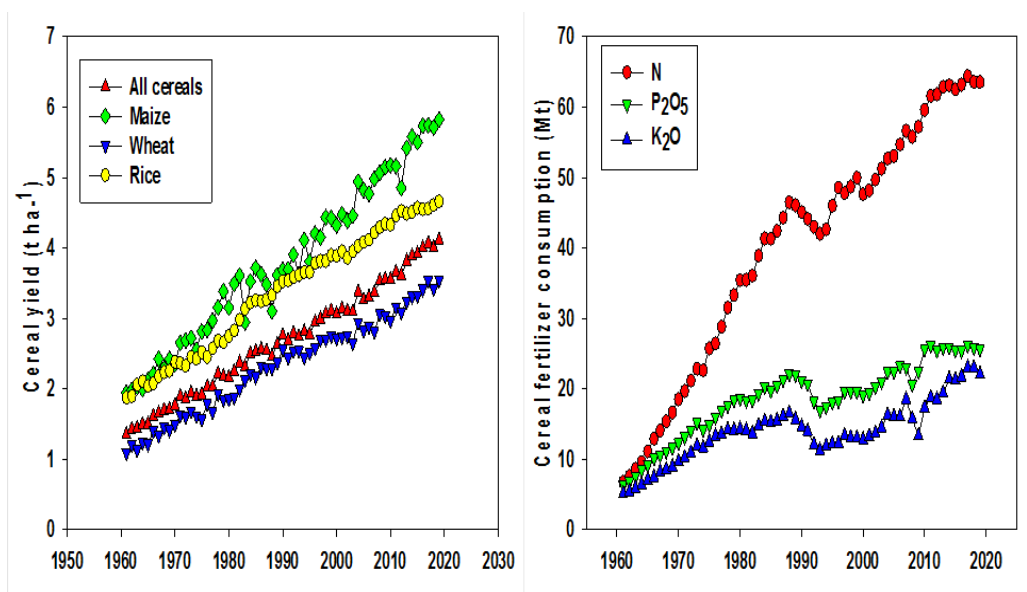
## CEREAL PRODUCTION AND FERTILIZER CONSUMPTION TRENDS

During the past 59-years, the world cereal production increased by 3.4-fold (from 876.9 Mt to 2979 Mt), whereas the area harvested increased moderately by 1.11-fold from 1961 to 2019 (Figure 1). This represents a 340% increase in cereal production over 59-years. Among the cereal crops, maize, wheat, and rice were the most cultivated crops representing about 90 percent of all cereal crops produced globally (FAOSTAT, 2021) and making up about two-thirds of calories in human diets (Cassman, 1999). Maize, wheat, and rice production increased by 5.6, 3.4, and 3.5-folds, and their area of production increased by 1.87, 1.05, and 1.4-folds over the 59 years, respectively (Figure 1). The overall area of production of maize and rice increased moderately but that of wheat remained constant. Additionally, the per hectare cereal productivity also showed an apparent increase over the period. The yield of cereal crops increased by 3-fold from nearly 1.35 to 4.1 t ha<sup>-1</sup> whereas maize, wheat, and rice productivity have increased by 3, 3.3, and 2.5 folds from 1.94, 1.1, and 1.87 t ha<sup>-1</sup> to 5.82, 3.55, and 4.66 t ha<sup>-1</sup> over the same period respectively (Figure 2). The fertilizer consumption also has enormously increased within the aforementioned period. The world N fertilizer use in cereal crop production increased from 6.9 to 65.2 Mt (by 9.45-fold), while P<sub>2</sub>O<sub>5</sub> fertilizer consumption increased from 6.6 to 26.3 Mt (by 4-fold) and that of K<sub>2</sub>O fertilizer consumption increased from 5.2 to 22.6 Mt (by 4.34-fold) (Figure 2).

