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RESEARCH ARTICLE

Improving Primary Nutrients (NPK) Use Efficiency for the Sustainable Production and Productivity of Cereal Crops: A Compressive Review

Alemu Andualem[1*], Tamirat Wato[1], Abera Asfaw[2], Gutema Urgi[3]

[1]Department of Plant Science, College of Agriculture and Natural Resource, Bonga University, Ethiopia
[2]Department of Horticulture, College of Agriculture, Wolaita Sodo University, Ethiopia
[3]Department of Resource Utilization and Plant Protection, College of Resource and Environmental Science, China Agricultural University, Beijing China

Corresponding Author: Alemu Andualem: email: zelaalemuandualem@gmail.com
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Abstract
Nutrient Use Efficiency (NUE) is the capacity of certain crops to use the available nutrients for growth, development, and productivity. Enhancing the efficiency of nutrient utilization by cereals is an admirable objective and a major problem for the fertilizer sector and agriculture as a whole. Nutrient Use Efficiency (NUE) is a critical concept in the evaluation of cereal production systems. Therefore, this study aimed to review methods for improving the efficiency of primary nutrient (NPK) use in cereals (Barley, Rice, Wheat, Maize, Sorghum, and Sugarcane) for sustainable production and productivity. Soil, plant water, and fertilizer management can have important impacts on the nutrient-use efficiency of cereals. Nutrient utilization aims to maximize the overall performance of cropping systems by providing the crop with the most inexpensive sustenance possible, while reducing nutrient losses from the field. The NUE takes care of some, but not all, of that performance. Thus, in addition to NUE, total productivity must is one of the aims of system enhancement. The question being posed and, frequently, the spatial or temporal scale of interest for which trustworthy data are available, dictate the most appropriate approach to NUE. For N, P, and K, the partial nutrient balance (the ratio of nutrients removed by crop harvest to fertilizer. Although opinions differ, agronomic nutrient use efficiency is the foundation for both economic and environmental efficiency. Economic and environmental efficiencies arise from increased agricultural efficiency. Therefore, different researchers have investigated ways to improve the nutrient use efficiency of cereals by using mechanisms including optimizing nutrient usage, nano-fertilizer usage, breeding for nutrient use efficiency, and precision farming.

Keywords: Primary plant nutrients; Nutrient uptakes; Nutrient use efficiency; Cereal crops

Introduction

Meeting societal demand for food is a global challenge, as recent estimates indicate that global crop demand will increase by 100–110% from 2005 to 2050 (Ali et al., 2020; Hunter et al., 2017). Others have estimated that the world will need 60% more cereal production between 2000 and 2050 (FAO, 2017), whereas others have predicted that food demand will double within 30 years, equivalent to maintaining a proportional rate of increase of more than 2.4% per year. It is quite difficult to fulfill such a demand sustainably, particularly in light of historical trends in grain yields, which have been linear for almost 50 years with slopes of barely 1.3% to 1.2 percent of the 2016 yields (FAO, 2017). The requirement for additional food grain can be met either by bringing more area under cultivation or by increasing the productivity and efficiency of existing crop varieties. Cereal crops are cultivated worldwide in large quantities. Since the Green Revolution began, the production of high-yielding cereals (maize, wheat, and rice), cotton, and sugarcane has significantly increased. Cereals especially, rice (*Oryza sativa* L.), maize (*Zea mays* L.), and wheat (*Triticum aestivum* L.) are essential commodities on which human nutrition is based. Expanding population and food demand have required higher production, which has been achieved by increasing fertilization, especially the primary macronutrients. Primary macronutrients play a very important role in improving the yield and quality of crops. The three main elements are nitrogen, phosphorus, and potassium (N, P, and K), which are required in abundance. They must be readily available in soil media or fertilizers (Isreal & Yonas, 2021).

Among the nutrients, nitrogen (N) is the fundamental nutrient that is needed the most for crop production while N deficiencies result in yellowing crop leaves and reduced tillering of cereal crops. Phosphorus (P) is a vital nutrient for plant growth and productivity that modifies cell division, enzyme activity, and carbohydrate processes (Malhotra et al., 2018). Moreover, phosphorus also plays a vital role in cellular processes by maintaining the membrane structure, synthesizing bimolecular molecules, and forming high-energy molecules (Malhotra et al., 2018).

Improving NUE and water use efficiency (WUE) has been listed among today’s most critical and daunting research issues (Thompson, 2012). NUE is a critically important concept for evaluating crop production systems and can be greatly affected by fertilizer management, as well as soil- and plant-water relationships. NUE indicates the potential for nutrient loss to the environment from cropping systems, as managers strive to meet the increasing societal demand for food, fiber, and fuel (Paul et al., 2015). NUE measures are not measures of nutrient loss, because nutrients can be retained in the soil, and systems with relatively low NUE may not necessarily be harmful to the environment, whereas those with high NUE may not be harmless (Paul et al., 2015). We provide examples of these situations later in the chapter that illustrate why the interpretation of NUE measurements must be performed within a known context.

Sustainable nutrient management must be both efficient and effective in delivering the anticipated economic, social, and environmental benefits. As the cost of nutrients increases, profitable use places increased emphasis on high efficiency, and greater nutrient amounts from higher-yielding crop removal means that more nutrient inputs will likely be needed and at risk of loss from the system. Providing a society with sufficient quantity and quality of food at an affordable price requires that production costs remain relatively low, while productivity increases to meet the projected demand. Therefore, productivity and NUE should be increased. These factors have spurred efforts by the fertilizer industry to promote approaches to best management practices for fertilizers, such as 4R Nutrient Stewardship, which focuses on the application of the right nutrient source, at the right rate, in the right place, and at the right time (IPNI, 2012) or the Fertilizer Product Stewardship Program (Fertilizers Europe, 2011). These approaches consider the economic, social, and environmental dimensions essential to sustainable agricultural systems and, therefore, provide an appropriate context for specific NUE indicators. NUE appeared on the surface as a simple term. However, a meaningful and operational definition is considerably complex because of the number of potential nutrient sources (soil, fertilizer, manure, atmosphere [aerial deposition], etc.) and the multitude of factors that influence crop nutrient demand (crop management, genetics, and weather). The concept is further stressed by variations in the intended use of NUE expressions, and because these expressions are limited to data available rather than the data most appropriate for interpretation.

The objective of nutrient use is to increase the overall performance of cropping systems by providing economically optimum nourishment to the crop, while minimizing nutrient losses from the field and supporting agricultural system sustainability through contributions to soil fertility or other components of soil quality (Tamirat, 2019). NUE addresses some aspects of that performance but not all (Mikkelsen et al., 2012). The most valuable NUE improvement contributed the most to the overall cropping system performance. Therefore, management practices that improve NUE without reducing productivity or increasing potential for future productivity are likely to be the most valuable. If the pursuit of improved NUE impairs current or future productivity, the need for cropping fragile land is likely to increase. Fragile lands usually support systems with lower NUE that also use water less efficiently. At the same time, as nutrient rates increase towards an optimum, productivity continues to increase, but at a decreasing rate, and NUE typically declines (Barbieri et al., 2008). The extent of the decline is determined by source, time, and place factors; other cultural practices; and soil and climatic conditions. Hence, this review was undertaken to provide information on improving primary macro-nutrient use efficiency in cereal (Barley, Rice, Wheat, Maize, Sorghum, and Sugarcane) crop plants.

