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# Plant Nutrition in Relation to Water-use Efficiency in Crop Production: A review
# Nutrisi Tanaman dalam Kaitannya dengan Efisiensi Penggunaan Air dalam Produksi Tanaman: Sebuah tinjauan

Agbesi Kwadzo Keteku[1]*, Patricia Amankwaa-Yeboah[1], Stephen Yeboah[1], Richard Dormatey[1], Kennedy Agyeman[1], Mavis Badu Brempong[1], Philip Ghanney[1], Samuel Aduse Poku[2], Eric Owusu Danquah[1], Felix Frimpong[1], Sylvester Addy[1], Franklin Bosompem[1], Habibah Aggrey[1]
[1])Council for Scientific and Industrial Research-Crops Research Institute, P. O. Box 3785, Kumasi, Ghana.
[2])Department of Plant and Environmental Biology, College of Basic and Applied Sciences, University of Ghana
*Email Coresponden: k.agbesi@cropsresearch.org

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## ABSTRACT
*Improving plant nutrition is an important global concern in the face of climate change because plant nutrition and soil moisture are interrelated. Nevertheless, the limited soil nutrient and water resources are still underutilized and their use efficiency is low, although there is considerable room for improvement in both areas. The interaction between nutrients and water depends on the crop's growth stage, the amount applied, and the balance between the two phenomena. Effective nutrient management can promote nutrient and water use efficiency. Prudent fertilizer management reduces soil erosion more than some mechanical measures because it promotes vegetative cover and provides organic matter that improves soil structure, permeability, and water-retention capacity. Effective water management can increase nutrient availability and their conversion from soil and fertilizers to plants. To increase yield through the efficient use of nutrients and water, the two resources must be combined to interact positively. Declining soil fertility, environmental degradation, and drought have prompted research into the interactive effects of nutrients and water on crop yields. Despite notable successes, some challenges still need to be addressed to improve water and nutrient use efficiency. Therefore, in this paper, we discuss the techniques to improve nutrient and water use efficiency from the perspectives of nutrient availability, nutrient movement, and distribution, nutrient use efficiency, the interactive effect of nutrients and water on crop yield through nutrient management, gaps, and future prospects.*

**KEYWORDS: integrated nutrient management, irrigation, nutrient use efficiency, sustainable agriculture, water use efficiency**

## ABSTRAK
*Peningkatan nutrisi tanaman merupakan perhatian global yang penting dalam menghadapi perubahan iklim karena nutrisi tanaman dan kelembaban tanah saling berkaitan. Namun demikian, sumber daya hara dan air tanah yang terbatas masih kurang dimanfaatkan dan efisiensi penggunaannya masih rendah, meskipun terdapat banyak ruang untuk perbaikan di kedua bidang tersebut. Interaksi antara unsur hara dan air bergantung pada tahap pertumbuhan tanaman, jumlah yang diberikan, dan keseimbangan antara kedua fenomena tersebut. Pengelolaan unsur hara yang efektif dapat meningkatkan efisiensi penggunaan unsur hara dan air. Pengelolaan pupuk yang bijaksana dapat mengurangi erosi tanah lebih baik dibandingkan tindakan mekanis karena hal ini meningkatkan tutupan vegetasi dan menyediakan bahan organik yang memperbaiki struktur tanah, permeabilitas, dan kapasitas retensi air. Pengelolaan air yang efektif dapat meningkatkan ketersediaan unsur hara dan konversinya dari tanah dan pupuk menjadi tanaman. Untuk meningkatkan hasil melalui efisiensi penggunaan unsur hara dan air, kedua sumber daya tersebut harus dikombinasikan agar dapat berinteraksi secara positif. Menurunnya kesuburan tanah, degradasi lingkungan, dan kekeringan telah mendorong penelitian mengenai dampak interaktif unsur hara dan air terhadap hasil panen. Meskipun terdapat keberhasilan yang signifikan, beberapa tantangan masih perlu diatasi untuk meningkatkan efisiensi penggunaan air dan nutrisi. Oleh karena itu, dalam makalah ini, kami membahas teknik untuk meningkatkan efisiensi penggunaan unsur hara dan air dari sudut pandang ketersediaan unsur hara, pergerakan dan distribusi unsur hara, efisiensi penggunaan unsur hara, pengaruh interaktif unsur hara dan air terhadap hasil tanaman melalui pengelolaan unsur hara, kesenjangan, dan prospek masa depan.*

**KATA KUNCI: Efisiensi Penggunaan Unsur Hara, Efisiensi Penggunaan Air, Irigasi, Pengelolaan Unsur Hara Terpadu, Pertanian Berkelanjutan**

