BOOSTING NUTRIENT USE EFFICIENCY THROUGH FERTILIZER USE MANAGEMENT

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(Received 18th Nov 2022; accepted 13th Apr 2023)

Abstract. Nutrient use efficiency (NUE) is the part of a larger concept of resource use efficiency in agriculture which is a cause of concern for the present as well as the future of sustainability in agriculture. The nutrients applied to soil if not utilized by the plants find their way into the water resources and atmosphere which can increase the ecological cost. There are various measures of nutrient use efficiency which are suitable in different situations as well as for the nutrients. Among all the factors determining NUE, fertilizer factors are the most important. The various measures included in fertilizer factor are balanced fertilization, addition of organic matter, plant growth promoting micro-organisms, use of advanced form of fertilizers, use of modern equipment including Soil Plant Analysis Development and understanding of nutrient interaction and consequent antagonistic and synergistic effects on crop plants.
Keywords: *nutrient use efficiency, fertilizer factors, organic matter, plant growth promoting microorganisms, nutrient interaction*

Introduction

World population is expected to reach 10 billion by 2050 (Khoshgoftarmanesh et al., 2010), and to meet its demands, there is an urgent need to double the food, feed and bio-fuel production from 2012 level (FAO, 2017). The requirement of the additional food grain can be met either by bringing more area under cultivation or by increasing the productivity and efficiency of existing crop varieties. Increasing land under cultivation is a major challenge as much of the additional land is not suitable for cultivation and has social, environmental and economic cost (FAO, 2017). Any attempt to increase yield directly increases pressure on the resources especially on soil health. Post Green Revolution, although the food grain production has tripled with

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2104_29312952

only 30% increase in the cultivated land, but it also led to the increase in the level of heavy metals in the soil and increase in pH due to excessive use of fertilizers and pesticides (Pingali, 2012; Sharma and Singhvi, 2016; John and Babu, 2021) An analysis by McDonald et al. (2013) shows that in the past five decades, there has been a steep increase in consumption of both N and P per hectare in Asia, whereas it has stabilized in Europe and America and remained at sub-optimal level in Africa, thus showing variation in global soil fertility. 50% of the total crop production is attributed to the commercial fertilizer input (Singh and Ryan, 2015), however, the nutrient use efficiency varies from less than 50% for Nitrogen, 10% for phosphorus and around 40% for potassium (Baligar and Bennett, 1986). Another estimate of efficiency of nitrogen use is 33% and of phosphorus is 16% (Dhillon et al., 2019). This is due to the losses through the various processes of volatilization, denitrification and fixation. Use of chemical fertilizers has impact on the Green House Emission. Also, Agriculture has the largest share in global methane and nitrous oxide emission, of which the nitrous oxides originate from the Nitrogenous fertilizer and manure management (FAO, 2017). Similar concerns are valid for phosphorus and potassium, where there is import dependency either for raw material or fertilizer. In recent years, there has been rising concerns for the emerging deficiency of secondary and micronutrients. Therefore, the efficient application of these nutrients becomes important. Though there are various factors impacting NUE, fertilizers use is the major factor as it has highest potential in reducing the economic and ecological burden of reducing the cost of farming. Thus, the following review has been conducted regarding the work done on various improvements and modifications in the application methods of fertilizers including the nutrient interaction aspects and environmental factors so as to increase the understanding of the researchers working in this field.

Measures of nutrient use efficiency

Efficiency in simple terms is the achievement of desired outcomes with the least cost (Reich et al., 2014). In simplest terms, Nutrient Use Efficiency can be expressed at three different levels i.e. at leaf level, which is potential maximum photosynthetic rate for certain nutrient content; at plant level which is ratio of biomass produced to the total nutrient uptake and at crop level, which is ratio of total biomass produced to the amount of nutrients available for uptake from soil (Ewel and Hiremath, 1998). In agronomic or operational terms, it is the differential response of crops/genotypes in yield when grown in nutrient deficient soils (George et al., 2012). The various measures of nutrient use efficiency are presented in *Figure 1*. It can be divided into two components i.e. nutrient acquisition efficiency (ratio of nutrient uptake to the nutrient supply) and nutrient utilization efficiency (ratio of biomass produced to the nutrient content in plant) (Nieves-Cordones et al., 2020). Partial factor productivity can also be termed as productive efficiency (Datta, 1986). In addition, Nutrient Efficiency Ratio (NER) expressed as ratio of unit of yield (kg) to unit of elements in tissue (kg) is utilized to differentiate the cultivars as inefficient and efficient nutrient utilizers (Baligar et al., 2001). While Agronomic efficiency is more suitable for the Nitrogen use efficiency where losses are through leaching, volatilization or denitrification; Partial nutrient balance is suitable for measuring phosphorus use efficiency as it provides a suitable measure for the recovery of P from soil reserve (Johnston and Syers, 2009).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Need for nutrient use efficiency in crop production

Different estimates reveal that there has been seven-fold increase in nitrogenous fertilizer consumption in past four decades; seven-fold increase in period of 1960-1995 (Hirel et al., 2007) and eight-fold increase in the period of 1960-2012 (Huang et al., 2017; Adem et al., 2020). This increase has serious implications for the ecosystem functioning and biodiversity (Hirel et al., 2007); ecologically hazardous in form of eutrophication of water bodies, green house gas emission and leaching (Hirel et al., 2007; Anas et al., 2020; Dimpka et al., 2020). With the increase in fertilizer consumption in India, nitrogen use efficiency has been reduced from 55% to 35% between 1960 and 2010 (Moring et al., 2021); globally it varies between 25% and 50% (Sharma and Bali, 2018). The N-losses from the field occurs through the process of volatilization, denitrification, immobilization, clay fixation and leaching, with nitrate leaching and denitrification being predominant under high rainfall conditions (Sharma and Bali, 2018) and having main environmental concern (Rutting et al., 2018). The major N losses under lowland rice system are through ammonia volatilization, denitrification, leaching and surface runoff (Huang et al., 2017; Datta, 1986).