Nutrient Management Practices

It is necessary to understand the possible effects of crop management techniques, such as mulching, minimum tillage, NPK fertilizers, balanced nutrient application, cereal crop yield, and household financial returns, to boost cereal yields and ensure sustainable productivity in smallholder farms. Nutrient application rate and NUE mostly have an inverse relationship (Fageria et al., 2015). Plants can take up the required amount of nutrients from the soil, and the unabsorbed nutrients either remain in the soil or are lost to the environment through several mechanisms (Tilman et al., 2002; Yang et al. 2019). Globally, the fertilizer recovery efficiency of plants is low (Omara et al., 2019; Chien et al., 2016; Cui et al., 2010; Ladha et al., 2005). Our results showed that the estimated global NUE values for cereal crops were 33% of N (Raun & Johnson, 1999), 16% of P (Dhillon et al., 2017), and 19% of K (Dhillon et al., 2019). Omara et al. (2019) also re-ported the world nitrogen use efficiency of 35%. This means that a total–65-67% of N, 84% of P, and 81% of K fertilizers remain 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%. Numerous factors, such as fertilizer application rate, timing, and techniques (Sharma & Bali, 2017), genotypes (Li et al., 2020), cropping system, native soil nutrient supply, and environment (Chen et al., 2018; Xu et al., 2014), to name a few, influence the fertilizer recovery efficiency. The leaching potential before peak N absorption increased when N fertilizer was applied before planting. Therefore, increasing NUE is a crucial and unrivaled strategy in contemporary agriculture to ensure that there is sufficient food to feed the growing human population while maintaining ecosystem services and lowering expenses.

Approaches to improve NUE in Cereal production

Improving NUE requires fundamental understanding of nutrient management. Below are some NUE improvement mechanisms applied in cereal production.

Soil management

Adoption of organic inputs: Unlike conventional agriculture, organic farming (OF) is mainly dependent on nutrient recycling, biological N fixation, and crop rotation (Timsina, 2018; Chmelíková et al., 2021). Recently, the use of organic fertilizers has become a better strategy to replace chemical fertilizers because of their ability to raise organic matter (SOM) concentration, yield, yield quality, and environmental reclamation (Song et al., 2015; Tesfaye, 2018). In addition, its use in arable land to enhance soil organic matter was adopted as an important strategy to boost food production, ensure food security, and mitigate 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 a lower N balance than conventional farming practices. Nutrient stewardship*:* The rational use of chemical fertilizers enhances crop growth and productivity, whereas excessive use results in potential yield reduction and adverse effects on the environment (Chandini et al., 2019; Tripathi et al., 2020). However, the use of appropriate sources, rational rates, appropriate timing, and effective application methods is the most important approach for solving the aforementioned challenges (Giday, 2019; Li & Jin et al., 2012). Nutrient-use efficiency can be increased by better matching the temporal and spatial nutrient supply with plant demand (Tilman et al., 2002). Therefore, the adoption of effective nutrient sources is an effective management approach for improving NUE and achieving higher crop yields.

Use of modified fertilizer: Nitrogen from conventional urea can easily be lost from the soil-plant system because of its dynamic nature (Zhu et al., 2020). Accordingly, a modified fertilizer is required to reverse its negative effects on soil, plants, and the environment. Different types of slow-release fertilizers (SRF) have been developed to improve NUE and reduce potential environmental losses (Giday, 2019; Giday et al., 2014). For example, controlled-release fertilizers (CRF) and nitrification inhibitors (NI) can either slow down nutrient-release patterns and/or interfere with nutrient transformation processes and reduce their 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 improves crop yield and NUE (Zhu et al., 2020). In addition, meta-analysis results 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 the root-zone fertilization approach: Split-surface broadcasting (SSB) is a widely adopted fertilization method that may enhance yield and NUE, but it is labor-intensive. The use of slow/CRU has been proposed as a decisive approach to reduce nutrient loss and thereby enhance yield and NUE over conventional urea (Zhu et al., 2020), but it is highly expensive. Therefore, one-time root-zone fertilization (RZF) has been proposed as a decisive approach to solving the aforementioned challenges. Optimal matching of the soil nutrient supply through the application of nutrients in the root zone of the crop is one of the most important strategies for enhancing NUE, maintaining high and stable grain yields, and protecting the environment (Jiang et al., 2019). One-time RZF is the approach of applying all fertilizers at one time during the plant's entire growth stage. This has been proposed as a better approach to replace traditional fertilizer application practices. A two-year field experiment in China revealed that RZ N fertilization has a higher yield potential (approximately 11.55%) than SSB (Jiang et al., 2019). It also increased N apparent recovery efficiency from 14.3-37.8% and total N uptake by 7.2-13.5% compared with SSB treatments, while it decreased N losses by 11.2–24.2%. In addition, Liu et al. (2017) showed that the RZF of urea enhanced the grain yield of rice (about 19.5%), macronutrient accumulation and uptake, and apparent N 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 improved nitrogen agronomic use efficiency, physiological efficiency, and partial factor productivity 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 labor costs and enhance yield, NUE, and potential nutrient loss to the environment. Use of plastic mulch: Plastic mulch helps increase soil temperature, preserve soil moisture, conserve soil, reduce weed pressure, boost grain yield, and result in more efficient use of nutrients (Bahadur et al., 2018; Kasirajan & Ngouajio, 2012). In addition, it enhances both macro-and micronutrient availability in soil and water use efficiency, reduces nitrate leaching, and prevents runoff and soil loss. Despite their potential advantages, conventional polyethylene mulches cause major waste disposal problems and are agronomic, economic, and environmental challenges. However, this problem has led to the development of biodegradable and photodegradable mulches (Kasirajan & Ngouajio, 2012) that are easily degradable and have lower environmental costs.

Plant management

Adoption of nutrient-efficient genotypes: Development and preferential planting of high-yield and high-efficiency cultivars are important steps to ensure food security, reduce fertilizer use, and mitigate environmental pollution (Chen et al., 2013). Different genotypes vary in terms of their N uptake and utilization potential. This variation might be associated with root morphology (length, volume, thickness, and surface area of roots), the potential of the crop 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 nitrogen levels, maize cultivars were grouped into four categories based on their nitrogen use efficiency, as reported by Chen et al. (2013). These are (i) efficiency efficiency (EE) (efficient at both low and high N levels), (ii) high-N efficiency (HNE) (efficient only at high N levels), (iii) low-N efficiency (LNE) (efficient only at low N levels), and (iv) nonefficient-nonefficient (NE) (inefficient at both low and high N levels). The identification of genetic variation in crops regarding nutrient acquisition and internal use efficiency can help identify, select, and use 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 mono-cropping) gradually decreases soil productivity because of its over-reliance on external inputs. Suitable adoption of crop sequencing is a vital approach for decreasing the use of chemical fertilizers and improving NUE. Biological N fixation (BNF) is a vital approach in the N cycle, which can help the crop by supplying nitrogen and replenishing the soil N pool (Yassine & Belhadj, 2012). The 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 chemical N demand and nitrate leaching (Fageria et al., 2015), which in turn improves yield and NUE. Management of biological stress*:* Pests, diseases, and weeds (PDW) continue to play a major limiting role in agricultural production. Crops infested with PDW have lower nutrient absorption potential and photosynthetic efficiency, which results in low yield and resource use efficiency. Tamene et al. (2016) demonstrated that poor weed management increases competition for soil nutrients, moisture, and sunlight, which affects resource use efficiency and crop productivity. Therefore, maintaining these factors at the threshold level is important for enhancing yield and NUE (Singh et al., 2018).

