Precision Nutrition- The Role of Nutrient Use Efficiency (NUE) in Next-Gen Agriculture: A Review

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ABSTRACT

The long-term use of chemical fertilizers poses a serious threat to crop productivity and soil quality. The public interest and awareness of the need for improving nutrient use efficiency is great, but nutrient use efficiency is easily misunderstood. The Nutrient use efficiency (NUE) is the integral part of a larger concept of resource use efficiency in agriculture, a cause of concern at present and as well as for the future of sustainable agriculture. The nutrients when applied to the soil, if not utilized by the plants, find their way to reach the water bodies and atmosphere, resulted in an increase of ecological cost. Nutrient use efficiency can be optimized by best management practices that apply nutrients at the right rate, time and place, from right source. Application of organic manures is recognized as a key strategy for smart farming, because it optimizes the nutrient use efficiency, by balancing nutrient supply with crop demand, reducing leaching and improving soil health. The application of organic manures improves soil health and plant growth by improving the soil organic matter (SOM), soil structure, aggregate stability, nutrient uptake, water-holding capacity, cation exchange capacity, nutrient use efficiency and microbial activities of soil. The intensity of abiotic stress is continuously increasing, which is a serious threat to crop productivity and global food security. However, the organic manures have been reported to improve tolerance against drought, salinity, heat and heavy metal (HM) stresses. The application of organic fertilizer improves the leaf water status, nutrient uptake, nutrient homeostasis, synthesis of chlorophyll, osmolytes, hormones, secondary metabolites, antioxidant activities and gene expression, resulting in improved tolerance against drought, salinity, heat and heavy metals. The advancements in next-generation agriculture rely heavily on precision nutrition. This review explores how the strategic application of organic manures, among other interventions, optimizes the nutrient use efficiency to support sustainable crop production and sustenance of soil fertility in smart farming.

Key words: Nutrient use efficiency, Organic manures, Precision nutrition, Smart farming, Soil fertility, Soil health.

The world population is expected to touch 10 billion by 2050 (Khoshgoftarmanesh *et al.,* 2010) and there is an urgent need to increase the food, feed and bio-fuel production from the present level, to meet the demand of exploding population (FAO, 2017). The additional requirement of the food grain shall be met either by increasing the area under cultivation or increasing the productivity through enhanced use efficiency of existing crop varieties. The increase in the cultivable land area is a major challenge and existing area under cultivation is getting degraded with its negative impact on social, environmental and economic cost (FAO, 2017). Every attempt to increase the yield directly, further increases the pressure on natural resources, especially on soil health. Although the food grain production has increased thrice with only 30% increase in the cultivated land during Post Green Revolution, but it also resulted in heavy metal contamination of soils and increase in soil pH due to excessive use of fertilizers and pesticides (John and Babu, 2021) and thereby on nutrient use efficiency (NUE) (Singh *et al*., 2019).

Awareness and interest in improved nutrient use efficiency (NUE) has never been greater. Driven by a growing public belief that crop nutrients are excessive in the environment and farmer concerns about rising fertilizer prices, energy crisis and stagnant crop prices, the fertilizer industry is under increasing pressure to improve nutrient use efficiency. The mineral nutrients applied but not taken by the crop are vulnerable to losses from leaching, erosion, denitrification, volatilization and temporary fixation. Low nutrient recovery efficiency not only increases cost of crop production but also causes environmental pollution. Agronomic nutrient use efficiency (kg crop yield increase per kg nutrient applied) is the basis for both economic and environmental efficiency. The use efficiency of Nitrogen (N) ranges from 20-30% under rainfed conditions and 30-40% under irrigated conditions, 10-30% for phosphorous (P), 50-60% for potassium (K), 8-12% for sulphur (S) and hardly 4-5% for the micronutrients. It indicates that, roughly 50% of

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nitrogen and 90% of phosphorus applied through chemical fertilizers are lost to water and the atmosphere, which causes water eutrophication, Green House Gases Emission (GHGE) and other associated environmental issues.