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## INTRODUCTION

Increasing the yield of crops per unit of land area to satisfy future food and fiber needs, increases nutrient removal from the soil (Keteku et al., 2022), and therefore the need to restore soil fertility through efficient nutrient management practices. Almost all of the world's cropland is cultivated, so future food and fiber needs can only be met by increasing crop yields per unit of land (Fan et al., 2012); as in what is known as sustainable intensification. Currently, over 50% of the global croplands are degraded, threatening our ability to meet food and fiber demands (Kopittke et al., 2019). Of the total arable land, only about 10% is suited for cultivation (Class I-III) (Schneider et al., 2022), and this needs to support the estimated 50% increase in food required to feed the expected 9.5 billion population by 2050 (CAST, 2013). Inherent soil nitrogen (N) deficiency is common (Aytenew & Bore, 2020), and phosphorus (P) deficiency occurs in at least one-third of the global croplands (Fitton et al., 2019). Attaining food security and alleviating hunger and poverty in the face of climate change are major challenges faced by agricultural stakeholders worldwide, especially, raising living standards in rural areas where a large proportion of the population lives and depends entirely on agriculture for their livelihoods (Gassner et al., 2019; Moritz & Agudo, 2013). Increased frequencies of unexpected floods (Adonadaga et al., 2022; Jarawura, 2014) and droughts (Ansah et al., 2020; Tengan & Aigbavboa, 2016) have been predicted. Water stresses caused by climate change affect soil's physical, chemical and biological properties, and therefore limit soil organic matter decomposition, response to applied fertilizers, increase nutrient loss, reduce photosynthesis, create anaerobic conditions and enhance autotrophic respiration among many others that hinders crop productivity (Kulczycki et al., 2022; Manik et al., 2019; Rodríguez et al., 2016; Tóth et al., 2017; Yuste et al., 2011). If agriculture should make the world's food secure, most agricultural reforms would have to focus on intensifying soil nutrition and producing high-yielding crop varieties in the face of increasing land and water scarcity (FAO, 2012). Although the development of high-yielding varieties and mineral fertilizer use for soil nutrition are good options, both are expensive and require a high financial commitment, which consequently increases farmers' production costs. Despite the small amount of fertilizer applied (especially, in sub-Saharan Africa) much of it is lost from the soil system due to poor management practices such as fertilizer timing and placement, soil erosion, nutrient leaching, drought, etc.

About 40% of the world's land area experiences arid and semi-arid climates (Gamo et al., 2013; Huang et al., 2016). Low annual rainfall and its erratic pattern in such areas result in low infiltration and high evaporative losses from the soil surface, leaving, soil-, surface-, and underground -water in deficit. These regions will be severely hit by climate change (water shortages), even though they contribute the least to it (UN, 2019; Trisos et al., 2022) . In the remaining high-rainfall areas, frequent storms often result in heavy runoff and water erosion, leading to significant soil degradation and nutrient losses. Therefore, water shortages and soil nutrient deficiencies are two major obstacles to crop production globally. FAO projects that crop production under rain-fed and irrigation conditions in 93 developing countries will have to increase by 49% and 81%, respectively from 1998-2030 (FAO, 2003), to meet food demand. Adequate crop nutrition is needed to achieve this goal. Increasing demand for food and diminishing water resources due to climate change have increased pressure to find new technologies for the efficient use of fertilizers and water in agriculture.

To achieve this goal, the improvement and application of agronomic techniques that promote appropriate nutrients and water use for optimal crop yields are crucial. In general, the recovery of applied N varies from 28% to 41% and the residual effect on succeeding crops is negligible in some cases. Fertilizer inefficiency is even more critical in drier areas due to inadequate soil moisture (Bista et al., 2017). To improve nutrient-use efficiency, it is crucial to estimate nutrients available at plants' root zone, supply required nutrients to plants, improve plants' nutrient uptake, and reduce nutrient loss from the plant root zone. Poor nutrient use efficiency (NUE) has not only resulted in low economic yield, but also has harmful effects on the environment, such as eutrophication, nitrate accumulation in food crops, nutrient enrichment of surface waters, and emission of greenhouse gases such as Nitrous Oxide ($N_2O$) (Martínez-Dalmau et al., 2021). Although water and nutrients have specific functions, they interact with each other to promote plant growth. The efficient use of one depends on the efficiency of the other (Fan et al., 2003; Bhale et al., 2009; Waraich et al., 2011). Nutrient supply promotes root growth for maximum water uptake and use. The interactive effect of nutrients and water on plant performance depends on the plant's growth stage, the amount, combination, and balance of inputs. A synergistic interaction between the two can only be achieved with an adequate supply of both resources (Chtouki et al., 2022; Panhwar et al., 2018); allowing both to play a greater role than their sequential additive effects. The effects of nutrients and water are often limited by each other, especially in drylands, because both resources are often in short supply (Waraich et al., 2011).

For instance, after four successive years of testing the effect of fertilization and moisture on the performance of millet under extremely dry conditions in Jodhpur, India, nutrients applied had no effect. However, it was quite beneficial for plant development and seed yield under sporadic drought conditions (Li et al., 2009). In a wheat experiment, the applied fertilizers were of little importance when rainfall was less than 120 mm during spring (Li et al., 2009). Dai and Yang (1995) found a negative effect of N and P fertilization on winter wheat when rainfall was less than 109 mm during the growing season. According to (Liu et al., 2020), the more nutrients applied to the soils under water stress, the greater the decrease in crop yield. Since changes in rainfall patterns affect the water and nutrient status of soils in dryland and high-rainfall areas, these changes should be taken into account to regulate water and fertilizer recommendations to prevent water deficiencies in dry and nutrient deficiencies in wet seasons. Research has proven that under moisture stress, the application of organic or inorganic fertilizers or their combination increases the water potential of plants, improves water content in plant tissues, increases the ratio of free to bound water, increases transpiration intensity, and thus improves the water status of plants (Cao et al. 2002; Zhang and Li, 2005; Panhwar et al., 2019).

In light of the above, we review plant nutrition in relation to water use in crop production, particularly where the roles of nutrients and water interact. It can be difficult to discuss the roles of soil nutrients and water independently, because of their inseparable significance to plant yields. We then proposed techniques to improve plant nutrition and water use from the perspective of nutrient availability, nutrient movement and use efficiency in plants, the interactive effect of nutrients and water on crop yield and improving water use efficiency through nutrient management. We presented research findings found research gaps, and recommended future needs since it is evident that both goals must be achieved to maximize crop yield in the face of climate change.