Integrated soil-crop system management approach

Achieving high yield and resource use efficiency simultaneously is a consensus that requires integrated adoption and application of soil and crop management approaches. Although world population and food demand are booming unprecedent-edly, 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, an integrated soil-crop system management (ISSM) approach was developed in China to improve yield and NUE without further increase in chemical fertilizer while reducing environmental pollution (Zhang et al., 2011). The management techniques employed in the ISSM paradigm have three major principles: (i) taking all possible and important measures to enhance the quality of soil, (ii) accounting for and cohesive use of different nutrient resources and matching nutrient supply with crop requirements, 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 increased nitrogen recovery efficiency, agronomic use efficiency, and partial factor productivity over HY and FP, and significantly reduced the N surplus. In addition, it reduced reactive N losses by 47% and 20% and greenhouse gas (GHG) emissions by 34% and 13%, respectively, compared with HY and FP, respectively (ibid). Based on a 7-years field plot (2009-2016), Zhang et al. (2019) summarized that the 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 for enhancing yield, improving NUE, and reducing environmental pollution.

Factors Influencing NPK Use Efficiency

Nutrient Use Efficiency (NUE) depends on several factors, such as the capacity of plants to take up nutrients effectively from the soil, internal transport, and storage remobilization of nutrients (Mikkelsen et al., 2012). It also indicates the ability of crops to produce the maximum yield while efficiently utilizing nutrients (Fixen et al., 2015). It is a critical factor for assessing crop production processes, which are significantly influenced by the dynamic relationship between soil, plants, and water, as well as nutrient management. It provides suitable solutions to managers who aim to satisfy the growing societal demand for food, fiber, and fuel against nutrient losses to the atmosphere from cropping systems. The aim of NUE enhancement is to enhance the productivity of cropping systems by providing economically optimal nourishment to the crop with minimum loss of nutrients from the field and ensuring the sustainability of the agricultural system by contributing to soil fertility and other components of soil quality.

Nutrient Use Efficiency Terminology

The nutrient use efficiency can be expressed in several ways. Mosier et al. (2004) described 4 agronomic indices commonly used to describe nutrient use efficiency: partial factor productivity (PFP, kg crop yield per kg nutrient applied); agronomic efficiency (AE, kg crop yield increase per kg nutrient applied); apparent recovery efficiency (RE, kg nutrient taken up per kg nutrient applied); and physiological efficiency (PE, kg yield increase per kg nutrient taken up). Crop removal efficiency (removal of nutrients from harvested crops as a percentage of nutrients applied) is also commonly used to explain nutrient efficiency. Available data and objectives determine

which term best describes nutrient use efficiency (Terry, 2008). Fixen (2005) provides a good overview of these terms with examples of how they might be applied.
The apparent use efficiency of fertilizer nutrients that are applied but not absorbed by the crop is affected by several factors, including leaching, erosion, denitrification (or volatilization in the case of N), and the possibility that they will be momentarily immobilized in soil organic matter before release (Terry, 2008). Dobermann et al. (2005) introduced the term system-level efficiency to account for contributions of added nutrients to both crop uptake and soil nutrient supply.

Current Status of Nutrient Use Efficiency

The single-year N fertilizer recovery efficiencies averaged 65% for maize, 57% for wheat, and 46% for rice according to a recent analysis of global data on N usage efficiency for cereal crops from researcher-managed experimental plots (Ladha et al., 2005). However, the efficiency achievable on a farm is not accurately reflected in the experimental plots. Lower nutrient usage efficiency is often the result of variations in the size of agricultural operations and management techniques (e.g., tillage, planting, weed and pest control, irrigation, and harvesting). Farmers seldom recover more than 50% of their nitrogen and typically recover considerably less. A review of the best available information suggests that the average N recovery efficiency for fields managed by farmers ranges from approximately 20% to 30% under rain-fed conditions, and 30% to 40% under irrigated conditions (Terry, 2008).
Cassman et al. (2002) looked at N fertilizer recovery under different cropping systems and reported 37% recovery for corn grown in the north-central U.S. They found that N recovery averaged 31% for irrigated rice grown by Asian farmers, and 40% for rice under field-specific management. In India, N recovery averaged 18% for wheat grown under poor weather conditions but 49% when grown under good weather conditions. Weather is an uncontrollable factor that affects fertilizer recovery, but management is something that can be managed.

Common Measures of NUE and their Application

Efficiency, in simple terms, is the achievement of desired outcomes with the lowest cost (Reich et al., 2014). In simplest terms, Nutrient Use Efficiency can be expressed at three different levels: at the leaf level, which is the potential maximum photosynthetic rate for certain nutrient content; at the plant level, which is the ratio of biomass produced to the total nutrient uptake; and at the crop level, which is the ratio of total biomass produced to the amount of nutrients available for uptake from soil (Ewel & Hiremath, 1998). In agronomic or operational terms, it is the differential response of crops/genotypes to yield when grown in nutrient-deficient soils (George et al., 2012). Excellent NUE measurements and common NUE terms are presented, along with their applications and limitations. The primary question addressed by each term and the most typical use of the term are listed in figure 2 (Dobermann, 2007).

Partial factor productivity (PFP) is a simple production efficiency expression calculated in units of crop yield per unit of nutrient applied. It is easily calculated for any farm that maintains input and yield records. It can also be calculated at regional and national levels, providing reliable statistics on input use and crop yields. However, partial factor productivity values vary among crops in different cropping systems because crops differ in their nutrient and water requirements. A comparison between crops and rotations is particularly difficult if it is based on fresh matter yields, because they differ greatly depending on the crop moisture content (e.g., potato vs.

cereals). Therefore, geographic regions with different cropping systems are difficult to compare using this indicator (Davis & Quick, 1998).

Agronomic efficiency (AE) was calculated as units of yield increase per unit of nutrients applied. It more closely reflects the direct production impact of an applied fertilizer and relates directly to economic return (Jagadish et al., 2021). Only once study plots with no nutrient input have been put into practice on the farm can the yield be obtained without nutrient input, which is necessary for calculating AE (Paul et al., 2015). The NUE of the applied fertilizer is frequently underestimated if it is computed using data from yearly trials rather than long-term trials, because of the residual effects of the application on subsequent crops. According to Dobermann (2007), long-term experiments are necessary to estimate the long-term effects of fertilizers on crop output.

Partial nutrient balance (PNB) is the simplest form of nutrient recovery efficiency and is usually expressed as nutrient output per unit of nutrient input (a ratio of "removal to use"). Less frequently it is reported as "output minus input." PNB can be measured or estimated by crop producers as well as at the regional or national level. Often, the assumption is made that a PNB close to one suggests that soil fertility will be sustained at a steady state. However, using a PNB of one as an indicator of soil fertility sustainability can be misleading, especially in regions with very low indigenous soil fertility and low inputs and production, such as sub-Saharan Africa, as the balance calculation is a partial balance and nutrient removal by processes, such as erosion and leaching, are typically not included (Paul, 2014). In addition, all nutrient inputs were rarely included in the balance calculations; thus, the modifier was partial in the term. Biological N fixation, recoverable manure nutrients, biosolids, irrigation water, and the atmosphere can all be nutrient sources, in addition to fertilizers.