Chemical inputs add approximately 200 million metric tons (Tg) of nutrients to global soils annually (Govindasamy *et al.,* 2023). Globally, the seasonal utilization rate of N fertilizer averages between 35% and 50% (Govindasamy *et al.,* 2023; Jayara *et al.,* 2023). In the United States, for instance, despite a steady rise in nitrogen inputs, NUE has declined in most regions, with core grain crops like corn frequently dropping below 40% efficiency (Goswami, 2025). Phosphorus efficiency is even lower, typically hovering around 10% due to its rapid fixation in soil matrices, while potassium efficiency averages roughly 40% (Jayara *et al.,* 2023). Because fertilizer can account for an average of 39.8% of total operating costs for high-input crops like corn, wasted nutrients represent a severe drain on farm profitability (Christine, 2026). Over-application forces farmers onto a "fertilizer treadmill"-as the soil's natural capacity to replenish and retain nutrients degrades from chemical saturation, producers are forced to apply increasingly higher, more expensive volumes just to maintain baseline crop yields (Goswami, 2025). The economic damages extending past the farm gate are immense. For example, economic valuations indicate that nitrogen over-application and its subsequent nitrous oxide emissions cost billions annually in environmental mitigation (Christine, 2026). When factoring in downstream water purification, air pollution cleanup and public healthcare costs associated with nitrate and ammonia pollution, the total negative externalities exceed $32 billion annually in high-production regions like the U.S. Midwest alone (Christine, 2026). In this context, the application of organic manures is recognized as a key strategy for smart farming, because it optimizes the nutrient use efficiency, by balancing nutrient supply with crop demand, reducing leaching and improving soil health.

Keeping in view of the above specific gap and the scope of making use of organic manures in Next-Gen Agriculture, this review focuses on the role of nutrient use efficiency (NUE) in Nex Gen Agriculture, current status of NUE, possible ways and means to enhance NUE through manures and the effect of organic manures on growth, yield and quality of crops, besides its impact on soil health and mitigating various abiotic stresses.

Measures of nutrient use efficiency

Nutrient use efficiency can be expressed several ways. Generally four agronomic indices (Mosier *et al.*, 2004) are commonly used to describe nutrient use efficiency: Nutrient use efficiency; Agronomic efficiency (AE, kg crop yield increase per kg nutrient applied); Physiological efficiency (PE, kg yield increase per kg nutrient taken up); Agro-physiological efficiency (APE); Apparent recovery efficiency (RE, kg nutrient taken up per kg nutrient applied) and utilization efficiency (UE), as detailed below:

Partial factor productivity (PFP, kg crop yield per kg nutrient applied) and Crop removal efficiency (removal of nutrient in harvested crop as % of nutrient applied) is also commonly used to explain nutrient efficiency. The various common measures of nutrient use efficiency are also presented in Fig 1.

The simplest approach to quantifying NUE is to divide the crop yield (Y) by the nutrient inputs (N) (Eq. 1).

$$NUE = \frac{Y}{N} \quad ...(1)$$

However, several authors have suggested that yield may be defined in several ways, including the mass of the harvested portion of the crop, total (aboveground) biomass of the crop, nutrient content contained in the harvestable portion and nutrient content of the total biomass. Fageria and Baligar (2005) proposed a number of general "groups" of approaches to calculate NUE that may be considered (Eqs. 2-7).

$$\text{Agronomic efficiency (AE)} = (Gf - GuNa) \quad ...(2)$$

Where,

Gf and Gu = The grain yields (kg) of the fertilized and unfertilized plots, respectively.

Na = The rate of nutrient applied (kg).

$$\text{Physiological efficiency (PE)} = (Yf\text{-}Yu)\ (Nf) - (Nu) \quad ...(3)$$

Where,

Yf and Yu = The total aboveground biomass (kg) of the crop in fertilized and unfertilized plots, respectively.

Nf and Nu = The Nutrient contents (kg) of the aboveground biomass in the fertilized and unfertilized plots, respectively.

$$\text{Agro-physiological efficiency (APE)} = (Gf\text{-}Gu)\ (Nf) - (Nu) \quad ...(4)$$

Where,

Gf and Gu= The grain yield in fertilized and unfertilized plots, respectively.

$$\text{Apparent recovery efficiency (ARE)} = (Nf - NuNa) \quad ...(5)$$

$$\text{Utilization efficiency (UE)} = (Yf - YuNa) \quad ...(6)$$

All of the above equations rely on the assumption that varied nitrogen rate as fertilizer input is the independent variable. Naturally, as the mass of nutrient inputs decreases, the calculated efficiency increases in equations using nutrient rate or difference in nutrient accumulation in the denominator. It would therefore be quite easy to interpret these as suggesting that the lowest rates of nutrient inputs result in the best NUE. This outcome ignores the importance of crop productivity.

Berendse and Aerts (1987) proposed a "biologically meaningful" definition of NUE as the product of nitrogen productivity (An/Ln) and the mean residence time (1/Ln) of nitrogen in the plant (Eq. 7).