## REVIEW METHODOLOGY

The focus was on developments in the fields of plant nutrition and plant water use. Literature on this area was searched from the following database: ScienceDirect (http://www.sciencedirect.com/science), WoS (SSCI, SCI, HSCI, ESCI) (http://jcr.clarivate.com/), Scopus (http://www.scopus.com/sources), PubMed (https://www.ncbi.nlm.nih.gov/PubMed) and Google scholar (scholar.google.cn). Concept keywords such as nutrient use efficiency, climate change and water use efficiency, nutrient availability, nutrient mobility, nutrient loss, nutrient-water interaction, water movement, and integrated nutrient management were used. Search questions such as: What is the effect of water and nutrient interaction on crop productivity? What methods are available globally to improve nutrient-water complimentary effects? How can integrated nutrient management improve soil water and nutrient use efficiency? Are there advanced technologies to reduce nutrient loss as a result of soil water movement? How do these technologies contribute to nutrient and water use efficiencies of crops? Intervention, Comparison, Outcomes, and Study (PICOS) design were employed as a framework to formulate eligibility criteria in the systematic review process. Related articles were extracted, categorized, and summarized to show the interdependency between nutrients and water and their interactive effect on crop productivity. New development techniques to improve water and nutrient relations in the soil were also summarized. Based on the checklist and database of PRISMA guidelines for systematic reviews (Liberati et al., 2009), the literature included in this review was deemed appropriate after the initial data search, identification, and removal of duplicates (Figure 1). Included in this review study are publications comprising reviews, research articles and conference proceedings.

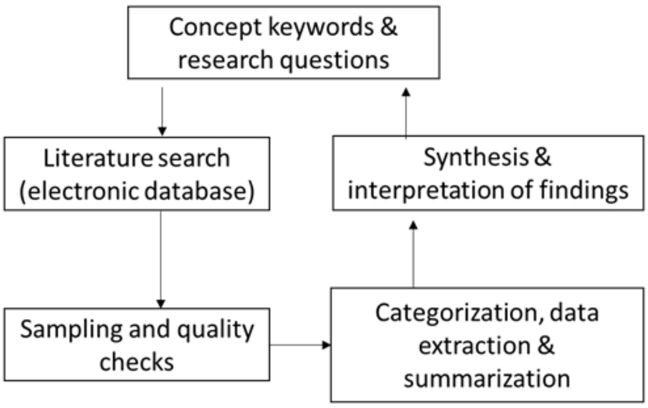


Figure 1. Scheme of procedure used in literature search for this review paper.

## RESULTS AND DISCUSSION

### Impact of climate-induced water stress on crop production

Climate change affects crop production through its direct impacts on soil and plant growth (Schmidhuber & Tubiello, 2007; Stuart Chapin et al., 2012; FAO, 2021). In most parts of the world, especially sub-Saharan Africa (SSA), climate-induced water stress (floods and droughts) may be due to changes in rainfall amounts and patterns, average temperature increases and rise in sea water level. Under this heading, we look at climate change's effect on crop production, especially in SSA. It is projected that with climate change, the wet regions (temperate areas) could become wetter and the dry regions (tropical areas) could turn drier (FAO, 2008; FAO, 2021). The intensity of rainstorms could increase (in some areas) and rainfall could become more variable and unpredictable. FAO (2008) projected that low-latitude (tropical and sub-tropical) countries where access to water is low, would record crop yield decreases even at 1 - 2°C of warming. SSA would experience decreased rainfall by about 20% (Parry et al., 2007). Thus, some agricultural lands in the SSA may become unsuitable for cropping (Bals et al., 2008), leading to crop yield reduction. The extent of these declines in yields is unclear, however, some analysts predict it could be severe (Bals et al., 2008). This increase in temperature plus reduced rainfall can lead to the loss of arable land due to decreased soil moisture, increased aridity, increased salinity and groundwater depletion (Bals et al., 2008). Water shortages may increase water costs and lead to water rationing which will limit the capacity to maintain or even expand cultivated arable lands by irrigation. Most farmlands (especially in SSA) depend on rain-fed agriculture, so distortion of the rainfall pattern would limit crop production and worsen the socio-economic hardship of smallholder farmers. Flooding promotes soil compaction which further destroys the soil structure through the breakdown of aggregates, deflocculation of clay, and destruction of cementing agents (Rodríguez et al., 2016). Floods are associated with anaerobic conditions which limit soil aeration affecting the respiration processes of plant roots and soil microbes, reducing mineralization rates, water and nutrient uptake, carbohydrate accumulation, and plant hormone synthesis, among others (Manik et al., 2019). Flooding reduces soil temperature below the optimum range (25 - 35°C), causing a reduction in nitrification rates and making $NO_3^-$ less available to plants (Havlin et al., 2014). Flooding increases the pH of acid soils by reducing ferric iron ($Fe^{3+}$) to ferrous iron ($Fe^{2+}$) and decreases the hydrogen ions (pH) of alkaline soils by facilitating the formation of carbonic acid ($H_2CO_3$) due to carbon dioxide ($CO_2$) accumulation. This change makes native acid/alkaline tolerant crops grown in such areas fail. Flooding promotes greenhouse gas ($CH_4$ and $N_2O$) emissions through methanogenesis and denitrification processes (Schlesinger, 2013). In coastal areas, flooding caused by a rise in seawater level increases soil salinity (Havlin et al., 2014), which inhibits nitrogen uptake by crops. On the other hand, seasonal or continuous droughts affect agroecosystem carbon and nitrogen cycles. Drought conditions accompanied by increased temperatures have been reported to reduce soil microbiota activities, leading to a 93% decline in the rate of soil organic matter decomposition (Tóth et al., 2017). Water is the main soil solvent that supplies nutrients to both microbes and plants; therefore, a lack of it limits nutrient availability to these entities (Bista et al., 2017). Under drought conditions, crops show little to no responses to applied fertilizer. Drought dries the soil and increases its susceptibility to wind erosion and its consequent loss of soil and soil nutrients. The higher predicted temperatures associated with droughts would also place high transpiration demands on crops leading to their wilt and eventual death due to carbon starvation.