Between 1960 and 1995, use of P fertilizers increased 3.5 times and will increase 3 times by 2050 if efficient management strategies are not followed (Adem et al., 2020).

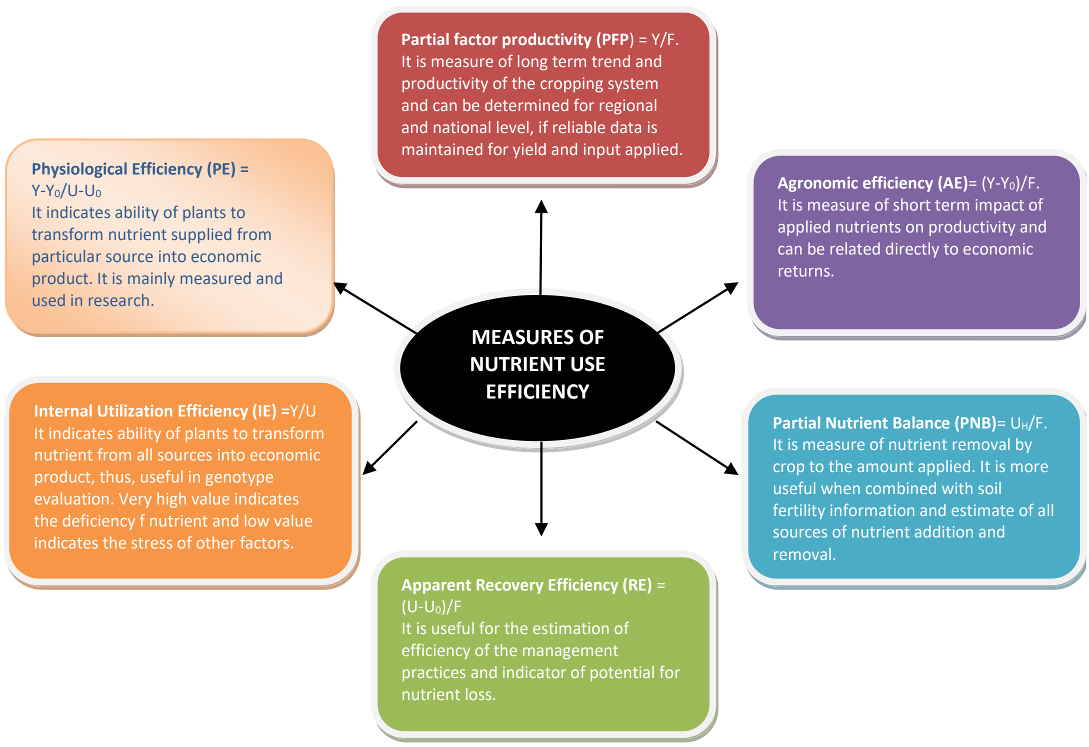

Figure 1. *Various measures of nutrient use efficiency (Fixen et al., 2015). Y = yield of harvested portion of crop with nutrient applied; Y_0 = yield with not nutrient applied; F = amount of nutrient applied; U_H = nutrient content of harvested portion of the crop; U = total nutrient uptake in aboveground crop biomass with nutrient applied; U_0 = nutrient uptake in aboveground crop biomass with no nutrient applied*

Due to inefficiency in the food production chain, serious imbalances exist in the depletion of phosphate reserves and its availability to the population through food

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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consumed (Schroder et al., 2011). The phosphate rock reserves are non-renewable (Syers et al., 2010; Hawkesford et al., 2012) and according to different estimates will last for 50-400 years or longer with current utilization rates (Schroder et al., 2011; Hawkesford et al., 2012; Roberts and Johnston, 2015; Dhillon et al., 2017). P use efficiency of Global cereal systems varies from 15% to 30% (Preriera et al., 2020) and may be as low as 10%–20% (Johnston and Syers, 2009). When phosphatic fertilizers are applied to the soil these get fixed mainly in four different pools. The first two pools which are generally measured in soil test and available to the crops comprising soil solution and readily extractable respectively, and third and fourth pool comprising of strong attachment to soil matrix and precipitated as part of soil mineral complex, respectively (Johnston and Syers, 2009; Syers et al., 2010; Roberts and Johnson, 2015). Phosphorus fixation is a problem in major soil orders of the world including oxisols, spodosols, ultisols, alfisols, mollisols and aridisols and subjected to leaching and sub-surface run-off in deep sandy soils, soils containing high organic matter and those having accumulated P due to overfertilization (Dhillon et al., 2017).

Around 96%–99% of Potassium in soil is in the mineral form (Shin, 2014), followed by exchangeable and non-exchangeable K (1%–2% each) and only 0.1%–0.2% is available to soil (Dhillon et al., 2019). The global availability of K resources is fixed and its availability depends on the nature of parent material, degree of weathering, erosion and leaching proneness of soil, addition of external nutrient sources and crop removal (Dhillon et al., 2019). In addition to the limited availability, K uptake is influenced by the presence of complementary ions such as NH_4^+ and Na^+ which interrupt the uptake, soil moisture content (Shin, 2014); release of root exudates which solubilize the non-exchangeable K in the soil and increases its mobility (Shin, 2014; Hartley, 2017).