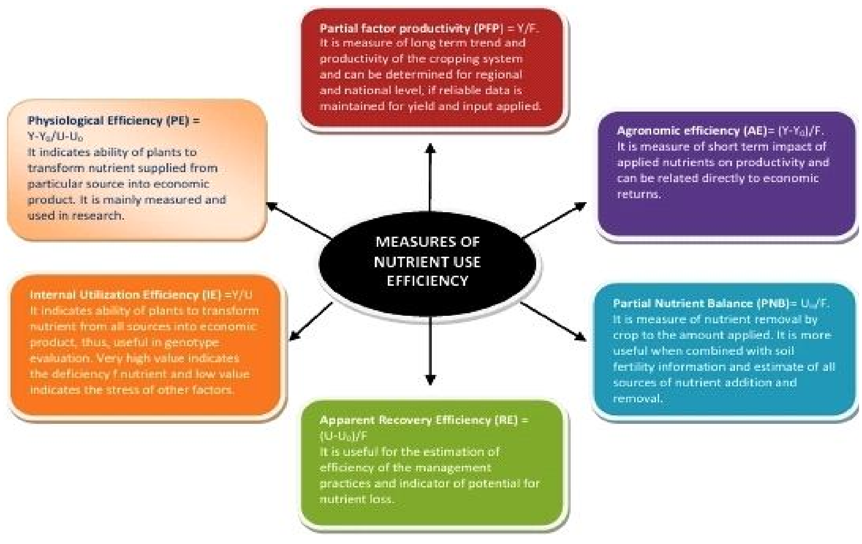
$$\text{Biologically meaningful NUE} = (AnLn) \quad ...(7)$$

Role of nutrient use efficiency in next-Gen agriculture

Various estimates reveal that there has been seven-fold increase in nitrogenous fertilizer consumption in past four decades. The same witnessed seven-fold increase in period of 1960-1995 (Hirel *et al.,* 2007) and eight-fold increase during 1960-2012 (Huang *et al.,* 2017). This increase has lead to various serious implications for the ecosystem functioning and biodiversity (Hirel *et al.,* 2007), especially in the form of eutrophication of water bodies, green house gas emission and leaching (Hirel *et al.,* 2007; Dimpka *et al.,* 2020). In the scenario of increased fertilizer consumption in India, the nitrogen use efficiency has been reduced from 55% to 35% between 1960 and 2010 (Moring *et al.,* 2021) and the same varies between 25% and 50% in the global scale (Sharma and Bali, 2018). The nitrogen lost from the field 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 causes main environmental concerns (Rutting *et al.,* 2018). Under low-land rice system, nitrogen is lost mainly through ammonia volatilization, denitrification, leaching and surface runoff (Huang *et al.,* 2017). A review of best available information suggests that the average N recovery efficiency for fields managed by farmers, ranges from about 20% to 30% under rainfed conditions and 30% to 40% under irrigated conditions (Cassman *et al.,* 2002).

The use of P fertilizers increased 3.5 times during the period of 1960 to 1995 and will further increase three fold by 2050, if proper management strategies are not implemented (Adem *et al.,* 2020). An inefficiency in the food production chain leads to cause a serious imbalances between the depletion of phosphate reserves and its availability to the population through food consumed (Schroder *et al.,* 2011). Worthwhile to mention that the rock phosphate reserves are non-renewable (Syers *et al.,* 2010) and will last for 50-400 years or longer with current utilization rates (Schroder *et al.,* 2011; Hawkesford *et al.,* 2012; Roberts and Johnston, 2015). Phosphorus use efficiency of Global cereal systems varies from 15% to 30% (Pereira *et al.,* 2020) and least as 10%-20% (Johnston and Syers, 2009). When the phosphatic fertilizers are applied to the soil, they may get fixed mainly in four different pools. The first two pools comprising of soil solution and readily extractable P, are generally available to the crops and third and fourth pool comprising of adsorbed P and precipitated P, respectively, are not available to plants (Johnston and Syers, 2009; Syers *et al.,* 2010; Roberts and Johnson, 2015). The fixation of P is a problem in major soil orders of the world including oxisols, spodosols, ultisols, alfisols, mollisols and aridisols. The P is lost through 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). While major emphasis is on nitrogen use efficiency, phosphorus (P) efficiency is also of vital interest, being one of the least available and least mobile mineral nutrients. Though the rate of recovery of applied fertilizer P ranges from less than 10% to 30% in the first year due to fixation and/or precipitation, the long-term recovery of P by subsequent crops can be much higher.

Almost 96-99% of the Potassium in soil is present in the mineral form (Shin, 2014), followed by exchangeable and non-exchangeable K (1%-2% each) and only a small



Y= Yield of harvested portion of crop with nutrient applied; Y0= Yield with not nutrient applied; F= Amount of nutrient applied; UH= Nutrient content of harvested portion of the crop; U= Total nutrient uptake in aboveground crop biomass with nutrient applied; U0= Nutrient uptake in aboveground crop biomass with no nutrient applied.