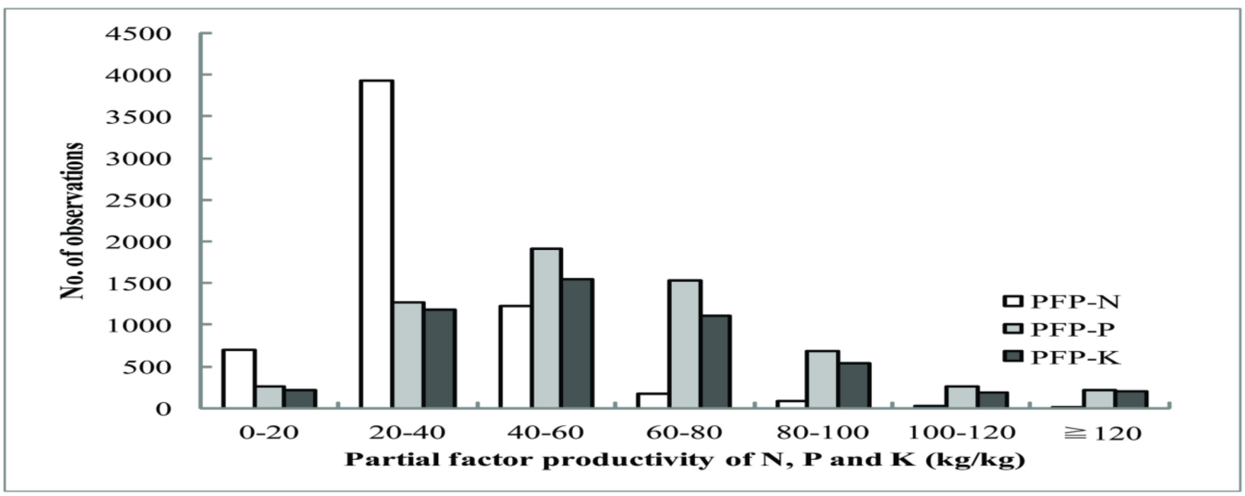

Figure 1 Distribution of the partial factor productivity of N, P, and K fertilizers (PFP-N, PFP-P, and PFP-K) in wheat in China. Source: Limin et al., 2016)

Nutrient inputs greatly outweigh nutrient removal at values far below 1, indicating preventable nutrient losses and the need for enhanced NUE (Suresh et al., 2017). However, attainable values are soil-specific and cropping systems. A PNB greater than 1 means more nutrients are removed with the harvested crop than applied by fertilizer and/or manure, a situation equivalent to "soil mining" of nutrients. This situation may be desirable if the available nutrient content in the soil is higher than that recommended. However, when the soil nutrient concentration is at or below the recommended levels, PNB >1 must be regarded as unsustainable (Suresh et al., 2017). Over the short term and on individual farms, PNB can show substantial fluctuations owing to cash flow and market conditions, especially for P and K. Therefore, the long-term assessment of PNB over several years is more useful (Zebarth et al., 2009). This is illustrated in Figure 1.

Apparent recovery efficiency (RE): One of the more complicated NUE expressions is apparent recovery efficiency (RE), which is usually described as the difference in nutrient uptake in the above-ground plant sections between the treated and unfertilized crops with respect to the amount of nitrogen provided. Scientists examining the nutritional response of crops frequently choose this as their preferred NUE expression (Addisu, 2022). Similar to AE, it is necessary to measure the concentration of nutrients in crops, which can only be assessed when a nutrient-free plot has been established (Prakash et al., 2021). Similar to AE, when calculated from annual response data, it will often underestimates long-term NUE (Paul, 2014).
Worldwide use of various fertilizers has made a remarkable contribution to increasing food production. It has been observed that nutrient inputs are responsible for 30–50% of crop yield (Meena et al., 2020). The recovery efficiency (RE) of Nitrogen, Phosphorus and Potassium fertilizers is approximately 20–40, 15–20, and 40–50%, respectively, while for secondary and micronutrients, it is considerably lower, ranging from 5% to 12% (Mandal et al., 2022). The important causes of low and declining crop responses to fertilizer nutrients include continuous nutrient mining from the soil due to imbalanced fertilizer use (7:2.8:1:NPK), leading to the depletion of some major, secondary, and micronutrients, such as N, K, S, Zn, Mn, Fe, and B (Kadyampakeni & Chinyukwi, 2021; Nadeem & Farooq, 2019). The reduction in the use of organic nutrient sources such as FYM, compost, and the integration of green manures/grain legumes in cropping systems has led to soil degradation. After several years of intensive research on nutrient management, field-specific fertilizer recommendations have been developed for almost all cultivated crops (Chivenge et al., 2022). The recommendations developed tell us about the amounts of different nutrients needed on a hectare basis and the time of application. Such blanket recommendations, which largely did not take into account the variability in the inherent soil fertility and other edaphic characteristics, resulted in the over-application of nutrients in some areas and under-application in others (Seth et al., 2020). This resulted in wastage of nutrients and low NUE. Research conducted in many Asian countries, including northwest India, has depicted the limitations of the conventional approach of fixed-rate, fixed-time (blanket) fertilizer recommendations (Singh et al., 2020). However, recognizing the defects in the blanket recommendations of nutrients, the concept of site-specific nutrient management (SSNM) of nutrients was developed. The original concept of SSNM for managing farm nutrient variability was first developed for rice in Asia (Arouna et al., 2021).

Internal utilization efficiency (IE) was defined as the yield of total nutrient uptake. It varies according to genotype, environment, and management. A very high IE value suggests a deficiency of this nutrient. Low IE suggests poor internal nutrient conversion due to other stresses (deficiencies of other nutrients, drought stress, heat stress, mineral toxicities, pests, etc.) (Zebarth et al., 2009).

Physiological efficiency (PE) is defined as the yield increase with an increase in crop uptake of nutrients in the aboveground parts of the plant. Similar to AE and RE, it requires a plot at a site where the nutrient of interest has not been applied. It also requires the measurement of nutrient concentrations in the crop, and is mainly measured and used in research (Zebarth et al., 2009).