Calcium deficiency is rare in nature (White and Broadley, 2003), however, it is common in leached and weathered acidic soils as well as saline soils, genetic factors and different cultivars impact Calcium use efficiency e.g. between cultivars of cauliflower and collard; and different tomato strains (González-Fontes et al., 2017). The use of calcium is impacted by the availability of water and its interactions with cations mainly NH_4^+, K^+ and Mg^{2+} (González-Fontes et al., 2017). Though Magnesium (Mg) constitutes 2% of the earth crust, 90%–98% is fixed in crystal lattice, therefore, not available to the plants (Senbayram et al., 2015; Chaudhry et al., 2021). It is deficient in the acidic soils as undergoes leaching and excess H^+, Al^{3+} and Mn^{2+} interfere with its uptake by plants (Wang et al., 2020a), though there may be increase in exchangeable Mg at lower pH (Senbayram et al., 2015). Magnesium uptake is also reduced in calcareous and alkaline soils due to presence of Ca and bicarbonates in former and due to formation of magnesium carbonate and gypsum respectively (Chaudhry et al., 2021). Agronomic efficiency of Mg fertilizers also varies with crop species with vegetable crop as most responsive and cereals least (Wang et al., 2020a). Magnesium uptake is antagonized by presence of the excess K and Ca in soil (Yan and Hou, 2018; Guo et al., 2016). Sulphur deficiency is getting more common in the soil due to lesser S rich fertilizers, crop removal of S from soil and reduced S emission to the atmosphere (Lucheta and Lambais, 2012; Lee et al., 2016; Aula et al., 2019). The sulphur use efficiency in global cereal system is 18% to 20.4% and the major causes for this low efficiency are leaching due to repulsion of SO_4^{2-} ions from the negatively charged clay colloids, adsorption of sulphur to Fe and Al oxides in acidic soils and insignificant losses of volatilsation under anaerobic conditions (Aula et al., 2019) and this

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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volatilization is in the form of carbon disulphide (CS_2), dimethyl sulphide (CH_3SCH_3), carbonyl sulphide (COS), hydrogen sulphide (H_2S), methyl mercaptan (CH_3SH) and dimethyl disulphide (CH_3SSCH_3) (Mc Neill et al., 2005).

Micronutrient deficiency is a major concern in global crop production system (Gaige et al., 2020). About half of the world soils are deficient in micronutrients (Baligar et al., 2001), which is further aggravated by their inadequate fertilization along with higher use of primary nutrients and low use efficiency in the crops (Dimpka and Bindraban, 2016). The deficiency is more visible after Green Revolution with cultivation of high yielding varieties, improved mechanization, use of high macronutrient fertilizers with lower trace elements along with decreased application of organic matter, modern irrigation system and extension of crop production to marginal lands which increased the crop yield, however, decreased the plant available micro-nutrients in soil (Khoshgoftarmanesh et al., 2010). Micronutrient use efficiency is only 1%–2% (Ramamoorthy, 2020). The availability of micronutrients to plants is determined by the edaphic and biological factors such as pH, organic matter, competing anions, cations, soil parent material and geomorphology and associated microbiology e.g. precipitation of micronutrients with carbonates and phosphates, clay colloids and mineral complex in soil or the micronutrients having same uptake mechanism can compete with each other for availability to plants (Dimpka and Bindraban, 2016).

Boosting nutrient use efficiency through fertilizer use management

The nutrient use efficiency in plants can be addressed through bringing modification in soil factors, agronomic management and fertilizer factors. Soil factors primarily comprises of addressing deficiency of organic carbon content, deficiency or toxicity of certain elements including the potentially toxic, problem of soil alleviation and water logging. The major agronomic management factors impacting nutrient use efficiency are tillage, choice of varieties, planting density, irrigation management, promoting efficient cropping system and efficient weed management.

Fertilizers currently supports 40%–60% of the total food grain production (Johnston and Bruulsema, 2014; Singh and Ryan, 2015) and also an essential input determining sustainability of cropping practices and food security of nations across the globe. The major factors associated with fertilizer impacting NUE use are source, rate, method of application, use of efficient fertilizers, site specific nutrient management and integrated plant nutrient management system (Baligar et al., 2001). Nowadays Fertilizer Use Efficiency is the alternative term used for nutrient use efficiency (*Fig. 2*).

4R nutrient stewardship in nutrient use includes right source, right rate, right time and right placement. These 4R also form the components of Site-specific nutrient management (Richards et al., 2015). Farmers' selection of right source are usually in favor of single nutrient, however, it is only suitable if other nutrients are sufficient in soil otherwise, it leads to the deficiency of other nutrients also more commonly of secondary and micronutrients (Johnston and Bruulsema, 2014). Balanced fertilization becomes more important in areas where there is continuous decline of the organic carbon in soil by erosion of top soil and exposed sub-soil which is less fertile. Nitrogenous fertilizers are lesser prone to the volatilization, denitrification and nitrate leaching losses if applied along with sources of Ca, Mg or as organically enhanced (Dimpka et al., 2020). Nitrogen when applied along with P and K reported an increase of 6%–150% increase in its agronomic efficiency varying with the type of crop (Ghosh

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et al., 2015). Balanced fertilization leads to reduction in nitrate leaching beyond root zone, maintains positive balance of nutrients in soil under continuous cropping, have synergistic effect on plant physiological functions and overcomes deficiency of secondary and micronutrients (Dwivedi et al., 2017).