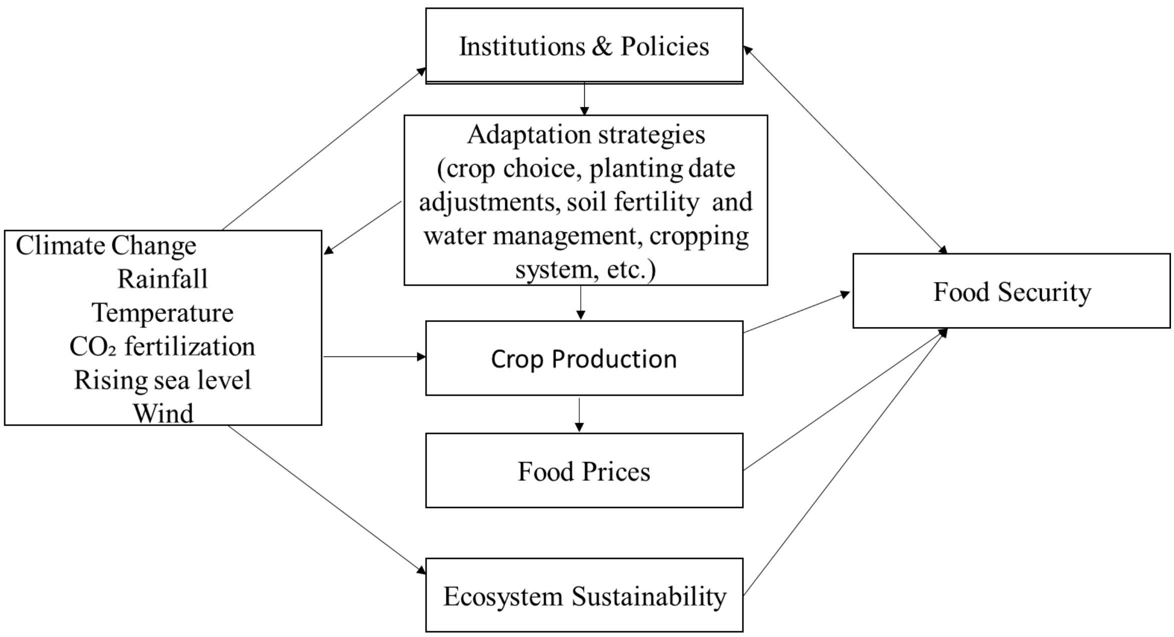


Figure 2. Climate change, crop production and food security linkages. Adapted from (Benedict Chijioke Mekbib Haile Christine Waschkeit, 2011)

## Nutrient availability

Inherent soil nutrients and nutrients supplied through fertilizers and manure are often lost through soil fixation, leaching, erosion/runoff, and gaseous emissions. These losses lead to nutrient shortages and water use inefficiency (Mohammad & Adam, 2010), which hampers rainfed and irrigated agriculture. Surface runoff/erosion also adversely reduces soil organic matter needed to build the soil's carbon stocks for better soil health and crop development (Wolka et al., 2018). Nutrients carried off-site by erosion are permanently lost before they reach the plant root zone. Percolated water (leaching) transports nutrients beyond the plant root zone, decreasing nutrient availability (Wolka et al., 2018). Nutrients fixed in the soil are inaccessible to plants. Farming activities increase nutrient loss through both phenomena (Waraich et al., 2011). Thus, nutrients lost to water dynamics not only contribute to the loss of inputs but also represent a significant economic loss of applied fertilizer to farmers. Lack of water also reduces both nutrient availability and assimilation, but the decline in net assimilation is more severe. Current agricultural systems, which depend primarily on mineral fertilizers are at great risk of nutrient loss (Meena et al., 2014; Yang et al., 2015; Descheemaeker et al., 2020; Keteku et al., 2022;) especially if they do not incorporate cultural practices that minimize nutrients and water losses. Water facilitates the conversion transformation of added fertilizers from unavailable nutrients into available forms. Appropriate agro-technical management strategies must be practised to conserve and effectively utilize this vital resource.

Ammonium and nitrate are the two major forms of nitrogen supply to plants. Most dryland soils are calcareous and have high pH, therefore the use of nitrate-N sources can reduce N volatilization, while nitrate-N–N leaching from sparse rainfall is negligible. Soil water content effectively affects ammonium-N–N nitrification. The nitrification rate mostly correlates linearly with an increase in soil water content in the range of 12–27%. Water holding capacity is closely related to soil organic matter content, application of fertilizers, especially organic manures, increases soil organic matter. This increases soil water-retention capacity and indirectly improves ammonium-N nitrification. According to (Wan et al., 2021), the addition of organic manure reduces $NO_3$- leaching beyond the root zone, which is important for maintaining surface and underground water quality. Zhang et al. (1982) reported that by applying 7.5-Mg of organic manure/ha to dry, infertile soil, the amount of water stored in a 2 m layer was 44.7 mm higher than without fertilizer application. Replacing part of mineral fertilizers with organic amendments and using minimum effective doses of sufficient and balanced amounts of mineral fertilizers integrated with effective bioinoculants offer a prospective approach to improving nutrient availability (Descheemaeker et al., 2020). Aside from immediate soil and crop benefits of combined nutrient sources, residual benefits are useful to subsequent crops even without further fertilizer applications. Nutrients supplied through inorganic fertilizers are short-lived and subject to many loss pathways, however organic fertilizers, on the other hand, take longer to mineralize and only a certain percentage of it is released in the growing season following application (Eghball, 2002). After the application of poultry manure and rock phosphate to okra, Akande et al., (2004) demonstrated that phosphorus (P) content increased by 112 to 153% two years after the field trial. An application of 184.8 kg/ha of N by mineral and organic fertilizers yielded 3463.8 kg/ha of potatoes in the first season and still increased potato yields to 4570.5 kg/ha in the second season without re-applications due to residual benefits (Cooke, 1970). Previous research works reported increases in soil nutrient content and crop yields when nutrients sources were combined compared to single applications and residual benefits years after application (De Rosa et al., 2018; Ng et al., 2016; Wang et al., 2017; Sarkar et al., 2021; Voltr et al., 2021; Wan et al., 2021). These findings are evidence that the integration of inorganic and organic fertilizers reduces nutrient loss, improves nutrient availability and consequently water use efficiency of crops.