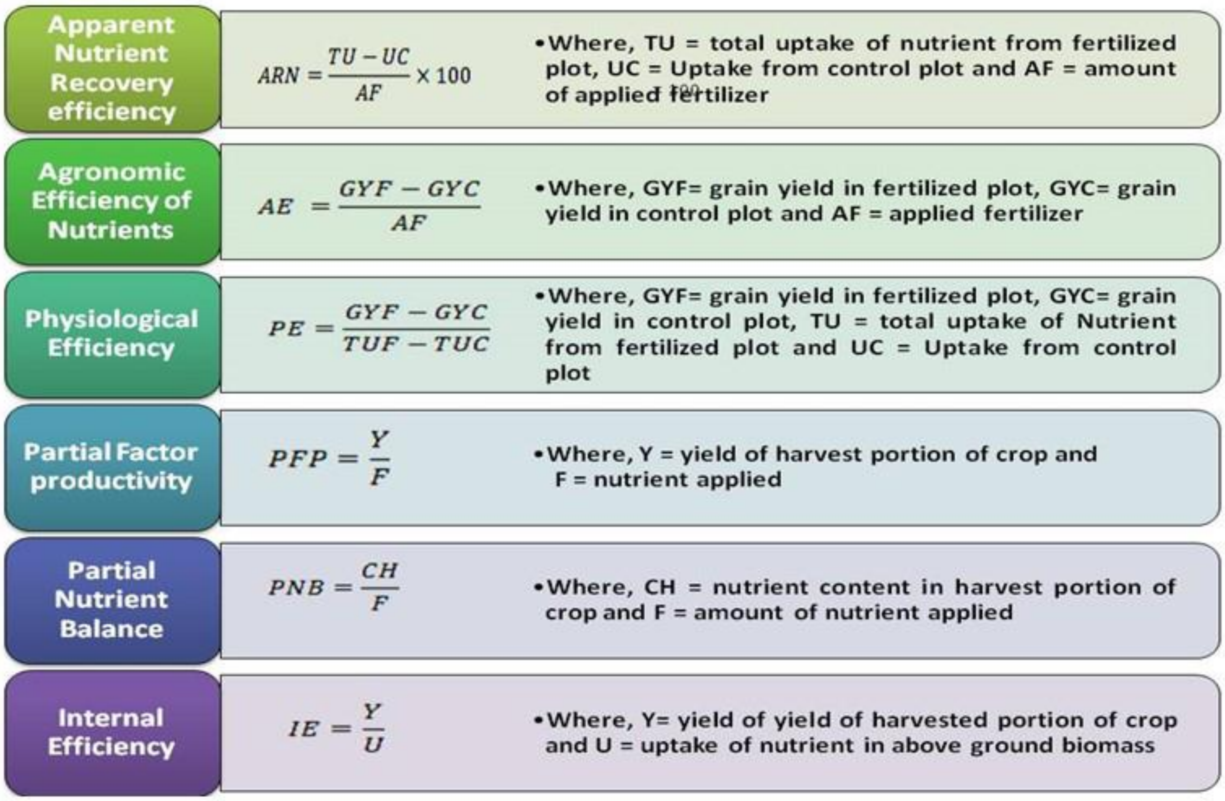

Figure 2 Common nutrient use efficiency indices (after Dobermann, 2007)

NUE Application and Benchmarks

In most cases, it is helpful to use more than one NUE term when evaluating any management practice, allowing for a better understanding and quantification of crop responses to the applied nutrients. Different indicators should be used simultaneously. The lowest fertilizer rates under consideration-rates linked to high PNB-often yielded the highest AE. Genetic modifications, such as the recent discovery of a Phosphorus Starvation Tolerance gene that helps rice to access more soil P (IRRI, 2012), will increase PFP and P removal during crop harvest. Such a development has great short-term value to farmers and may allow the system to operate at a lower level of soil P. However, if P use is less than the enhanced removal level, soil P depletion occurs (PNB is greater than 1). Therefore, even with such genetic changes, an appropriate PNB must be obtained for system sustainability. Although individual NUE terms can be used to describe the efficiency of fertilizer application, a complete analysis of nutrient management should include other NUE terms such as grain yield, fertilizer rates, and native soil fertility (Olk et al., 1999). For example, under low soil P availability, the AE for P could be very high with low P rates; however, the PNB for P under this condition could be well above 1, depleting already low soil P reserves. In this case, a low P rate with high AE for P, although a better practice than no P application, would not be considered the best management practice (BMP).

This section highlights the wide range of significant NUE metrics and trends as well as the main influencing variables. Improvements in nutrient stewardship can be facilitated by identifying relevant measures of NUE for the scale of interest, collecting data for these measures, and establishing benchmarks for evaluating the collected data. Benchmarks are best set locally within the appropriate cropping system, soil, climate, and management context and with full knowledge of how NUE measures are being calculated. As indicated in Figure 3, global fertilizer NPK consumption in crops has increased (FAO, 2019).

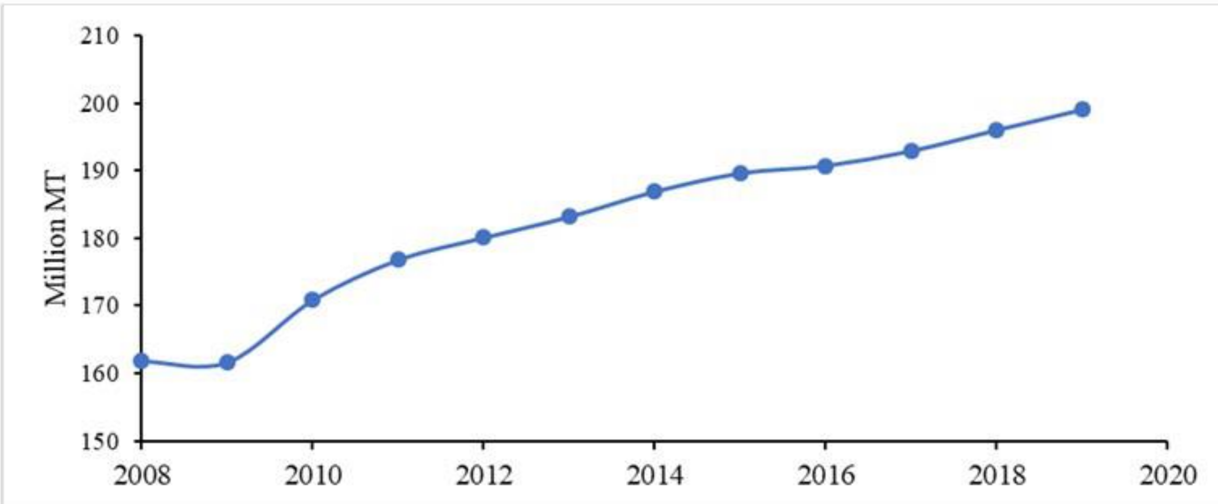

Figure 3. ***Global nutrients (N+P +K) consumption*** *(Source: FAO, 2019)*

Technological Innovations and Best Management Practices

Nanofertilizers

Nanofertilizers are nutrient fertilizers composed, in whole or part, of nanostructured 83 formulations that can be delivered to plants, allowing efficient uptake or slow release of ingredients. Conventional bulk fertilizers have low plant uptake efficiencies; thus, larger amounts are required. Two major challenges of low nutrient uptake efficiency for nitrogen- and phosphorus-based fertilizers are the rapid changes in chemical forms that the plants do not take up and runoff, leaching, or atmospheric losses. The resultant effects are the emission of harmful greenhouse gases, such as certain oxides of nitrogen, and eutrophication, with negative outcomes for soil and environmental health (Dimkpa et al., 2017). Therefore, it is important to develop smart fertilizers that are readily taken up by plants. Consequently, scientists are working hard to develop a variety of metal and metal oxide nanoparticles for use in plant science and agriculture. Because nanoscale particles are smaller in dimension than bulk particles, plants can absorb them with various dynamics compared to bulk particles or ionic salts, which presents an added advantage (Subbaiah et al., 2016). Kumar et al. (2021) reported that the highest grain yield of wheat was 4.8 t/ha with an additional increase of 425 ha^{-1} over FFP, giving a 9.76% increase was found under treatment 50% N-FFP with 2 sprays of nano-urea at active tillering and panicle initiation stage. Azam et al. (2022) found that foliar application of Nano fertilizers with different concentrations increased the plant growth, photosynthetic pigments and antioxidant activity by 59.28, 48.19% and 52.91%, respectively, in maize. The environmental health and safety aspects of nanotechnology should also be considered, and it is important to determine the toxicity and biocompatibility of nanofertilizers (Babu et al., 2022).