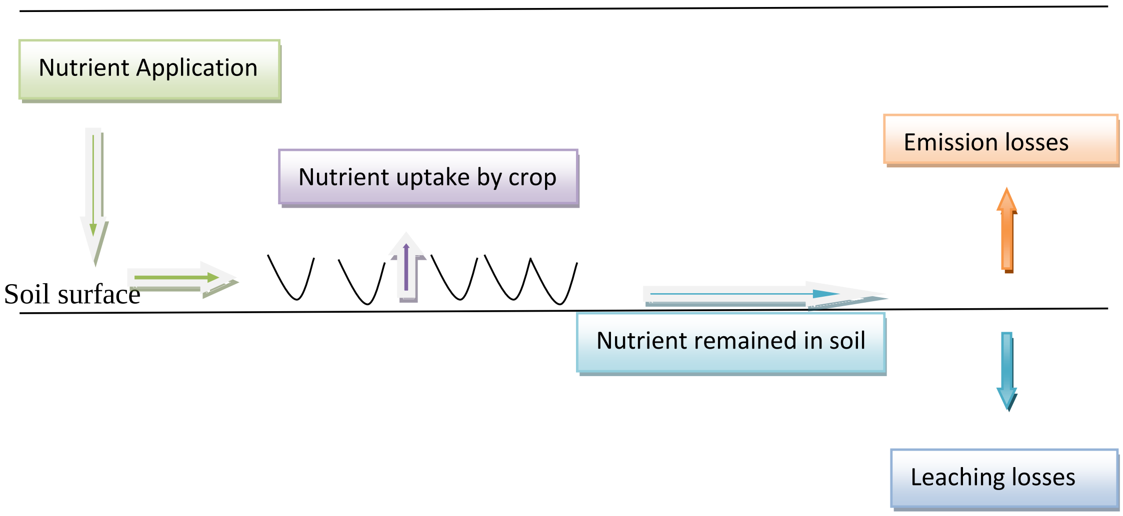

Figure 2. *The nutrient applied to soil surface is partly utilized by the crop, part of it remains in soil which undergo emission or leaching losses determining the nutrient use efficiency (Reich et al., 2014)*

Higher level of corn yield was obtained with increasing levels of nitrogen, however, further reached to highest level with increased potassium levels in the soil (Johnson et al., 1997). Selladurai and Purakayastha (2016) reported an increase in N, P and K efficiency by 16.4%, 9.3% and 18.3%, respectively with the use of humic acid based multinutrient mixture as compared to chemical fertilizers.

Addition of organic matter along with chemical fertilizers can serve as source of the other nutrients which can be helpful in boosting nutrient use efficiency. Its addition along with the chemical fertilizers has witnessed yield improvement in various crops such as wheat, corn-rice rotation and potato (Havlin and Heiniger, 2020) and thus can contribute to higher nutrient use efficiency. In a 3 years research study in China, it was observed that with organic matter addition along with chemical fertilizers led to average increase of 8.9% in maize yield and also increased top soil organic matter, total N and available P due to efficient storage of fertilizer nutrients and also increased N use efficiency (Wang et al., 2020b). In addition, there is reduction in soil bulk density, improves physico-chemical properties and soil structure which positively influences the chemical nutrient cycle in soil (Wang et al., 2020b). In a 40 years research trial on soybean-maize crop rotation, increasing the amount of organic matter addition along with chemical fertilizers increased yield and N use efficiency due to enhanced crop growth, increased soil organic matter and nutrient availability, increased soil pH due to neutralization of soil acidity, increase in negative charge of soil and soil CEC due to dissociation of acidic functional group, improved soil physical and chemical properties (Hua et al., 2020). Kakraliya et al. (2017) reported that application of FYM, vermicompost and chemical fertilizers along with strains of *Azotobacter* significantly increased the nutrient use efficiency compared to chemical fertilizers alone in rice-

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wheat cropping system in Indo-Gangetic plains. Organic manure based nutrient management had higher uptake of nutrients including N, P, K, Ca, Mg and Na in all the plant parts including root, shoot, leaf and fruit of chilli peppers due to favorable condition for its growth, reduced N losses due to volatilization, increased nutrient uptake and their mobility within plants, increased plant biomass and yield parameters and favorable condition of beneficial micro-organisms growth (Khaitov et al., 2019). Addition of organic matter and crop residues supplements soil organic carbon, balances macro and micro nutrients and thus, increases physiological N use efficiency and same has also been witnessed in the organic fertilizers-based SRI management in central highlands of Madagascar (Tsujimoto et al., 2019).

Another important source of nutrients to the crops can be addition of living strains of plant growth promoting rhizobacteria (PGPRs) which causes the fixation and solubilization of the nutrients. The various mechanism through which PGPR^{s} enhance nutrient availability is by increasing root surface area, nitrogen fixation, phosphate solubilization, siderophore production and HCN production (Backer et al., 2018); K solubilizing bacteria such as *Acidothiobacillus* spp., *Bacillus edaphicus, Bacillus mucilaginosus etc* (dos Santos et al., 2020); prevents nutrient leaching (Vejan et al., 2016) and indirectly promotes plant growth and development by production of phytohormones (Basu et al., 2021). Nitrogen content in field corn grain and uptake of N, P and K from the soil was significantly enhanced with inoculation of PGPR (*Bacillus sp.* strains) and Arbuscular mycorrhiza fungi (*Glomus intraradices*) when compared to control (Adesemoye et al., 2008). Increase in nitrogen and phosphorus use efficiency in maize due to inoculation with PGPRs were more pronounced under moderate to severe water stress conditions than well-watered conditions (Pereira et al., 2020). Symbiotic and free-living bacteria also fix atmospheric N and supply it to the plants and thus reduce their external demand (*Table 1*). Inoculation of rice seeds with selected Rhizobium strain led to increased Agronomic NUE and in combination of supplementary N application significantly increased the uptake of P, K and Fe (Biswas et al., 2000).