## Reducing volatilization and denitrification of nutrients

If the soil is not sufficiently moist, the applied N is lost by volatilization ($NH_3$) and denitrification ($N_2O$ and $N_2$ gas). Loss through volatilization can be minimized by:

Using urease inhibitors. After urea is applied, it is rapidly hydrolyzed by the enzyme urease, which increases the pH of the surrounding soil and promotes the loss of $NH_3$. Urease inhibitors play an effective role in reducing $NH_3$ losses. Compounds such as N-(n-butyl)-thiophosphoric triamide, thiourea, methyl urea, caprylohydroxamic acid, phenyl phosphorodiamidate, and ammonium thiosulfate act efficiently as urease inhibitors (Kiss & Simihăian, 2002). Urease inhibitors block the active sites of the urease enzyme to reduce the release of $NH_3$.

Again, coatings of various materials are used to reduce nutrient losses and increase fertilizer use efficiency. Compounds such as gypsum-coated urea, sulphur-coated urea, plastic-coated urea, and slurry ball urea tend to reduce nutrient volatilization and denitrification.

Additionally, synthetic urea-based slow-release fertilizers such as crotobylidene diurea and isobutylidene diurea, etc., may be applied to decrease the rate of urea hydrolysis, and hence reduce volatilization of ammonia.

Furthermore, nitrogen fertilizer with soil after urea application instead of surface spreading; for example, in puddle rice fields, deep application of urea super granules is recommended. It is also advisable to add inorganic K, Mg, and Ca salts to urea.

Denitrification of $NO_3$ primarily produces nitrous oxide ($N_2O$). This occurs mostly under anaerobic conditions due to excess moisture as in lowland rice fields. Loss of soil N through the emission of this greenhouse gas can be reduced by using denitrification inhibitors such as neem-coated urea, AM (2-Amino, 4-Chloro, 6-methyl pyrimidine), Dicyandiamide, N-serve (2-Chloro, 6-Chloro methyl pyridine) and coated calcium carbide. It can also be reduced by avoiding $NO_3$ fertilizers such as potassium nitrate, calcium ammonium nitrate, etc. in rice farms and wetlands. In flooded rice farms, deep placement of urea sugar granules with proper water management can also minimize losses. INM practices are also efficient in minimizing $N_2O$ production by replacing some of the mineral fertilizers with organic amendments. Organic N supply replaces mineral N which can reduce the rate of release of N and cause temporal N immobilization by microbes for decomposition processes (De Rosa et al., 2018; Brempong et al., 2022). As such, less N is available for denitrification. Lower N availability limits the denitrification process since N is the substrate for denitrifying microbes; leading to lower $N_2O$ emissions (Lv et al., 2018).

## Reduction of leaching and erosion losses

Mobile nutrients namely; nitrogen, calcium, magnesium, and sulfur are often lost from the soil-plant system due to leaching and erosion (Wolka et al., 2018). In addition to reducing soil nutrients, they also cause economic losses to farmers. Leached nutrients contribute to soil acidification and groundwater contamination (groundwater containing > 10 mg $NO_3$ or N/L) making it non-potable. Loss of $NO_3$ and other micronutrients can be minimized by efficient irrigation (manipulating water supply at rooting depth), the addition of organic amendments, splitting fertilizer applications to synchronize nutrient supply with crop needs, proper fertilizer placement such as band application or injection, application of nitrification inhibitors and slow-release fertilizers and appropriate crop rotations. Though the use of artificial nitrification and urease inhibitors has chalked up success in research farms, they are rarely accepted by farmers due to their high cost. However, neem coating can be promoted to farmers to improve nitrogen balance and reduce the future environmental hazards of nitrate leaching and denitrification. Efficient micro-irrigation methods such as drip and fertigation can reduce the over-application of water or place water and nutrients in the right places for easy root uptake. Runoff and erosion reduce water use efficiency (WUE) and facilitate drought stress and soil crusting. Both phenomena significantly degrade soil hydrological properties by reducing organic matter, soil depth, aggregate stability, and water-holding capacity. Run-off carries soil and water-soluble nutrients off-site. To minimize this, proper cropland management (selection of appropriate crops and cropping systems) must be implemented. Appropriate water conservation measures such as stone bunds, soil bunds, bench terraces, and tied ridges are effective protective measures that conserve rainwater behind the ridges or bunds preventing erosion and nutrient loss. Ridges or bunds must be the same height to retain water and improve water infiltration into the soil. Contour tillage reduces rill formation when surface water collects in small depressions (Gilley, 2005), thus, minimizing soil runoff. The application of mulch minimizes surface evaporation (Diaz et al., 2005), minimizes runoff by reducing the intensity of raindrops when they intercept the soil and delays runoff by improving water infiltration (Mohammad & Adam, 2010). This increases the percolation time and infiltration capacity of the soil. Percolation time can be enhanced by vegetative barriers to water flow, conservation tillage, mechanical structures, incorporating organic amendments, strip cropping, appropriate rotational cropping, and mulching. In-situ nutrient conservation can be achieved when water erosion is reduced and infiltration is enhanced. The amount of N and P removed from the soil by leaching and runoff in an experiment is shown in Table 1.