The increase in food production since Borlaug's green revolution (GR) is related to the influence of various factors such as increased use of chemical fertilizer, adoption of high yielding varieties, and increased irrigation system. Liu et al. (2015) and Zhang et al. (2011) demonstrated that the increase in food production since the GR is due to the accessibility of new agricultural technology and the intensive use of production factors. Following the GR, the N fertilizer application on responsive and resistant



**Figure 1.** A 59-years (1961-2019) world cereal production (in million tons (Mt)) and area coverage (in million hectares (Mha)) of all cereals (A), maize (B), wheat (C), and rice (D). The term 'All cereals' representing maize, wheat, rice, sorghum, millet, oats, barley, rye, and other minor cereal crops. Data was collected from (FAOSTAT, 2021).



**Figure 2.** A 59-years (1961-2019) world cereal productivity ( $t\ ha^{-1}$ ) and chemical fertilizer use (Mt) in cereal production. Data was collected from (FAOSTAT, 2021).

modern genotypes of rice and wheat has increased the output by about 260% (Ladha *et al.*, 2005). For example, the crop productivity in China increased by six folds from  $1\ t\ ha^{-1}$  in 1960 to  $6\ t\ ha^{-1}$  by 2015 due to the aforementioned reasons and strong government policies (Jiao *et al.*, 2018). Moreover, world cereal production and fertilizer consumption have local and regional differences. For example, the average cereal productivity of East Asia and Pacific, European Union, North America, and SSA were 5.13, 5.24, 7.65, and  $1.44\ t\ ha^{-1}$ , respectively, by 2018 (World Bank, 2021a). More importantly, the yield is stagnating in different parts of the world despite the intensive use of pro-

duction factors. For example, the maize and rice yields are stagnating across 31% and 36% of maize and rice-growing areas in India and 52% and 79% in China, respectively (Ray *et al.*, 2012). In China, despite the N,  $P_2O_5$ , and  $K_2O$  fertilizer supply increased by about 24, 48, and 176%, respectively, and pesticide use increased by 28%, the grain yield has only increased by 3.5% from 1996 to 2005 (Zhang *et al.*, 2011). Similar results were also reported in Europe (Brisson *et al.*, 2010). It is obvious that increasing fertilizer rate lifts crop yield to a specific level and then the yield increase becomes negligible and starts declining. However, meeting the future food demand through producing ade-

quate food production while simultaneously increasing NUE and reducing environmental pollution is one of the major challenges of our time.

### NUTRIENT USE EFFICIENCY AND ITS IMPROVEMENT APPROACH IN AGRICULTURE

The nutrients application rate and NUE mostly has an inverse relationship (Fageria *et al.*, 2015). Plants can take up the required amount of nutrients from the soil and the unabsorbed by nutrients either remains in the soil or are lost to the environment by several mechanisms (Tilman, *et al.*, 2002; Yang *et al.*, 2019). Globally, the fertilizer recovery efficiency by plants is low (Omara *et al.*, 2019; Chien *et al.*, 2016; Cui *et al.*, 2010; Ladha *et al.*, 2005). Our review result showed that the estimated global NUE values for cereal crops were reportedly 33% of N (Raun and Johnson, 1999), 16% of P (Dhillon *et al.*, 2017), and 19% of K (Dhillon *et al.*, 2019), respectively. Omara *et al.*, (2019) also reported the world nitrogen use efficiency of 35%. This means that a total of 65-67% of N, 84% of P, and 81% of K fertilizers remains unaccounted for and either remain in the soil or are lost to the environment. Ladha *et al.* (2005) reported that the N-recovery efficiency by the first crop is about 30% to 50%. The fertilizer recovery efficiency is affected by several factors including rate, time, and methods of fertilizer application (Sharma and Bali, 2017), genotypes (Li *et al.*, 2020), cropping system, indigenous soil nutrient supply, environment (Chen *et al.*, 2018; Xu *et al.*, 2014) to mention a few. Applying N fertilizer before planting increases the leaching potential before peak N uptake. Therefore, in order to produce sufficient food for escalating human population without compromising on the ecosystem service and to minimizing economic costs, the improvement of NUE is an important and unsurpassed approach in modern agriculture.