Fig 1: Various measures of nutrient use efficiency.

portion of 0.1%-0.2% is available to soil (Dhillon *et al.,* 2019). The global availability of K reserves is limited and its availability is mainly 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). Besides the limited availability, K uptake is also influenced by complementary ion effect (NH^{4+} and Na^{+}) and soil moisture content (Shin, 2014); root exudates released (Shin, 2014; Hartley, 2017). The information pertaining to potassium (K) use efficiency is scarce, however, it is generally considered to have a higher use efficiency than N and P, due to its immobile nature in most of the soils and therefore not subjected to the gaseous losses as like N or fixation reactions as like P. The use efficiency of K is generally ranged from 20% to 60%.

Though the calcium deficiency is rare in nature (White and Broadley, 2003), it is very common in leached and weathered acidic soils as well as saline soils (González-Fontes *et al.,* 2017). The use of calcium is mainly affected by the availability of water and interactions with other cations mainly NH^{4+}, K^{+} and Mg^{2+} (González-Fontes *et al.,* 2017). Though the magnesium (Mg) constitutes 2% of the earth crust, 90%-98% is present as fixed in crystal lattice and therefore not available to the plants (Senbayram *et al.,* 2015; Chaudhry *et al.,* 2021). As it undergoes leaching, it is deficient in the acidic soils and the presence of excess H^{+}, Al^{3+} and Mn^{2+} also interfere with its uptake by plants (Wang *et al.,* 2020a). It is also observed that there may be a 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 magnesium carbonate and gypsum in later, respectively (Chaudhry *et al.,* 2021). The agronomic efficiency of Mg fertilizers also varies with crop species; vegetable crops are found to the most responsive and cereals, the least responsive (Wang *et al.,* 2020a). The presence of the excess K and Ca in soil leads to interfere with magnesium uptake through antagonistic effect (Yan and Hou, 2018; Guo *et al.,* 2016). Sulphur deficiency, is becoming more common in the soil over the years, due to lesser S-rich fertilizers, low 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 found to be varied from 18 to 20.4% and the reason for the same is attributed to the leaching loss due to repulsion of $SO4^{2-}$ ions from the negatively charged clay colloids, adsorption of sulphur to Fe and Al oxides in acidic soils and insignificant losses of volatilzation 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), under anaerobic conditions (Aula *et al.,* 2019).

Micronutrient deficiency is a major concern in global crop production system (Gaige *et al.,* 2020). More than fifty per cent of the world soils are deficient in micronutrients (Baligar *et al.,* 2001). This 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 significant in the post-Green Revolution scenario, with the cultivation of high yielding varieties, improved mechanization, use of high macronutrient fertilizers with lower trace elements along with decreased application of organic matter. Though the modern irrigation system and extension of crop production to marginal lands resulted the increased crop yield, there is a substantial decrease in the plant-available micro-nutrients in soil (Khoshgoftarmanesh *et al.,* 2010) and the use efficiency of micronutrients efficiency is only 1%-2% (Ramamoorthy, 2020). The low nutrient recovery efficiency not only increases cost of crop production but also causes environmental pollution.

The fertilizers, an essential input determining sustainability of cropping practices and food security of nations across the globe, currently supports 40%-60% of the total food grain production (Johnston and Bruulsema, 2014; Singh and Ryan, 2015). The major factors associated with NUE use are the 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 and the pathway of applied nutrient in the soil and its availability to the plants is subjected to various loss mechanisms is presented in Fig 2.

Boosting nutrient use efficiency through organic manures

Organic manures are the natural materials from plants and animal sources (Fig 3) that directly and indirectly affect the soil's physiochemical and biological properties (Amujoyegbe *et al.,* 2007; Basel and Sami, 2014). A bio-fertilizer, a misnomer, is also a type of organic carrier that contains beneficial microbes (algal, fungal, bacteria) that improves plant growth by mobilizing the soil available nutrients through their biological activities (Chew *et al.,* 2019; Singh *et al.,* 2020).

These microorganisms enhance nutrient use efficiency (NUE) by fixing atmospheric N, solubilizing insoluble P and K, production of phytohormones, siderophores and improving plant nutrient uptake through enhancement of root architecture and rhizosphere interactions. Apart from nutrient supply, bio-fertilisers enhance soil enzymatic activity, increase soil organic carbon, promote soil carbon stabilization and restore microbial diversity.

Moreover, they contribute to climate-resilient agriculture by improving plant tolerance to drought, salinity and temperature stress and reducing greenhouse gas (GHG) emissions (Bhatt *et al.,* 2019). Animal excreta is the greatest source of organic manure around the globe, followed by poultry and pig manures (Thangarajan *et al.,* 2013). Animal manures are a good and sustainable source of NPK and the total N excreted in animal manure globally ranges from 81.5 to128.3 Tg per year (Potter *et al.,* 2010; Liu *et al.,* 2017), though the type and amount of N in animal manure vary significantly. The fertilizer industry supports the application of nutrients at the right source, right rate, right time and in the right place (4R Stewardship) as a best management practice (BMP) for achieving the optimum nutrient efficiency.