Table 1. Mean concentration of nitrogen and phosphorus removed by leaching and runoff in conservative agriculture (CA) and conventional tillage (CT)

| | **2018** | | **2019** | |
|---|---|---|---|---|
| | **CA** | **CT** | **CA** | **CT** |
| $NO_3$-N (leachate) g/ha | 20.1±7.8[b] | 21.6±9.1[a] | 15.1±12.8[b] | 16.6±16.2[a] |
| $NO_3$-N (runoff) g/ha | 148.8±66.2[b] | 384.0±75[a] | 333.7±122[b] | 866.0±359[a] |
| $PO_4$-P (leachate) g/ha | 8.4±4.0[a] | 5.6±2.6[b] | 15.1±4.2[a] | 16.6±2.6[b] |
| $PO_4$-P (runoff) g/ha | 243.0±66.2[a] | 389.0±75[b] | 500.8±215[a] | 702.6±312[b] |

Mean values with identical alphabets under the same row heads and year are not significant (5%). Adapted from Belay et al., (2020).

## Split application of nitrogen

Split application of N is driven by the 4R management technique (right-source, right amount, right time, and right place) to supply N at crop demand stages to limit N lost from the soil and allow for N rate adjustment (Mikkelsen, 2011; Kabir et al., 2021). N fertilizer is relatively expensive and forms the bulk of the production cost budget. In addition, N application is the major cause of nitrogen gas emissions, nitrate leaching, and possibly ammonia volatilization. This nutrient management technique is more efficient than the basal method (application at planting). Basal application is an idea for P and K but the split application of K is advised for some light-textured soils. The method of fertilizer application significantly affects its agronomic efficiency by influencing nutrient availability to plant roots and losses. Fertilizer application two weeks after germination has superior use efficiency compared to the application at seeding (Amali & Namo, 2015). Similarly, in rice production, volatilization of $NH_3$ can be minimized by basally applying urea 10 days after transplanting without standing water rather than doing the same in standing water. Band placement of water-soluble phosphate fertilizers adjacent to or below the seed row can improve its use efficiency. Therefore, the application of N in a split can be a win-win situation for the environment and the economy.

## The movement and use efficiency of nutrients in plants

Global water scarcity affects the movement and uptake of nutrients from fertilizers by plants and can limit plant productivity (Swarbreck et al., 2019). Plants' demands for nutrients and water are interdependent. Water controls all chemical reactions in the soil and also transports nutrients to the root surfaces in mass flow and diffusion. Thus, an adequate supply of water improves the nutritional status of plants, while balanced nutrition saves water. With appropriate water and nutrient management strategies, farmers can optimize water use and increase crop yields. Water scarcity leads to a depleted water and nutrient zone around the roots. Therefore water-saving approaches that hold or deliver water directly within the root zone promote uptake and distribution. Drip irrigation/fertigation systems deliver nutrients and water directly to plants' root zone. Efficient water management goes beyond how water is applied but the amount, when and how often. To avoid over- or under-irrigating crops, farmers need to study the weather and soil moisture and adjust irrigation schedules to current conditions and key plant nutrient demand growth stages. Compost or organic amendments have been reported to improve soil structure and increase water-retention capacity making it easier for plants to absorb water and nutrients. Organic mulch or black plastic mulch used as a soil cover suppresses weeds and reduces the evaporation of water and volatile plant nutrients. Mulches are best suited for areas with low to moderate rainfall and less suited for areas with extremely wet conditions. The use of cover crops also reduces weeds, increases soil organic matter and fertility, and helps prevent soil compaction and erosion, allowing water to easily percolate through the soil. Conservation tillage which uses a special plough to partially loosen the soil, leaving about 30% of crop residue as the surface cover is also a useful approach to reducing soil, water and nutrient losses. Soil organic matter and microorganisms serve as a sponge that provides moisture to plants. Water affects nutrient transportation through mass flow (82%), diffusion (7%), and interception (11%) (Oliveira et al., 2010). Water deficit affects not only the amount of nutrients in solution but also the rate of mass flow and diffusion, especially of nitrate-N. Foliar fertilization is a faster method to improve nutrient transport in plants, but reports have shown that water stress increases cuticle thickness by about 33%. Most significantly, water deficit increases the prevalence of cuticular wax and alters the composition of lipid components toward more long-chain hydrophobic lipids, further hindering the uptake of nutrients through the leaf. Therefore, foliar application is not ideal under water stress or in cold water due to problems with solubility. Foliar fertilizer uptake is maximum at sunrise and sunset and lowest at noon, so the time of application can affect nutrient movement. Optimal allocation of water under conditions of water deficit should involve quantifying water use (evapotranspiration or transpiration) relative to crop biomass and using optimization models. Crop simulation models can be used to schedule irrigation under various levels of soil moisture. Increasing the transpiration component of evapotranspiration (ET), will increase crop water use and thus increase biomass production. Transpiration can be increased by efficient irrigation methods and scheduling, fertilization, mulching, and tillage. Song and Li (2006) studied the effects of water movement and root uptake of $NO_3^-$ -N (Figure 3). Under irrigation, differences in $NO_3^-$ -N concentrations were small at all measured points with just 6.5 mg N/kg between the highest and lowest values along the roots, indicating that water movement enhances nitrate–N uptake by roots. Without irrigation, $NO_3^-$ -N concentration sharply decreased at 26 mg N/kg from the highest to the lowest points, indicating a non-uniform movement and $NO_3^-$ -N uptake at different parts of the roots. This shows the coordination between water and nutrients and the need to keep both resources in balance.