### APPROACHES TO IMPROVE NUE IN AGRICULTURE

Improving NUE requires a fundamental understanding of nutrient management. Herewith below reviewed some of the NUE improvement mechanisms applied in agriculture.

#### Soil management

**Adoption of organic inputs:** Unlike conventional agriculture, organic farming (OF) is mainly dependent on nutrient recycling, biological N-fixation, and crop rotations (Chmelíková *et al.*, 2021; Timsina, 2018). As of late, the use of organic fertilizer has become a better strategy to replace chemical fertilizers due to its ability to raise organic matter (SOM) concentration, yield and yield quality, and environmental reclamation (Song *et al.*, 2015; Roba, 2018). Also, its use in arable land to enhance soil organic matter was adopted as an important strategy to boost food production, ensure food security as well as mitigating climate change during the "4 per 1000 initiative" at COP 21 (UNFCCC, 2015). Chmelíková *et al.*, (2021) demonstrated that OF systems had the highest nitrogen use efficiency and lower N balances over conventional farming practices. **Nutrient stewardship:** Rational use of chemical fertilizers enhances crop growth and

productivity whereas excessive usage results in a potential yield reduction and adverse effects on the environment (Chandini *et al.*, 2019; Tripathi *et al.*, 2020). However, the use of apposite sources, rational rates, appropriate timing, and effective application methods are the most important approach to solve the aforementioned challenges (Giday, 2019; Li and Jin *et al.*, 2012). Nutrient-use efficiency can be increased by better matching temporal and spatial nutrient supply with plant demand (Tilman *et al.*, 2002). Therefore, the adoption of effective nutrient sources is a good management approach to improve NUE and attain higher crop yields.

**Use of modified fertilizer:** Nitrogen from conventional urea can easily be subjected to loss from the soil-plant system due to its dynamic nature (Zhu *et al.*, 2020). Accordingly, a modified fertilizer is needed to reverse its negative effects on soil, plant, and the environment. Different types of slow-release fertilizers (SRF) have been developed to improve NUE and reduce potential losses to the environment (Giday, 2019; Giday *et al.*, 2014). For example, controlled-release fertilizers (CRF) and nitrification inhibitors (NI) could either slow down nutrient-releasing patterns and/or can interfere with nutrient transformation processes and reduce its loss (Singh *et al.*, 2018). It potentially delays the N release pattern and reduces N losses; which may improve the synchronization potential between crop demand and soil N supply (Giday *et al.*, 2014). A meta-analysis conducted in China revealed that the application of CR urea significantly improved crop yield and NUE (Zhu *et al.*, 2020). Also, the meta-analysis result demonstrated that the use of enhanced efficiency nitrogen fertilizer could increase yield by 5.7% and N uptake by 8% (Linquist *et al.*, 2013).

**Adoption of root-zone fertilization approach:** Split-surface broadcasting (SSB) is a widely adopted fertilization method that may enhance yield and NUE, but it is labour-intensive. The use of slow/CRU is proposed as a decisive approach to cut nutrient loss and thereby enhance yield and NUE over the conventional urea (Zhu *et al.*, 2020), but it is highly expensive. Therefore, one-time root-zone fertilization (RZF) was proposed as a decisive approach for solving the aforementioned challenges. Optimal matching of the soil nutrients supply through applying nutrients in the root zone of the crop is one of the most important strategies to enhance NUE, maintain high and stable grain yield, and protect the environment (Jiang *et al.*, 2019). One-time RZF is the approach of applying all the fertilizers at one time during the plant's whole growth stage. It is proposed as a better approach to replace the traditional fertilizer application practices. The two-year field experiment in China revealed that RZ N fertilization has a higher yield potential (about 11.55%) over the SSB (Jiang *et al.*, 2018). It also increases N apparent recovery efficiency from 14.3-37.8% and total N uptake by 7.2-13.5% compared with SSB treatments, while it decreases N losses by 11.2-24.2%. Also, Liu *et al.* (2017) showed that the RZF of urea enhanced grain yield of rice (about 19.5%), macronutrients accumulation and uptake and N apparent recovery efficiency over farmer fertilizer practice in both sandy and loam soils. A two-year field experiment revealed that one-time RZF increased