Right source

Organic sources of nutrients are considered as the most sustainable and environment friendly than synthetic inorganic fertilizers because they release nutrients slowly; ensuring a steady supply of nutrients to the plants, reducing the risk of nutrient wastage, water pollution and harming beneficial soil organisms. In addition to increasing soil fertility, organic manures improve soil organic carbon (SOC) content, soil microbial activity for crucial nutrients recycling, water retention and soil aeration, aggregates stability,maintain soil pH and minimize risk of groundwater contamination. Due to their slow-release nature, organic manures reduce volatilization of nitrogen species and their ability to prevent acidification, while increasing organic matter content of soils, promotes carbon sequestration, further preventing greenhouse gases emission. Since organic manures are derived mainly from waste, they are renewable and do not compete with humans and animals for food. Organic manures are therefore a sustainable alternative to inorganic fertilizers.

Most crops are location and season specific-depending on cultivar, management practices, climate, *etc*. Key strategies for enhancing NUE *via* organic sources include.

Organic amendments

Compost, animal manure, de-oiled cakes and crop residues add nutrients to soil, while enhancing soil organic matter and microbial activity, which helps nutrient cycling.

Cover crops and rotations

Planting cover crops, especially legumes, fixes nitrogen and reduces nutrient leaching, with some holding onto nitrogen that would otherwise be lost.

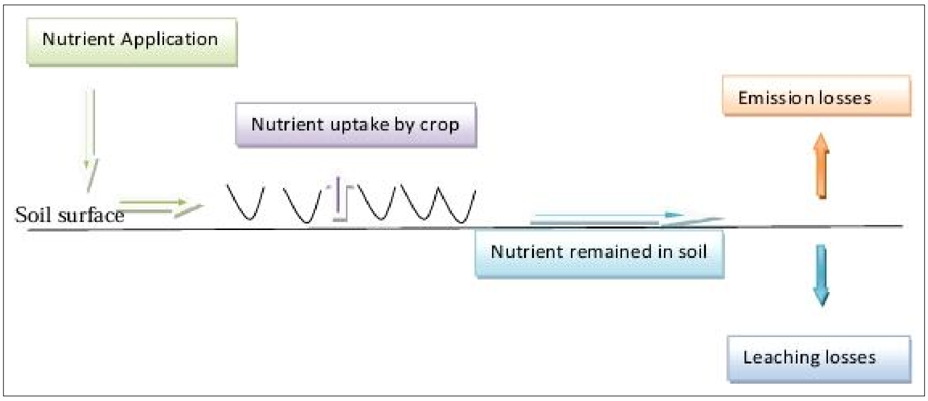


Fig 2: The nutrient applied to soil surface is partly utilized by the crop, part of it remains in soil which undergo emission or leaching losses determining the nutrient use efficiency (Reich *et al.,* 2014).

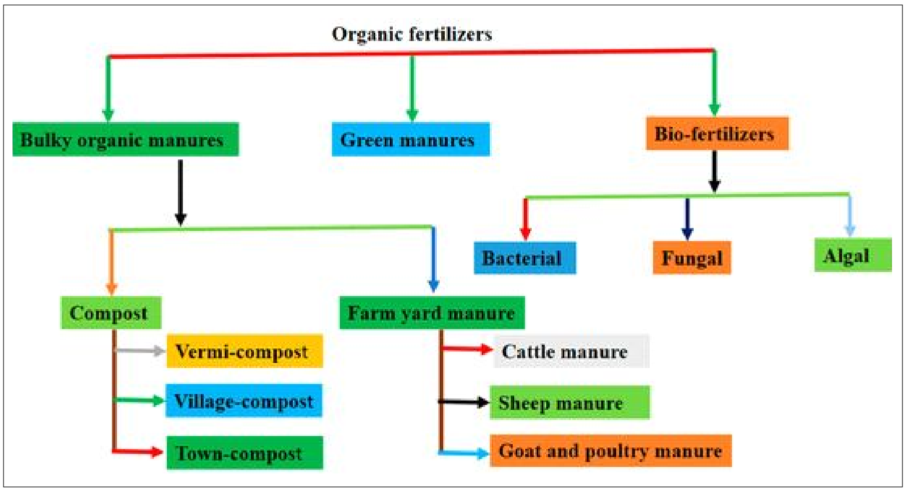


Fig 3: Different types of organic manures used in agriculture.

Precision application

Utilizing precision agriculture techniques, such as variable rate technology (VRT), enables applying organic amendments exactly when and where needed.