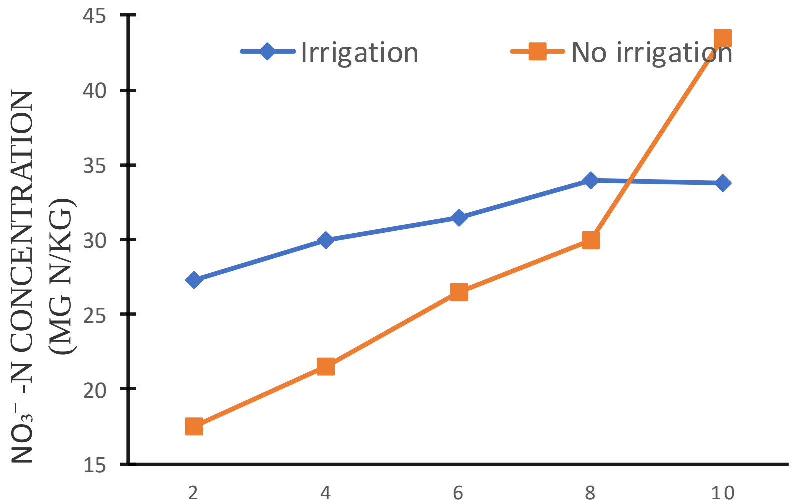


Figure 3. Effect of soil water on nitrate movement in roots under field conditions. Adapted from Song and Li (2006).

Sustainable intensification can only be achieved through the efficient use of plant nutrients. NUE is a function of the soil providing the required amount of nutrients and the plant's ability to absorb, transport them within the plant, and remobilize them to other plant parts. NUE can be increased by reducing the pathways by which nutrients escape from the soil-plant system. This can be achieved by integrating nutrients from different sources in an adequate manner, optimizing nutrient supply among crops, and improving the uptake and utilization of native and applied nutrients. Given the increasing demand for fertilizer (>food demand) in this time of climate vagaries (Figure 2), it is important to increase the utilization of applied nutrients(Wang et al., 2019). Therefore, to increase NUE, there is a need to Quantify the capacity of nutrient supply in soils, Improve cropping practices, and Improve nutrient-management technologies, including nutrient sources, amount, and timing.

Although crop yield and NUE are reduced by soil water shortage, higher yields are often achieved with higher fertilizer applications, notably in less developed countries (Zhu & Chen, 2002; Wang et al., 2019) even though this can be harmful to the environment. Understanding the mechanisms that control water and nutrient use is therefore critical not only for semi-arid and arid regions but for all in general. Water deficit reduces plant root development, minimizes nutrient uptake capacity and area, increases the viscosity of the solution, and thereby, reduces nutrient utilization. The use efficiency of applied N and P is only about 30-40% and 20-40%, respectively, therefore, increasing NUE will reduce costs and environmental drawbacks. Low crop NUE means less yield for farmers and higher costs to consumers and thus lower competitiveness. Suggested techniques to reduce nutrient losses and increase use efficiency include:

Using the most appropriate fertilizer material, using coated nitrogen fertilizer, integrating organic and inorganic fertilizer, using fertilizer prudently and sparingly for synergistic interactions, using application techniques that include split application and placement, and practicing efficient agronomic management practices such as the use of nutrient-efficient crop varieties, plant stands, tillage, irrigation, mulching, intercropping, and weed control.

Allocating fertilizer to crops based on the correlation of soil test and plant for target yield can help improve NUE. Balanced plant nutrition addresses nutrient deficiencies, and improves soil fertility, NUE, WUE, crop yields, and farmers' income. It is important to have good-quality seeds, with an emphasis on timeliness and precision in farm operations to reap the benefits of balanced plant nutrition. Reports show that an adequate water supply increases NUE by increasing the solubility and availability of nutrients applied to the soil (Wang et al., 2012; Mugwe et al., 2019; Bu et al. 2021; Barłóg et al., 2022). The combined effect of nitrogen and water is usually greater than the sum of their individual effects (Aggarwal, 2000; Ru et al., 2022). Nutrients and water are complementary inputs and the response of plant growth to nutrients or water depends on the availability of the other inputs. Application of fertilizers, especially organic fertilizers/manures to dryland soils can increase water content and water potential at the early stages of plant growth, making some ineffective water available to plants, resulting in a mobilizing effect of fertilization on WUE (Lamessa, 2016; Mugwe et al., 2019). Improvement in WUE and NUE will help bring additional land under irrigation to produce more plants per drop of water and unit of nutrients (Anonymous, 2013). Sustainable soil management strategies that store carbon in the soil such as INM must be encouraged (Smith et al., 2014; Voltr et al., 2021). The organic inputs supplement nutrients and improve the soil water-holding capacity and WUE of plants allowing them to make good use of the available soil water during water stress (Descheemaeker et al., 2020). With INM, there is an opportunity to reduce the amount of inorganic fertilizers and supplement them with organic amendments without compromising crop yields through the technique of micro-dosing. In some sub-Saharan African countries, INM practices such as effective fertilizer placement, use of coated nitrogen fertilizers, and application of organic amendments have enabled effective adaptation of micro-dosing technology (Mugwe and Otieno, 2021). In Mali, for example, fertilizer micro-dosing combined with organic manures has improved WUE and NUE for higher economic yield at a reduced crop duration (Kahsay & Hansen, 2016), allowing crops to escape drought. Bharali et al., (2018) reported that the application of NPK along with Azolla compost effectively built the highest carbon stock (16.93 g/kg) and improved rice grain yield capacity to 6.55 Mg/ha compared to NPK, control and Azolla alone. Over the years, the INM strategy has emerged as an important climate change adaptation strategy to improve NUE for higher crop yields.