maize yield by 4%, apparent N recovery efficiency by 18% and also improved nitrogen agronomic use efficiency, physiological efficiency and partial factor productivity as compared with SSB in the Anhui province of China (Jiang *et al.*, 2019). Therefore, adopting one-time RZF is an appropriate fertilization approach to reduce labour cost, enhance yield, NUE, and potential nutrient loss to the environment. Use of plastic mulch: Plastic mulch helps to increase soil temperature, preserve soil moisture, conserve soil, reduce weed pressure, boosts grain yield, and result in more efficient use of nutrients (Bahadur *et al.*, 2018; Kasirajan and Ngouajio, 2012). Also, it enhances both macro and micronutrient availability in soil, water use efficiency, reduces nitrate leaching, and prevents run-off and soil loss. Despite its potential advantage, the conventional polyethylene mulches cause a major waste disposal problem and are an agronomic, economic, and environmental challenge. However, this problem led to the development of biodegradable and photodegradable mulches (Kasirajan and Ngouajio, 2012); which are easily degradable and have lower environmental costs.

### Plant management

Adoption of nutrient use efficient genotypes: Development and preferential planting of high-yield and high-efficient cultivars are important steps to ensure food security, reduce fertilizer use and tackle environmental pollution (Chen *et al.*, 2013). Different genotypes vary in N uptake and utilization potential. This variation might be associated with root morphology (length, volume, thickness, and surface area of roots), the crop's potential to absorb and solubilize nutrients in the rhizosphere, and the balance between source-sink relationships (Fageria *et al.*, 2015; Ladha *et al.*, 2005). Depending on the grain yield achieved at different levels of nitrogen, maize cultivars were grouped into four categories based on their nitrogen use efficiency as reported by (Chen *et al.*, 2013). They are (i) efficient-efficient (EE) (efficient at both low and high N levels), (ii) high-N efficient (HNE) (efficient only at high N levels), (iii) low-N efficient (LNE) (efficient only at low N levels), and (iv) nonefficient-nonefficient (NE) (inefficient both at low and high N levels). The identification of genetic variation in crops regarding the nutrient acquisition and internal use efficiency can help in identifying, selecting, and the use of relevant crop genotypes with greater NUE for sustainable production. Therefore, selecting NUE efficient genotypes reduces the intensified use of fertilizer and has economic and environmental benefits.

Crop rotation and using biological N-fixing crops: Growing the same crop in the same field over many years (known as monocropping) gradually decreases the soil productivity due to its over-reliance on external inputs. Suitable adoption of crop sequencing is a vital approach to decrease the use of chemical fertilizer and improve NUE. Biological N fixation (BNF) is a vital approach of the N cycle which can help the crop by supplying nitrogen and replenishing the soil N pool (Yassine and Belhadji, 2012). Inclusion of legume crops in the agricultural field fixes free atmospheric nitrogen and makes it available for the succeeding crops grown in the sequence, reducing the chemical N

demand and nitrate leaching (Fageria *et al.*, 2015), which thereby improve yield and NUE. Management of biological stress: Pests, diseases, and weeds (PDW) continues to play a major limiting role in agricultural production. Crops infested by PDW lower nutrient absorption potential and photosynthetic efficiency, which results in low yield and resource use efficiency. Tamene *et al.* (2015) demonstrated that poor weed management increased inter-competition for soil nutrients, moisture, and sunlight; which affects resource use efficiency and crop productivity. Therefore, keeping these factors under the threshold levels is an important step to enhance yield and NUE (Singh *et al.*, 2018).