Right rate

Adequate and balanced application of mineral nutrients is one of the most common practices for improving the efficiency of applied N. Both over-and under-application of plant nutrients result in reduced nutrient use efficiency or losses in yield and crop quality. Soil testing is the most powerful tool available for determining the nutrient supplying capacity of the soil, thereby enabling the farmers to make appropriate decision on right rate of nutrient application, through organic manures. Unfortunately, soil testing is not available in all regions because reliable laboratories using methodology appropriate to local soils and crops are inaccessible or calibration data relevant to current cropping systems and yields are lacking (Witt and Doberman, 2002).

Right time

Greater synchrony between crop demand and nutrient supply, is highly necessary to improve the nutrient use efficiency, especially for N. Split application of N during the growing season is effective in increasing N use efficiency (Cassman *et al.,* 2002). Tissue testing is a well-known method to assess N status of growing crops, but other diagnostic tools are also available. Chlorophyll meters are useful in fine-tuning in-season-N management (Francis and Piekielek, 1999) and leaf colour charts (LCC) have been highly successful in guiding split N applications in rice and maize (Witt *et al.,* 2005). Precision farming technologies have introduced and now commercialized, on-the-go-N sensors that can be coupled with variable rate fertilizer applicators to automatically correct crop N deficiencies on a site-specific basis. Use of N stabilizers and controlled release fertilizers synchronize the release of N with crop need. Similarly, nitrogen stabilizers {Nitrapyrin, DCD (dicyandiamide), NBPT [N-(n-butyl) thiophosphoric triamide]} inhibit the nitrification or urease activity, thereby slowing the conversion of the applied nitrogen forms into nitrate. The most promising coated-fertilizers like neem coated urea (NCU), sulphur coated urea (SCU) and lac-coated urea (LCU) are the slow release fertilizers that release the nitrogen in a controlled manner, thus enhance the nutrient use efficiency.

Right place

Application method has always been critical in increasing nutrient use efficiency. Numerous placements are available, but most of these involve surface or sub-surface applications before or after planting. Prior to planting, nutrients can be broadcast, applied as a band on the surface, or applied as a subsurface band, usually 5 to 20 cm deep. At planting, nutrients can be banded with the seed, below the seed, or below and to the side of the seed.

The recommended dose of phosphorus must be applied through basal application, preferably in root zone at planting. After planting, the application is usually restricted to N and in some cases for K. Placement can be as a top-dress or a subsurface side-dress. In general, nutrient recovery efficiency tends to be higher with banded applications because less contact with the soil lessens the opportunity for nutrient loss due to leaching or fixation reactions. Placement decisions depend on the crop and soil conditions, which interact to influence the nutrient uptake and availability (Fixen *et al.,* 2005).

Effect of organic manures on growth and yield of crops

Application of organic manures improved the seedling growth, green leaf area, panicles, seed set and final grain production of most of the crops by improving microbial activity, nutrient availability, nutrient uptake, physiological and antioxidant activities of plants (Gao *et al.,* 2019). Use of cow, pig, rabbit, poultry manures, green manure and NPK reported to increase the yield of okra by 57.9, 36.2, 35.3, 39.2, 45.5 and 3.2%, respectively (Adekiya *et al.,* 2020). Application of organic manures also improved the tomato yield by 42.2% (Gao *et al.,* 2019) and the same way, there is a considerable yield increase in maize and soybean, upon addition of organic manures (Joshi *et al.,* 2020). The crop productivity and soil nutrient (Zinc, copper, iron and manganese) concentration increased with the application of poultry and farmyard manure (Bolinder *et al.,* 2020; Randhawa *et al.,* 2021; Hua *et al.,* 2020).

Effect of organic manures on quality of crops

Application of organic manures effectively promotes the vegetative as well as reproductive growth and final quality of crops (Hou *et al.,* 2018). Use of organic manures markedly reduced the nitrate contents of pepper (Yao *et al.,* 2011) and there is an appreciable effect on fruit water contents, total soluble solids (TSSs) and flavonoid contents of Ziziphus jujuba (Red date), with the application of biochar and soybean cake (Ye *et al.,* 2022). Similarly, organic manures increased the TSSs, soluble sugars (SSs), lycopene, vitamin C and nitrate content of tomato by 11.86, 42.18, 23.95, 18.97 and 8.36%, respectively (Gao *et al.,* 2023). Use of organic manures substantially increased the seed quality parameters and nutrient content of plants (Sheoran *et al.,* 2017; Li *et al.,* 2019). The application of organic manures to blueberries significantly increased their yield and quality (Munoz-Vega *et al.,* 2016). Poultry manure plus millet husks enhanced sesame growth, seed yield and seed protein content than crop residues and animal manure applied individually (Anguria *et al.,* 2017). Vermicompost, yet another organic manure, significantly improved the acid contents, antioxidant activity and fruit yield of vegetable crops (Negi *et al.,* 2021). Similarly, chicken manure increased the tomato yield and soluble protein content by 43 and 23%, respectively (Tao *et al.,* 2022). No doubt, organic manures, appreciably improve the quality of crops; however, this depends on the type of organic manures applied.