The 4Rs of fertilizer management

The fertilizer industry supports the application of nutrients at the right rate, time, and place as a best management practice (BMP) to achieve optimum nutrient efficiency (known as 4Rs).

Right rate: Most crops are location- and season-specific, depending on cultivar, management practices, climate, etc.. Therefore, it is critical that realistic yield goals are established and that nutrients are applied to meet the target yield. Over- or under-application results in reduced nutrient-use efficiency or losses in yield and crop quality. Soil testing remains one of the most powerful tools available for determining the nutrient-supplying capacity of the soil, but to be useful for making appropriate fertilizer recommendations good calibration data is also necessary. Unfortunately, soil testing is not available in all regions of the world because reliable laboratories using methodologies appropriate to local soils and crops are inaccessible or calibration data relevant to current cropping systems and yields are lacking. Other techniques, such as omission of plots, are useful for determining the amount of fertilizer required to attain a yield target (Witt & Doberman, 2002).
This strategy ensures that yield is not restricted by the lack of additional nutrients by applying N, P, and K at sufficiently high rates. Plots with infinite NPK are used to calculate the target yield. To obtain a nutrient-limited yield, one nutrient was removed from each plot. For instance, an N omission plot receives sufficient P and K fertilizers to guarantee that these nutrients do not restrict output, but there is no N fertilizer (Terry, 2008). The gap between the crop's need for nitrogen and the natural supply of the element, which must be filled by fertilizers, results in a difference in grain production between a completely fertilized plot and an N omission plot. The removal of nutrients from crops is an important consideration. Unless nutrients are removed from the harvested grain and crop residues are replaced, soil fertility is depleted.

Right time: Greater synchrony between crop demand and nutrient supply is necessary to improve nutrient use efficiency, particularly for N (Vijay et al., 2017). It is well known that dividing N treatments over the growing season, as opposed to applying a large amount all at once before planting, improves the N consumption efficiency (Cassman et al., 2002; Giller et al., 2004). Tissue testing is a well-known method used to assess the N status of growing crops; however, other diagnostic tools are available. Chlorophyll meters have proven useful in fine-tuning in-season N management (Francis & Piekielek, 1999), and leaf color charts have been highly successful in guiding split N applications in rice and maize production in Asia (Witt et al., 2005). Precision farming technologies have been introduced and are now commercialized. On-the-go N sensors can be coupled with variable-rate fertilizer applicators to automatically correct crop N deficiencies on a site-specific basis.
Another approach to synchronize the release of N from fertilizers with crop needs is the use of N stabilizers and controlled-release fertilizers (Addisu, 2022). Nitrogen stabilizers (e.g., nitrapyrin ($ClC_5H_3NCCl_3$), DCD [dicyandiamide] DCD), [n-butylthiophosphoric triamide] NBPT)) inhibit nitrification and urease activity, thereby slowing the conversion of the fertilizer to nitrate (Havlin et al., 2005). When soil and environmental conditions are favorable for nitrate loss, treatment with a stabilizer often increases the N fertilizer efficiency. Controlled-release fertilizers can be grouped into low-solubility and water-soluble compounds.
Most slow-release fertilizers are more expensive than water-soluble N fertilizers and have traditionally been used for high-value horticultural crops and turfgrass. However, technological improvements have reduced manufacturing costs and controlled-release fertilizers are available for use in corn, wheat, and other commodity grains (Blaylock et al., 2005). The most promising for widespread agricultural use are polymer-coated products,

which can be designed to release nutrients in a controlled manner (Addisu, 2022). Nutrient release rates are controlled by manipulating the properties of the polymer coating, and are generally predictable when the average temperature and moisture conditions can be estimated.

Right place: The application method has always been critical in ensuring that fertilizer nutrients are used efficiently. Determining the correct placement is as important as determining the correct application rate. Numerous placements are available, but most generally involve surface or subsurface applications before or after planting. Before planting, nutrients can be broadcast (i.e., applied uniformly on the soil surface and may or may not be incorporated), applied as a band on the surface, or applied as a subsurface band, usually 5–20 cm deep. When applied at planting, nutrients can be applied to the seed, below the seed, or below and on the side of the seed. After planting, the application is usually restricted to N, and the placement can be either a top dressing or subsurface side dress. In general, nutrient recovery efficiency tends to be higher with banded applications because less contact with the soil reduces the opportunity for nutrient loss owing to leaching or fixation reactions. Placement decisions depend on the crop and soil conditions, which interact to influence nutrient uptake and availability.

Plant nutrients rarely function independently. Interactions between nutrients are important because a deficiency in one restricts the uptake and use of the other. Numerous studies have demonstrated that the interaction between N and other nutrients, primarily P and K, affects crop yields and N efficiency. For example, data from a large number of multi-location on-farm field experiments conducted in India have shown the importance of balanced fertilization in increasing crop yield and improving N efficiency. Adequate and balanced application of fertilizer nutrients is one of the most common practices for improving the efficiency of N fertilizer, and is equally effective in both developing and developed countries. In a recent review based on 241 site-years of experiments in China, India, and North America, balanced fertilization with N, P, and K increased first-year recoveries by an average of 54% compared with a recovery of only 21% when N was applied alone (Fixen et al., 2005).

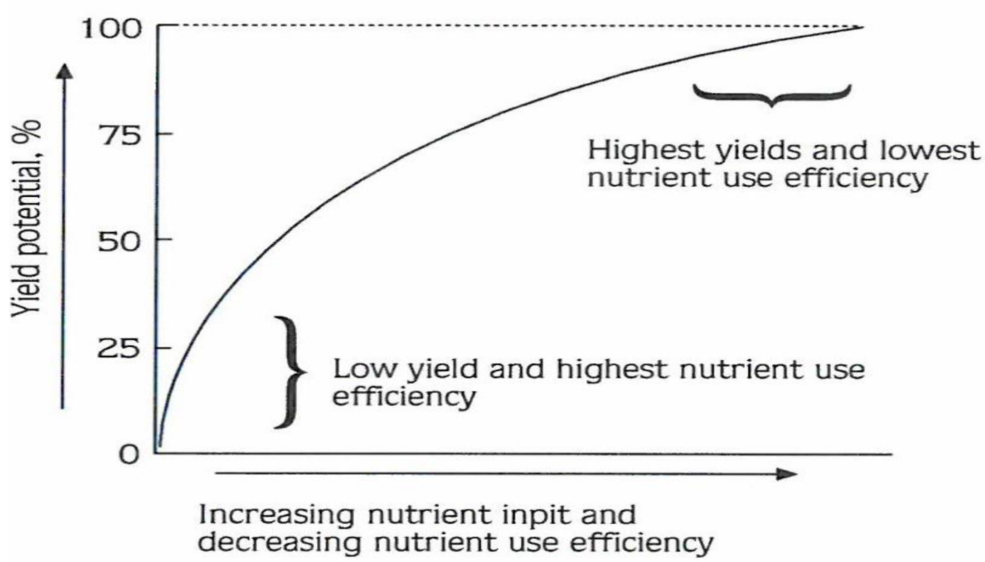

Figure 4 Relationship between yield response and nutrient use efficiency (adapted from Dibb, 2000).