### Integrated soil-crop system management approach

Achieving high-yield and high-resource use efficiency simultaneously is a consensus that requires an integrated adoption and application of soil and crop management approaches. Although world population and food demand are booming unprecedentedly, the crop yield is stagnating in many parts of the world and the fertilizer use efficiency is declining quickly, particularly in high fertilizer supply regions such as China. To mitigate such challenges, integrated soil-crop system management (ISSM) approach was developed in China to improve yield and NUE without further increase of chemical fertilizer while reducing environmental pollution (Zhang *et al.*, 2011). The management techniques employed in the ISSM paradigm has three major principles i.e., (i) taking all possible and important measures to enhance the quality of soil, (ii) accounted and cohesive use of different nutrient resources and matching nutrients supply with crops requirement and (iii) integrating soil and nutrient management practices with the high-yielding production system (Jiao *et al.*, 2018; Zhang *et al.*, 2011).

Wang *et al.* (2020) in their 11-years field experiment in China reported that adoption of ISSM practices could result in relatively at par maize yield with high yielding practices (HY), but it was increased by 27% over farmers' practice (FP). Moreover, it significantly increase nitrogen recovery efficiency, agronomic use efficiency, and partial factor productivity over HY and FP and significantly reduced N surplus. Also, it reduced the reactive N losses by 47% and 20% and greenhouse gas (GHG) emissions by 34% and 13% as compared with HY and FP, respectively (ibid). Based on a 7-years field plot (2009-2016), Zhang *et al.*, (2019) summarized that adoption of ISSM can be an effective agricultural management approach to enhance yield, phosphate utilization, and soil available phosphorous. Therefore, the adoption of an ISSM strategy is an effective approach to enhance yield, improve NUE and lessen the environmental pollution.

### Precision agriculture

Achieving high yield and high efficiency depends on the sophisticated management of soil and water resources and applied inputs. Precision agriculture (PA) is an integrated information and technology-based field management approach that aims to use technology to identify and manage the temporal and spatial variation of fields, which will help to improve agricultural pro-

duction, productivity, and efficiency while abating adverse environmental effects (Alemaw and Agegnehu, 2019; Singh et al., 2018). PA tools help to provide the requisite resources according to the requirements without excess or deficiency at each point in time during the crop growing season (Cassman, 1999). It has comprehensive use in agriculture such as for precise analysis of soil, planting, agrochemical application, proper crop monitoring, irrigation, and crop health assessment (Clercq et al., 2018). Soil test and tissue analysis methods are widely used conventional approaches to determine the nutrient status of the soil; but, the use of PA tools such as GIS, drone, satellite imagery, green seeker, Holland Crop Circle, and other related tools found to be comparatively better than the conventional methods (Sharma and Bali, 2017) and assists in optimized use of resources, improve NUE and reduce environmental problems.

## Conclusion

The world cereal production has more than tripled (3.4-fold) from 1961 to 2019 providing food for the ever-increasing human population. The overall cereal crop productivity increased from 1.35 to 4.1 t ha<sup>-1</sup> (3-fold) in the aforementioned periods. However, the increase in production and productivity could be attributed to the intensive use of production factors, particularly chemical fertilizers. The N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O fertilizer use have increased by a factor of 9.45, 4, and 4.34 in the past 59-years. Over-application and misuse of chemical fertilizer results in yield stagnation, lower NUE, and high environmental costs. Lower NUE has agronomic, environmental, and economic implications. To improve NUE in agriculture, scientists developed several management approaches such as soil and crop management, ISSM, the use of precision agriculture, and the adoption of RZF approaches to optimize agricultural inputs, enhance productivity and reduce adverse environmental challenges. However, the integrated use of these NUE management approaches is more effective and highly recommendable than their sole use.

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## Conflict of interests

The authors declare that they have no known competing financial interests.

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