P solubilizing bacteria (mainly *Pseudomonas, Bacillus* and *Azotobacter*) inoculation has recorded increase in P uptake and crop yields in wheat, mustard, rice, maize, chickpea, sugarcane, potato and legumes (Kalayu, 2019). Inoculation with mixed strain of PSBs (*Bacillus aryabhattai* & *Pseudomonas auricularis*) resulted in an increase of N uptake by 8%–12% and P uptake by 8%–38% depending on the levels of P fertilizer supplied in *Camellia oleifera* (Wu et al., 2019). However, the benefit of PSBs is realized when P availability in soil is limiting factor with either nil or intermediate level of fertilizer P addition (Raymond et al., 2020). Inoculation with PGPRs (*Bacillus sp., Agrobacterium tumefaciens, Klebsiella pneumonia, Pseudomonas sp, Azotobacter chroccum*) along with 75% of the fertilizer levels had similar growth parameters and N, P, K content of wheat to that with 100% fertilizers (Wang et al., 2020c). The major K solubilizing bacteria (*Acidothiobacillus ferrooxidans, Paenibacillus* spp., *Bacillus mucilaginosus, B. edaphicus,* and *B. circulans*) reported to have significant effect on yield and K uptake of wheat, cotton, tomato, rape etc through production of organic acids which dissolve the minerals as well as release K ions through chelation of Ca^{2+}, Fe^{2+}, Si^{4+} and Al^{3+} (Etesami et al., 2017). K solubilizing bacteria recorded not only significant K uptake but also N and P uptake in the *Mikania mircantha* seedling as compared to control (Sun et al., 2020). Siderophores are the low molecular weight compounds synthesized by the micro-organisms namely *Pseudomonas, Bacillus,*

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Azotobacter, *Azospirillum*, *Rhizobium*, *Enterobacter* which form complex with iron, molybdenum, cobalt, nickel and manganese and make them available to plants and in some cases they are also reported to enhance nodulation and N fixation (Pahari et al., 2017). Co-inoculation with *Bacillus subtilis* and *Rhizobium tropici* significantly enhanced the yield, zinc partitioning to grains, Zinc use efficiency, agro-physiological efficiency, its utilization efficiency and zinc recovery efficiency in common beans among other combination of rhizobacteria (*Rhizobium tropici*, *Bacillus subtilis*, *Pseudomonas flourescens*, *Azospirillum brasilense*) and control (Jalal et al., 2021).

Table 1. *N fixation by different legume crops. Nonsymbiotic fixation is lesser when compared to symbiotic one (Werner and Newton, 2005; Gopalkrishnan et al., 2015; Saha et al., 2017; Raza et al., 2020)*

Legume	**N-fixation (kgNha^{-1})**
Groundnut	126-319
Soybean	33-643
Pigeonpea	77-92
Cowpea	25-100
Greengram	71-74
Blackgram	125-143
Chickpea	135
Lentil	80
Hyacinth bean	214.6
Hairy Vetch	163
Medicago	140.1
Vicia faba	200
Phaseolus vulgaris	20-60
Pisum sp.	150
Clover	104-160
Alfa-alfa	128-600
Lupines	150-169
Alnus	40-300
Non-symbiotic fixation	10-160

Nanofertilizers can prove as an innovative solution to increase nutrient use efficiency. Nanofertilizers can be classified into three types i.e. nanomaterial made of micro-nutrient; nano-material made of macro-nutrient and nanomaterial used as carrier of macro-nutrient (Guo et al., 2018). Owing to their smaller size and consequent larger surface area compared to their bulk counterparts it facilitates better penetration in plant cells and higher reactivity which activate plant and microbial activity resulting into higher nutrient use efficiency (Tarafdar et al., 2015; Seleiman et al., 2021). In addition, the coating of nanofertilizers with nanomaterials leads to their slow and demand-based release leading to better uptake and reduce losses, enhances mobilization of nutrients by influencing metabolic processes and their higher solubility than other synthetic fertilizers leads to higher nutrient use efficiency (Seleiman et al., 2021). Application of 50% of the dose of farmers' fertilizer practice (FFP) along with two spray of nano-urea had resulted in significantly higher yields than the FFP in various rabi crops including

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wheat, lentil, potato and peas, thus, enhancing nutrient use efficiency (Kumar et al., 2020; Tiwari et al., 2021). For the equivalent amount of nitrogen dose, 4%–11% higher nitrogen use efficiency for sugar in sugarcane was reported with application of nano-nitrogen chelates than urea (Alimohammadi et al., 2020). Urea coated with nano-Zn and nano-Rock phosphate reported significant decrease of 30%–40% in nitrous oxide emission losses and 10%–20% increase in nitrogen use efficiency (Kundu et al., 2017). Application of zinc coated chitosan nanoparticles at 10 times lower concentration compared to $ZnSO_4$ application reported only 10% decrease in Zn uptake and an increase of 14% with similar concentration of $ZnSO_4$ (Dapkekar et al., 2018). Hagab et al. (2018) reported 79% and 39% increase in P recovery efficiency with application of nano-zeolite phosphorus when compared to super phosphate fertilizer and zeolite phosphorus fertilizer, respectively. Application of phosphorus and potassium incorporated zeolite based nanofertilizer reported 129% increase in P uptake and almost similar K uptake as compared to the conventional fertilizer (Rajonee et al., 2017). Application of foliar spray of nanopotassium enhanced the yields in wheat crop and reduced leaching of potassium in soil when compared to conventional fertilizers (Sheoran et al., 2021) thus enhancing the potassium utilization efficiency. Application of nanofertilizers of Cu + Fe + Zn in wheat reported significantly higher yields and micronutrients uptake when compared to traditional application Cu + Zn + Fe (Al-Zuthery et al., 2019).