Improving nutrient efficiency is an appropriate goal for all involved in agriculture, and the fertilizer industry, with the help of scientists and agronomists, is helping farmers work towards that end. However, their effectiveness cannot be sacrificed for their efficient use. Simplifying the process of sacrificing yield to obtain far better nutrient efficiency will not benefit the environment or the farmers economically. The relationship between yield, nutrient efficiency, and the environment was described by Dibb (2000) using a theoretical example. For a typical yield response curve, the lower part of the curve is characterized by very low yields because few nutrients are available or applied with very high efficiency (Figure 4). However, efficiency does not necessarily indicate effectiveness. Because a small amount of applied nutrients might result in a substantial yield response, nutrient utilization efficiency is high at low yield levels. Nutrient usage efficiency can be attained in the bottom portion of the yield curve if it is the only objective (George, 2014). However, poor crop growth would result in fewer surface residues to shield the land from wind and water erosion, and less root growth to increase soil organic matter, which would lead to serious environmental problems. Yields grow, albeit more slowly, as you go up the response curve, whereas nutrient-usage efficiency usually decreases.

However, the BMPs used (*i.e.*, appropriate rate, right time, right site, improved balance in nutrient inputs, etc.), along with soil and climate conditions, determine how much of a drop occurs. Fixen (2006) provided an additional explanation for the relationship between efficiency and effectiveness when he proposed that the value of increasing nutrient use efficiency depends on the effectiveness of meeting nutrient use objectives, such as providing the crop with the least amount of nutrients at a reasonable cost, reducing nutrient losses from the field, and contributing to system sustainability through soil fertility or other soil quality components, as presented in Table 1.

Table 1. NPK nutrient requirements for major cereal crops

Crop	N Requirement (kg/ha)	P Requirement (kg/ha)	K Requirement (kg/ha)	Location	References
Wheat	250	150	150	China	Ali et al. (2020)
Maize	49-61	19-23	46-57	Ethiopia	Workneh (2021)
Rice	125	62.5	62.5	India	Prakash (2021)
Sugarcane	281	140	275	Pakistan	Kandhro et al. (2021)
Barley	60	30	20	India	Hansram (2017)

Breeding for Nutrient Use Efficiency

Breeding for improved NTUE will be influenced in part by how NTUE is defined, because it will affect the screening method used, including the measurements that need to be taken, whether fertilizer treatments need to be imposed, and the selection of sites for assessment. More importantly, the type of germplasm that is developed can differ depending on the definition of NTUE used to guide the selection (Glenn, 2014). The problem associated with the definition of NTUE inbreeding for improved nutrient efficiency has been recognized for some time (Blair, 1993; Gourley et al., 1994), although it is far from complete.

One commonly used definition is that proposed by Moll et al. (1982), which was originally used for N use efficiency (NUE) but was subsequently extended to other nutrients (Ortiz-Monasterio et al., 2001). It is defined as the yield per unit of nutrient supplied and has two components: the ability to extract nutrients from the soil (uptake efficiency) and the ability to convert the nutrients absorbed by the crop into grain (utilization or physiological efficiency). While plants derive their nutrients from soil and fertilizer, nutrient supply is often considered to be the nutrients supplied as fertilizer; thus, NTUE is often the yield per unit of fertilizer applied. A problem with using this definition to identify more efficient genotypes is that one essentially selects yield potential. If it is used to assess NTUE of a diverse range of genetic material, lower-yielding varieties (such as landraces or old varieties) will have low NTUE even if they possess traits that may enhance nutrient uptake and use. Differences in the yield potential confounded the assessment of efficiency when this definition was used.

Precision Farming

Precision farming is an information- and technology-based farm input management system that aims to use technologies and principles to identify, analyze, and manage the spatial and temporal variability associated with all aspects of agricultural production within fields to maximize profitability and sustainability, enhance crop performance, protect land resources, and maintain or improve environmental quality (McBratney et al., 2005). Measurement of variability in the field concerning N and the application of the right amount of N at the right time using a variable rate applicator, remote sensing, geographic information systems (GIS), and global positioning system (GPS) technology may act as important information tools for farmers to improve NUE under the specific conditions of each field.

Precision farming tools help 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 is comprehensively used in agriculture for precise analysis of soil, planting, agrochemical application, proper crop monitoring, irrigation, and crop health assessment (Clercq et al., 2018). Soil tests and tissue analysis methods are widely used conventional approaches to determine the nutrient status of the soil; however, the use of precision farming tools such as GIS, drone, satellite imagery, green seeker, Holland Crop Circle, and other related tools were found to be comparatively better than the conventional methods (Sharma & Bali, 2017) and assist in optimizing the use of resources, improving NUE, and reducing environmental problems.

Enhancing Nutrient Cycling and Soil Health

Soil amendment has become a popular and quick way to improve soil quality in recent years. To preserve soil nutrient homeostasis, soil amendments can include sources of carbon (C) as well as other nutrients, including potassium (K), phosphorous (P), and nitrogen (N) (Yanhong et al., 2023; Garbowski et al., 2023). Additionally, soil amendments improve the soil structure and increase water retention to counteract nutrient loss and maintain soil fertility (Zhang et al., 2023). In dry and semiarid locations, the ability of soil amendments to retain more water is especially important for reducing the effects of seasonal drought and high rainfall events caused by climate change (Kuanyan et al., 2022). Furthermore, because the availability of these elements greatly affects microbial diversity and community structure, changes in soil nutrient and moisture levels can have a substantial impact on soil microorganisms. Fungal communities are notably affected by soil moisture conditions, which in turn affect their radial growth, sporulation, germination, and mycelial cord formation (Maryann & Huhta, 2000). However, bacterial populations are affected by changes in soil nutrients, particularly when organic fertilizers are added. This may lead to an increase in the relative abundance of beneficial bacteria (Jiai et al., 2021). The soil nutrient cycle may also be changed by modifying the activity of soil microorganisms (Chao et al., 2024). For example, Anaeromyxobacter and Haliangium facilitate N and P solubilization (Masuda et al., 2020; Wang et al., 2021). The vital roles of these microorganisms in controlling soil nutrient cycling, especially in arid and semi-arid regions, have been overlooked in favor of previous studies that have focused on how soil amendments affect fungi or bacteria in response to changes in the soil environment (Tran et al., 2023; Shiv et al., 2024).

For crops to continue growing healthily, soil nutrient cycling is essential (Prasad et al., 2021). Certain components (such as organic C) can be quickly enriched by soil amendments; thus, additional N must be microbially decomposed to maintain a steady C/N ratio. Additionally, through recycling and decomposition, soil microbes help liberate mineral nutrients from soil additions, increasing their availability for plant uptake, and consequently, soil fertility (Liu et al., 2023). Although fungi may play a more significant role than bacteria in soil nutrient cycling during forest conversion, some studies have found strong correlations between bacterial diversity and soil organic carbon (SOC), total nitrogen (TN), and soil multi-nutrient cycling in sandy ecosystems and coastal wetlands (Liu et al., 2021; Zhang et al., 2022).