Effect of organic manures on soil quality

Application of organic manure is considered as an imperative strategy to improve the soil fertility (Fig 4) and sustain the agro-ecosystem (Patil *et al.,* 2014; Liu *et al.,* 2014), as a whole, by improving the soil organic matter (SOM), soil structure, aggregate stability (Du *et al.,* 2022), nutrient uptake, water-holding capacity, cation exchange capacity, microbial activities and of course, nutrient use efficiency of soil (Cen *et al.,* 2019; Piaszczyk *et al.,* 2017; Allam *et al.,* 2022). The increase in the NUE through the application of organic materials emphasizes the importance of balanced crop nutrition that can ensure better crop productivity.

Vermicompost applied @ 5 t/ha appreciably increased the moisture retention and available water content (Shang *et al*., 2020). Soil microbes play an important role in the decomposition and release of nutrients from organic materials. Soil microbial biomass carbon (MBC) and N are considered as the important indices of microbial load and soil fertility (Nair *et al*., 2010). Application of organic manure changes the soil bacterial structure and increases the abundance of beneficial bacteria including Bacilli and Flavobacteriales. Addition of organic matter, applied through organic manures, not only increases the microbial population and activity, but also improves the soil fertility status, through enhancing the nutrient availability by degradation of soil organic matter (SOM) and consequent release of mineral nutrients to plants (Liu *et al.,* 2023).

Role of organic manures on combating abiotic stresses

The biochemical and molecular processes of plants are being favourably altered due to the application of organic materials, that enables the plants abiotic conditions. Besides this, organic manures also enhance crop growth and yield under both normal and stress conditions, through substantially improving the soil fertility (Bello *et al.,* 2021).

Application of organic manure resulted in improving the tolerance against drought, salinity, heat and heavy metals, through increasing the leaf water status, nutrient uptake, nutrient homeostasis, synthesis of chlorophyll, osmolytes, hormones, secondary metabolites, antioxidant activities and gene expression (Bidabadi and Abdel Latef, 2022; Alkharabsheh *et al.,* 2021) (Fig 5).

Role of organic manures to mitigate salinity stress

Application of organic manures significantly improves plant performance under saline conditions (Gohari *et al.,* 2019). Vermicompost improves the morphological and biochemical traits of plants under saline conditions (Gohari *et al.,* 2019; Ebrahimi *et al.,* 2019). Biochar, an organic material, improves root growth, dry matter production, leaf area and yield, under saline conditions (Huang *et al.,* 2019; Muhie *et al.,* 2020; Lashari *et al.,* 2015).

Role of organic manures to mitigate drought stress

The growth and productivity of plants, through physiological and biochemical changes, is drastically affected by drought stress, a serious threat to food security (Carvalho *et al.,* 2021). Application of organic manures (compost, vermicompost, biochar and FYM) improves the crop yield and offer high resilience against drought stress (Song *et al.,* 2022; Ait-El-Mokhtar *et al.,* 2022; Murtaza *et al.,* 2021; Boutasknit *et al.,* 2021). The increase in soil organic carbon and soil organic matter, mineral nutrient concentration and soil-water holding capacity, with use of organic manures, allow the plants' ability to withstand drought conditions (Boutasknit *et al.,* 2020). Organic manures also induce the tolerance against water deficit conditions through increasing the microbial activity and fungal-to-bacterial ratio in soil (Lin *et al.,* 2019).

Role of organic manures to mitigate heavy metals stress

Heavy metals (HMs) are also a serious threat to crop productivity and human health. The concentration of HMs is increasing in the environment due to anthropogenic activities. The use of organic fertilizers can reduce the concentration and availability of HM in contaminated soils

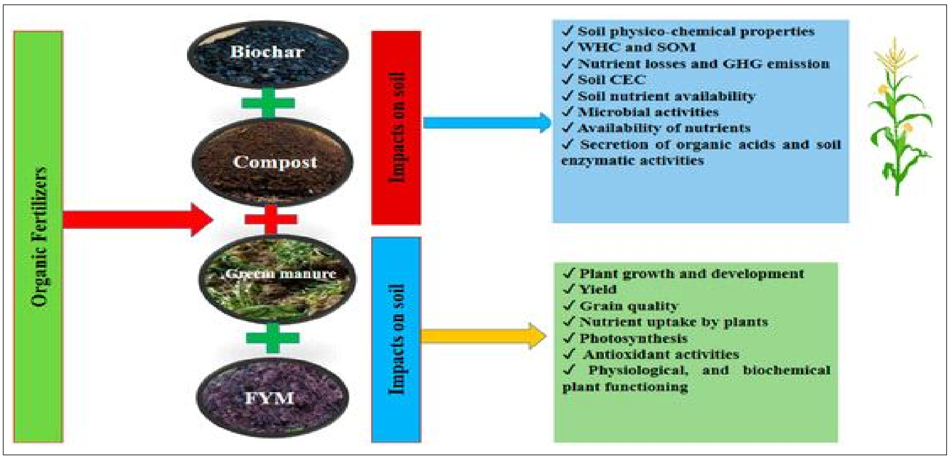


Fig 4: The application of organic manures improves the growth and yield of crops, soil organic matter, cation exchange capacity, nutrient uptake, microbial activity and plant functioning.