Right rate of application is determined by the inherent nutrient supplying capacity which needs suitable soil testing facility prior to the crop establishment. Also in season methods like Soil Plant Analysis Development (SPAD) or chlorophyll meter, leaf color charts (LCC) and optical sensors may also be used (Johnston and Bruulsema, 2014). Soil testing is still a powerful tool for determining nutrient supplying capacity of soil, however, it requires good calibration and tissue testing can be used in season especially for determining N content (Singh et al., 2018). Soil test crop response (STCR) based fertilizer strikes a balance between fertilizing the crop and soil and balance between soil available and applied nutrients, thus providing basis for balanced fertilization (Singh et al., 2016). STCR based approach of fertilizer recommendation in direct seeded rice reported significantly higher N, P and K use efficiency when compared to general recommended dose and soil test-based recommendation (Singh et al., 2021). SPAD meters generally determine the leaf N content on the basis of chlorophyll content and the recommendation of N application is generally done either on fixed threshold value approach or sufficiency index approach. In the former case N application is done when the SPAD value is less than preset critical reading, and in latter, when sufficiency index i.e. SPAD value of test plot expressed as percentage of SPAD value of reference overfertilized plot falls generally below 90% (Singh et al., 2002, 2010). Leaf color chart comprising of quality plastic strips with different shades of green color often available with 6 and 8 panels is also available, however, with less precision than SPAD (Singh et al., 2010). Optical sensors namely Greenseeker emit and record the reflectance of radiation within visible and near infra-red radiation of the with specific wavelength, NDVI values is derived from these reflectance values and midseason yields are obtained by dividing NDVI values by Growing degree days from planting to sensing and then the yield potential and N response index is developed for N recommendation (Li et al., 2009; Aula et al., 2020). Maiti et al. (2004) conducted a comparative experiment of nitrogen management through SPAD and LCC and the recommended practice of split application of nitrogen in wheat crop. The highest yields were reported when nitrogen

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was applied with SPAD threshold value of 37 in addition to basal dose of 20 kgN/ha which was 12% higher over the 150 times the recommended nitrogen dose with normal split practice. This was followed by the nitrogen application with LCC threshold value of 5 in addition to the basal dose of 20 kg N/ha. Significantly highest agronomic efficiency, physiological efficiency and partial factor productivity were reported when N management was practiced through SPAD and LCC compared to the normal splitting. It was also found that SPAD based nitrogen management was more correlative with wheat yields than the LCC based management (Maiti et al., 2004). Significantly higher agronomic efficiency of nitrogen in sweet corn was reported with SPAD (threshold value 40) followed by NDVI (threshold value 0.6), SPAD (threshold value 50) and LCC (threshold value 4) (Umesh et al., 2018). SPAD based N management with skipping of basal dose in Maize-Wheat cropping system reported significantly highest agronomic efficiency (Jat et al., 2008). Both Agronomic and Recovery efficiency was found to be significantly higher with LCC (threshold value 4) than LCC (threshold value 5) and other doses of nitrogen in hybrid rice (Gupta et al., 2011). LCC values of (threshold value 4) and (threshold value 5) were found suitable for higher N use efficiency in field crops (Hussain et al., 2003; Mathukia et al., 2014; Singh et al., 2014; Sen et al., 2011; Gudadhe and Thanki, 2021). With no basal application of nitrogen in rice crop, there was saving of 41.7%–54.2% of nitrogen with use of Green seeker, SPAD and LCC, lowest for LCC and similar for SPAD and Greenseeker (Baral et al., 2021).

Variable rate Technology (VRT) is an efficient technology for determining the right rate of application (Roberts, 2009), however the economic feasibility of the technique increases with increase in field variation (Koch et al., 2004). VRT is either map based where the systematic sampling is done to develop variability map and site-specific fertilizer application map to guide the applicator whereas sensor based VRT utilizes optical sensors and consequent NDVI values for real time variable application (Mohan et al., 2021). The variable application of nitrogen in maize crop on the delineated management zone basis, sensor basis and combining use of sensor within the delineated management zones resulted in the increase of 41%, 89% and 50%, respectively compared to its uniform application (Dahal et al., 2020) and variable N based on optical sensor led to 11.8% and 32.6% increase in N uptake and Agronomic N use efficiency, respectively compared to uniform application in corn (Bragagnolo et al., 2016). Though the variable rate of P application does not increase yield uniformly for the whole field, it increases where soil test value is less and simultaneously reduces total P application (Phillips, 2016) thus, can increase P use efficiency. Dense soil sampling based Variable rate application of P and K in the Maize-soybean rotation though did not influenced yields significantly, however, slightly reduced the fertilizer use when compared to uniform application (Mallarino and Wittry, 2006). Site specific N management has recorded increase in NUE up to 368% compared to farmers' practice (Hedley, 2015).