Microbes are important entities that give life to the soil and are responsible for soil health, environmental sustainability, and sustaining the life of plants and animals on Earth. It has been said by a renowned microbiologist CR Woese "If we wiped off all the multicellular organisms (plant and animals) from the earth's surface, then it would barely affect the microbial community where the destruction of the microbial community would lead to instant death of all life forms on earth". Healthy soil is characterized by the presence of a diverse range of microorganism populations, including bacteria, fungi, protozoa, viruses, archaea, archaea, cyanobacteria, actinomycetes, and microalgae. Microbes play a major role in nutrient cycling, and thus help in nutrient acquisition and availability. These characteristics have placed microbes into different categories depending on their potential for enhancing nutrient uptake by plants. Plant growth-promoting rhizobacteria are potential biofertilizers that play a significant role in improving nutrient availability through nitrogen fixation, phosphorus solubilization, potassium solubilization, phytohormone production, organic matter decomposition, and iron nutrition through siderophore production (Goswami et al., 2016). An increase in nutrient use efficacy is one of the many beneficial effects of soil microorganisms. Furthermore, plant growth-promoting rhizobacteria (PGPR) are environmentally friendly and can help reduce environmental degradation.

Economic and Environmental Implications

Balanced fertilization ensures the application of appropriate amounts and proportions of nitrogen (N), phosphorus (P), potassium (K) and trace elements based on crop requirements and soil fertility performance. Many countries have been actively promoting and applying this approach. In certain regions, China has conducted experimental research and established demonstrations of the efficient application of trace elements and K fertilizer. Examples include the combination of P and Zn applied to wheat seedlings (Yang et al., 2009), boron and calcium applied to rape (Du, 2003), and N and K applied to potato (Xian et al., 1993). After decades of experimentation and promotion, both the theory and practice of appropriate fertilizer application have been well-established in China. However, because of the great differences in climate, soil fertility, and soil texture, as well as the cultivation of new crop varieties and climate change, it is difficult for farmers to be certain about amounts and proportions, and inappropriate use of fertilizer still occurs. The goal of balanced fertilization is to maximize the yield to meet the growing population's demand for agricultural products. Consequently, the ideal amount of fertilizer is typically chosen based on yield or financial gains (Hui et al., 2015). Crop quality, agricultural sustainability, and environmental issues associated with fertilization have not been fully considered (Zhu & Chen, 2002). Many studies have shown that fertilizer treatments that produce the highest yields tend to result in lower crop quality and greater nutrient losses. Nitrate leaching increases significantly when the nitrogen application rate exceeds 150–180 kg hm^{-2} (Zhu & Chen, 2002; Li et al., 2019). Excessive application of N fertilizer can lead to a significant increase in nitrate-nitrogen content in groundwater (Akbariyeh et al., 2018), and N_2O production increases significantly when the amount of nitrogen applied exceeds 180 kg hm^{-2} (Nan et al., 2016). In recent years, with the improvement in China's economy and living standards and the enhancement of environmental protection, people not only want to consider the yield and economic benefits delivered by fertilizer application but also pay more attention to its relationship with crop quality and the environment. Thus, the determination of appropriate fertilizer application rates for each region and crop should take into account the relationship between crop yield, quality, and environment, and should not trade quality and environment for high yield.

In studies of balanced fertilization, potassium plays a more important role than other elements in improving crop quality and reducing environmental pollution caused by the loss of N and P fertilizers. Many studies have shown that when there is sufficient K, K ions significantly promote the absorption and utilization of N and P by crops in the form of compensation charges (Barnes et al., 1976), improving the utilization rate of N and P fertilizers (Reid et al., 2016), thus reducing pollution. The application of K fertilizer also promotes carbohydrate and N metabolism, thus improving the quality of crop products, for example, by increasing the protein content of grain crops (Gaj et al., 2013), crude fat and palmitic acid content of oil crops (Choon-Hui et al., 2009), starch and sugar content of potatoes and sugar crops (Westermann et al., 1994), and fiber length, strength, and fineness of fiber crops and cotton (Pervez et al., 2004). Despite the above advantages of K fertilizer, the proportion of N, P, and K nutrients applied is still often inappropriate due to the habits of farmers and a lack of guidance regarding K fertilizer. The average ratio of N, P, and K fertilizers used in China is 1:0.43:0.17, which is significantly lower than the world average of 1:0.47:0.37 and 1:0.57:0.55 in developed countries (Gu et al., 2014).

Challenges and Future Directions for NUE of Cereals

Enhancing our understanding of how different sources of nitrogen and their management affect the root systems of crops, along with their implications for aboveground growth, is crucial for the advancement of improved nitrogen fertilizers and management approaches. This understanding can help align soil nitrogen availability with crop nitrogen requirements, leading to enhanced nutrient use efficiency. Likewise, a more intentional consideration of plant physiological mechanisms, encompassing various methods of mineral nutrient uptake, their movement within the plant, and metabolic processes, is essential in the formulation of contemporary fertilizer solutions (Bindraban et al., 2015). Efforts to enhance nutrient-use efficiency play a vital role in achieving sustainable and productive agriculture. Through a combination of traditional practices and innovative technologies, farmers can optimize nutrient uptake, improve yield, and minimize environmental harm. The ongoing challenge lies in translating the research findings into practical and accessible solutions for a diverse range of farming systems.

General Future Directions

- Soil test recommendations should be followed.
- Inclusion of legumes in the rotation cropping system.
- Balanced NPK application with organic manure is key to efficient fertilizer use and sustainable agriculture.

- About 60-70% of K removed by crops is in straw; therefore, crop residue recycling is a good way to replenish soil K.
- Non-monetary inputs,, such as proper tillage, sowing time, seed rate, water and weed management, and proper plant measur,es, increase the efficiency of applied NPK.

Conclusions

Enhancing nutrient efficiency is an admirable objective and a major problem for the fertilizer sector and agriculture as a whole. Increasing the effectiveness of applied nutrients may be achieved using current tools and opportunities. However, we must be careful so that increases in efficiency do not compromise the environment or farmers' capacity to make a living. Farmers, society, and the environment will all profit from the prudent use of fertilizer BMPs, or the right rate, right time, and right place, which aim for both high yields and nutrient efficiency. There has never been more interest in and awareness of increased nutrient-usage efficiency. The fertilizer industry is facing increased pressure to increase nutrient usage efficiency due to the growing public view that crop fertilizers are excessive in the environment, and farmers are worried about rising fertilizer prices and stagnating crop prices. Nonetheless, there are several ways to define efficiency, which can sometimes be misinterpreted. The nutrients collected in the aboveground portion of the plant or the nutrients retrieved across the soil, crop, and root systems are two possible definitions of agronomic efficiency. Because future yield increases, nutrient costs, and crop prices are unknown before the growing season, economic efficiency is the state in which farm revenue is maximized by the appropriate use of nutritional inputs. However, this is not always accomplished or anticipated. The only way to establish environmental efficiency is to research local goals that are susceptible to nutrient influences. Unused nutrients by the crop may end up in the environment, although how susceptible they are to loss depends on the nutrient, soil, climate, and geography. In general, nutrient loss to the environment is only a concern when fertilizers or manures are applied at rates above agronomic needs; therefore, applying nutrients by area and crop-specific rates for cereals, especially primary macronutrients, is best. Moreover, scientists have developed various management approaches to enhance nutrient use efficiency in agriculture, including soil and crop management, integrated soil management, precision agriculture, and root zone fertilization; however, their combined use is more effective.

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