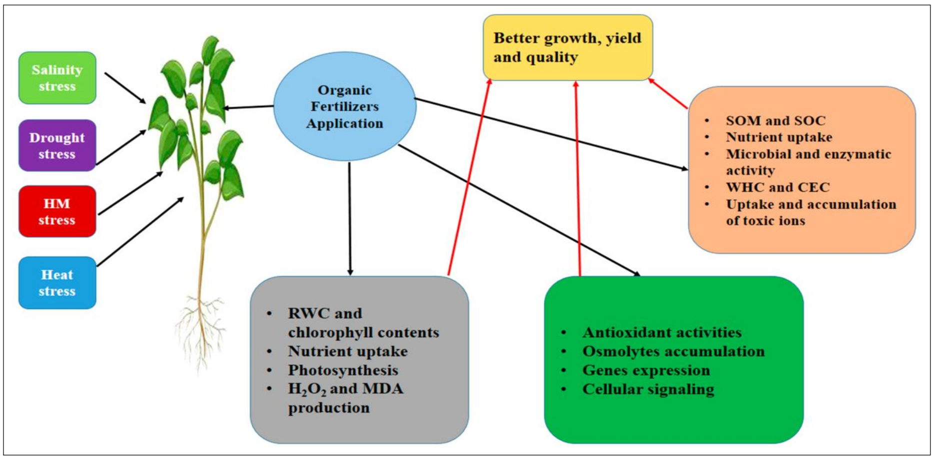


Fig 5: The application of organic manures improves nutrient uptake, photosynthesis, antioxidant activities, gene expression and soil properties and reduces MDA and H_2O_2 accumulation, improving the stress tolerance of plants.

(Park *et al.,* 2011). Organic materials (Cow manure, compost, poultry manure, sheep manure and biochar) form complexes with HMs, therefore reducing their availability and uptake by plants (Alam *et al.,* 2020; Shahmansouri *et al.,* 2005; Somerville *et al.,* 2018; Paradelo *et al.,* 2019).

Role of organic manures to mitigate temperature stress

Temperature is one of the most important environmental factors regulating growth and yield (Tesfaye *et al.,* 2017); however, both low and high temperatures adversely affect plant growth and yield (Mangani *et al.,* 2019). The use of organic manure is suggested as an important approach in improving heat tolerance in plants. Organic fertilizers enhance plant heat tolerance by improving soil organic matter, organic carbon, microbial activity, soil structure thereby increasing soil water retention, reducing acidification, that help plants withstand high temperatures. They increase leaf chlorophyll, leaf area and biomass yield, allowing crops to maintain growth, reduce nutrient uptake inhibition and improve root development during temperature stress. Organic manure application significantly improved the chlorophyll concentration, leaf area, plant height, stem width and biomass yield by 35, 36, 41, 59 and 78% under heat stress, respectively (Chukwudi *et al.,* 2021).

CONCLUSION

Improving nutrient use efficiency is a challenge facing the farmers, fertilizer industry and agriculture in general. But opportunities are there and tools are available to accomplish the task of improving the efficiency of applied nutrientsin smart farming. However, we must be cautious that improvements in efficiency do not come at the expense of the farmers' economic viability or the environment. Application of organic manures improves soil organic matter, macro-aggregates, enzymatic activities and microbial activities, improving crop growth and yield. The application of organic fertilizers substantially improves water uptake, water use efficiency, nutrient uptake, osmolyte accumulation, antioxidant activity and gene expression, providing better resistance against abiotic stresses. Judicious application of organic manures, best management practices following the concept of 4R Stewardship *i.e*., right source at right rate, right time and right place, targeting both high yields and nutrient efficiency will benefit farmers, society and the environment alike. Use of organic manure must be optimized for different crops considering the climate, soil and crop conditions and their combined use with synthetic chemical fertilizers can provide an excellent solution. Increasing the awareness among the farmers on the benefits of organic manures in improving the crop productivity, besides sustaining the soil fertility and agro-ecosystems, remains a pressing priority and critical imperative for advancement of sustainable smart farming.

Conflict of interest

The author declares that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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