Right time refers to the supply of nutrients during the critical growth stages of plant when the demand is high and thus there is least loss of fertilizers to environment e.g. N is applied in split doses and P is applied as basal dose to be made available to the growing seedling (Johnston and Bruulsema, 2014). However, split application can be advantageous for the entire three primary nutrients under sandy soils and high leaching conditions, thus affecting their use efficiency. Split application in paddy crop is determined by soil texture e.g. 50:25:25 at basal, 21 days after transplanting and panicle initiation, respectively for fine textured and 25:50:25 for coarse textured and the type of cultivar e.g. early varieties have single peak absorption from tillering to flowering

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DOI: http://dx.doi.org/10.15666/aeer/2104_29312952

whereas medium and late duration varieties have two peaks i.e. from transplanting to maximum tillering and panicle initiation to little after flowering separated by vegetative lag phase, thus, basal application in former and split in latter is suitable (Nayak et al., 2018). Splitting nitrogen in 5:5 ratio at sowing and jointing stages in wheat reported the increase of 17% in nitrogen use efficiency (Zhang et al., 2020). Splitting phosphorus dose in potato crop between basal and growth period reported an increase of use efficiency by 20%–30% over a period of four years (Cui et al., 2020). Four splitting of nitrogen, phosphorus and potassium fertilizer in maize reduced the leaching losses by 60%, 75% and 50%, respectively; increased the uptake by 55%, 14% and 28%, respectively and increased yield by 129% in sandy textured soil (Sitthaphanit et al., 2009). Split application will lead to higher K use efficiency as the demand for K varies with growth stage e.g. initial growth and panicle emergence in rice, initial growth and reproductive stage in wheat and maize, boll and fiber formation in cotton, grand growth and sugar formation phase in sugarcane are critical, and its efficiency is observed in Rice-maize system (Singh et al., 2021). Split application of K in soils having lower CEC and coarse textured may give higher use efficiency owing to lesser leaching and luxury consumption (Dwivedi et al., 2017). Higher agronomic efficiency of potassium fertilizer has been reported with two splits in rice (transplanting + tillering) and maize (basal + before silking) under Rice-Maize cropping system; 2-4 splits in cotton depending on the dose; 2 splits in sugarcane (basal + grand growth phase) (Dwivedi et al., 2017).

Controlled release fertilizers (CRF) can form essential component of optimizing time of application (Roberts, 2015). These form part of the enhanced efficiency fertilizers (EEF). These are fertilizers having coating of less permeable material and one or more inhibitor as extra additive in formulation or as coatings designed to regulate nitrification or urea hydrolysis or both (Nayak et al., 2018) or the low solubility compounds with complex or high molecular weight structure that releases nutrient either through chemical or microbial decomposable compound (Lawrencia et al., 2021). EEF achieve efficiency through urease inhibition, nitrification inhibition, modifying rhizosphere, slow or controlled release of the nutrients depending on the solubility and mineralization of product and type of coating (Singh et al., 2010). At the same yield levels, these CRF can reduce the fertilizer use by 20%–30% (Lawrencia et al., 2021). CRF such as coated urea slowly release the nitrogen during the life cycle of the crop and thus, helps in reducing volatilization and leaching losses (Singh et al., 2019). Coated urea application in winter wheat resulted in increase of 47%, 68% and 45% in Fertilizer N use efficiency compared to normal urea at the similar doses of 150, 162 and 180 $kgNha^{-1}$, respectively (Fan et al., 2004). In a meta-study, it has been concluded that Controlled release urea increased the agronomic efficiency of nitrogen by 47.55% compared to 45.21% with the use of split application of urea as the former can continuously supply nitrogen to N demands of the crops than later and it was found to have best effect on potato followed by maize, wheat and rice (Zhang et al., 2022).

Right placement is important for fertilizers susceptible to soil fixation like P so that it is easily available to seed when applied in band near the seed row, however, any injury to seed due to salt needs to be avoided (Johnston and Bruulsema, 2014). Band placement of fertilizers has higher recovery efficiency compared to other as less contact with soil reduces vulnerability to fixation or leaching (Singh et al., 2018). Deep placement of the urea super granules in reduced zone of rice fields or its foliar application to rice enhances N use efficiency (Singh et al., 2018; Nayak et al., 2018).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2104_29312952

Deep placement of urea/urea + DAP/urea + DAP + KCl at 7-10 cm after transplanting not only increase N use efficiency but also reduces the P runoff losses, thus, increasing their use efficiency (Singh et al., 2010). Deep placement of urea significantly enhanced Agronomic N use efficiency and partial factor productivity than conventional application (Khalofah et al., 2021). Though the Agronomic Nitrogen use efficiency was found to be at par with deep placement of urea balls and broadcast prilled urea in rice, the recovery efficiency was found to be 45% higher in the former case at lower doses of nitrogen (Islam et al., 2016). Maize yields were highest with the surface band placement of the P fertilizers, significantly higher to broadcast application and statistically at par with the deep placement method (Alam et al., 2018). Banding of P reduced the fertilizer use by one third when compared to broadcasting for optimum yields on lettuce (Sanchez et al., 1990). Rice seedling dipping in P slurry had produced similar biomass yield with less than 1/3rd of P required with soil incorporation (Oo et al., 2020). Similarly, significantly higher P use efficiency was obtained with seedling dip at half dose of P compared to the broadcast application at transplanting (Rakotoarisoa et al., 2020). Banding K fertilizers in soils with low K levels is efficient than surface broadcasting and deeper placement has advantage in areas in areas of low rainfall (Dhillon et al., 2019).

Nutrient interaction can be considered as a significant factor in fertilizer use and nutrient use efficiency. Some of the synergistic interactions include N × K, N × P, N supplied as NH_4^+ and Mn, N and the nutrients enhancing biological fixation such as Ca and Mo, macronutrients and micronutrients such as Fe and Zn due to positive effect of macro-nutrients e.g. N and S on root reductase activity and the phytosiderophores production and antagonistic interactions include P × Zn, Mg × K, between cations such as Zn, Cu, Mn and Fe due to competition for similar uptake mechanism, NH_4^+ × K (Rietra et al., 2017); other synergistic interactions are P × Mn, K × Mn, Mg × Ca (Brindraban et al., 2015). Combined application of P and S resulted in increase in N uptake, increase in Agronomic efficiency and recovery efficiency of both P and S in wheat, however, decreased with increase in dose (Assefa et al., 2021); combined application of P and K increases N use efficiency by inducing root length and width and distribution of N between shoots and roots (Salim and Raza, 2019). N and P uptake was significantly enhanced with 60 kg S ha^{-1} in maize compared to lower dose which decreased with further increase in S-dose, however, K uptake was not influenced with S-application (Sarfaraz et al., 2014). The combined application of 0.6 kg N and 0.3 kg P per plant had 160% and 80% higher yield compared to N alone and P alone, respectively; 0.6 kg N and 0.3 kg K per plant yielded highest and 83% more compared to N alone; similar increase was found with 0.2 kg P and 0.3 kg K per plant in citrus crop (Li et al., 2019). In a multilocational trial in Rice-Wheat Cropping systems, N along with P and N along with K increased PFP_N, further increase was observed when N was applied along with P and K and highest increase was observed with NPK + Zn when compared to N alone in both rice and wheat (Panwar et al., 2019). The application of recommended K dose to potato crop increased apparent N use efficiency by 95% over no application, however, it was found at par with 150% of the recommended dose (Grzebisz et al., 2017). Such increase of N use efficiency is also reported in various crops including rice, wheat, pearlmillet, sorghum and maize with application of K (Brar et al., 2011). Application of Boron significantly increase N, P, K content in the leaves with 12% increase in N with 2 kg B ha^{-1}, 78% increase in P and 36% K with 3 kg B ha^{-1} compared to control (Ali et al., 2015). There exists a synergistic interaction between B

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DOI: http://dx.doi.org/10.15666/aeer/2104_29312952

and P, however, there is need to have balanced fertilization (varying levels of both fertilizers simultaneously) of both to obtain high P-use efficiency (Zhao et al., 2021).

Among the various interactions, Zn and P has the significant antagonistic interaction owing to the reduced mycorrhizal growth under high P supply leading to Zn deficiency (Marschner, 2012), Zn deficiency causing P toxicity in leaves by depressing its transport, precipitation of Zn by high P levels, however, has a little significance at field level (Longeragan and Webb, 1993). Among the other interactions of Zn is antagonistic interaction with alkaline macronutrients Ca, Mg, K and micronutrients such as Cu, however reduced Fe in soil increases Zn absorption and vice-versa due to increase in activity of reductase activity and enhanced release of phytosiderophores (Longeragan and Webb, 1993). There are several methods of fertilizer application including soil, seed, foliar or irrigation, however, to increase nutrient use efficiency the combination of application should be to increase synergism and decrease antagonistic interactions e.g. foliar application of Fe or Zn or Mn along with urea or S with NPK increases synergism (Rietra et al., 2017).

One of the important determinants of nutrient utilization by the crops is climatic factors. Solar radiation, precipitation and temperature have an impact through determination of nutrient release rate from organic and inorganic constituents of the soil, their subsequent uptake and translocation within the plant system (Baligar et al., 2001). Solar radiation has impact on the photosynthesis, thus, indirectly determining the nutrient demands of crop. The precipitation becomes important especially in rainfed areas where it is mainly responsible for the soil moisture balance and consequent nutrient uptake, root growth which also has influence on the nitrogen fixation and fertilizer interaction with the soil (Baligar et al., 2001). Elevated CO_2 levels influences the stomatal adjustment as well as the reduced carbohydrate supply to the roots, thus, lowering the nitrogen use efficiency (Xu et al., 2012). The stressed conditions including water stress, salinity stress, heavy metals, temperature stress and photosynthates deprivation can negatively influence the nitrogen fixation (Kebede, 2021). Selection of crops and varieties play an important role in modifying the environmental effects. C_4 plants has higher physiological efficiency of nitrogen use compared to C_3 plants due to higher photosynthetic rate per unit leaf N content e.g. maize has higher physiological efficiency over rice (Cassman et al., 2002). The selection of crops depending on the climatic conditions is essential for optimizing the nutrient use efficiency (Salim and Raza, 2019). Similarly, the selection of efficient cultivars can increase the nutrient use efficiency under drought conditions (Ullah et al., 2019). Management strategies during the crop growing season also influence the nutrient use efficiency e.g. water availability influences the root growth ultimately influencing the nutrient absorption whereas reverse occurs when there is moisture deficiency or there will be increased leaching and denitrification due to excess moisture can lead to reduced nitrogen use efficiency (Aulakh and Malhi, 2005; Ullah et al., 2019). It has also been reported to vary the amount of irrigation and frequency according to the texture and water retentivity of soil to obtain higher nitrogen use efficiency (Aulakh and Malhi, 2005).

Conclusions

The increased nutrient use efficiency in agriculture is important for its economy and ecology, however, its advantage can also be realized in increased quality of produce. Most of the researches point out that lower use of fertilizers can lead to higher

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efficiency, however, it is to be realized that the effective yields cannot be sacrificed for increasing the nutrient use efficiency. It is essential to focus on the better uptake of nutrients by the crop plants and effective replenishment of soil pool through external application of fertilizers. More research is needed for the alternate delivery of nutrient especially for the nutrients such as phosphorus which are prone to fixation in soil. The plant factors need to be harnessed in tandem with the fertilizer factors for the better utilization of the fertilizers. However, it will require a better understanding of the differences between the species and genotypes in terms of nutrient uptake and utilization. Coordinated and interdisciplinary approach can further boost the efforts of increasing nutrient use efficiency in agriculture.

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