Another measure to increase NUE is to incorporate beneficial microorganisms. Microbe-assisted nutrient management is an environmentally and cost-effective approach to increasing nutrient utilization. Microbes, convert inorganic and organic soil nutrients into bioavailable forms through various mechanisms of solubilization and mineralization, to facilitate plant uptake (Kalayu, 2019). Several studies have reported increased nitrogen and phosphorus uptake when microbes were incorporated (Bargaz et al., 2018; Hazratullah et al., 2022). Improved nutrient utilization can also be achieved through enhanced nutrient synchronization (Aulakh, 2010) and the priming effect (Wildman, 2016). The priming effect allows the soil to make available nutrients that are either fixed in the soil or bound in microbial tissue. Priming effects indicate that after the combined application of organic-inorganic fertilizers, the organic fertilizer enhances soil microbial population and activity, contributing to higher rates of nutrient mineralization and solubilization in the soil than normal. While the mineral fertilizer makes the nutrients readily available, the organic amendment improves the pH of the soil, allowing the fixed nutrients to get into the solution. In effect, the added nutrient sources act only as precursors for improved nutrient availability. The improved mechanism of nutrient synchronization also means that when both nutrient sources are applied, soil microbes immobilize some of the nitrogen added by the fertilizer to break down the organic material, resulting in some of the being temporally unavailable during the early stages of plant growth when the nutrient requirement is low. The nutrients are made available at a later stage of plant growth when the nutrient requirement is higher. At this stage, mineralization peaks, and soil microbes are lysed to release their in-bound nutrients. As a result, the period of highest mineralization coincides with the period of highest plant nutrient demand (Brempong et al., 2022; Brempong & Addo-Danso, n.d.). These mechanisms may not apply to every crop but suggest that nutrient availability in the soil and plant is enhanced by INM compared to single-source applications.

## Interactive effect of nutrients and water on crop yield

In drylands, the best approach to crop production is the rational combined use of water and fertilizers (Waraich et al., 2011). The combined effect of water and nutrients can be estimated based on Liebig's law of the minimum to obtain an approximate yield (SHIMSHI, 1970). Crop biomass is limited by water supply under water-limited conditions (<200) and by nutrients under conditions between 200 to 400 mm. Underwater deficit, the efficiency of phosphorus utilization is greater than the efficiency of nitrogen utilization, which decreases sharply. There is an intense interaction between water and nutrients, and when one changes it also leads to a change in the other (Fan et al., 2003; Bhale et al., 2009; Waraich et al., 2011) . Since the mineralization of organic N and nitrification of ammonium–N are linearly related to soil moisture, water has a direct and indirect function on plant growth and soil fertility. The interaction of water and fertilizer is time-dependent. Studies have shown that irrigation of 60 mm water combined with an application of 105 kg N and 52 kg $P_2O_5$/ha before sowing of wheat resulted in an increase of 585 kg grain/ha as an interaction effect and, the interaction effect increased to 857 kg/ha when the irrigation rate was increased to 120 mm (Chen et al., 1992). Wang and Xing (2017) found that moderate irrigation of 75% ET° and high fertilizer level of 240N:120$P_2O_5$:150$K_2O$ kg/ha produced the highest tomato yield compared to their high or low combinations. Smika et al.,(n.d.) found that when the available water supply was less than 250 mm, crop production was very low, and plants did not respond to nitrogen fertilizer in any case. However, when the available water supply was increased to more than 400 mm, crop yield increased, and the slope of a linear regression between yield and water quantity was increased with the increase in nitrogen rate. Greater interaction between water and nutrient also depends on the growth stage of plants. Although the early application of water and fertilizer has been practised, recent results have shown that in wheat (Zhai & Li, 2005) and maize (Gao et al., 2006), the elongation stage of the plant may be the most efficient stage. Irrational combinations can have adverse effects; the worst situation is a negative interaction. For instance, an excess supply of water and N can delay plant maturation by promoting excessive vegetative growth with weak stems, which in turn leads to lodging. Excess water can lead to nutrient loss through leaching, while water deficit can lead to high nutrient concentrations in the soil that inhibit nutrients and water uptake. Based on these considerations, attention should be paid not only to the supply of water and nutrients but also to their rational combination. Bhale et al. (2009) reported a significant and positive interaction between applied water and N supply in a wheat experiment on sandy loam soil (Table 2). At 80 kg N/ha, NUE increased up to a water supply of 300 mm but at 120 kg N/ha, NUE did not increase when the water supply was increased from 50 mm to 125 mm.

Table 2. Effect of nitrogen and irrigation on NUE (kg grain/kg fertilizer N) and WUE (kg/grain/mm)

| Irrigation (mm) | WUE | | | NUE | | |
|---|---|---|---|---|---|---|
| | N rate (kg/ha) | | | N rate (kg/ha) | | |
| | 40 | 80 | 120 | 40 | 80 | 120 |
| 0 | 7.6 | 8.1 | 6.0 | 8.5 | 5.5 | 1.5 |
| 50 | 9.5 | 11.3 | 13.3 | 20.2 | 18.4 | 17.8 |
| 125 | 10.3 | 11.9 | 11.8 | 33.3 | 25.5 | 17.0 |
| 300 | 7.4 | 9.5 | 10.2 | 30.2 | 30.3 | 23.7 |

Source: Adapted from Bhale et al. (2009)

It increased when the water supply was increased to 300 mm indicating that an optimal balance between fertilizer and water supply is necessary to achieve efficiency in both resources. The strength of the interaction also depends on the fertilizer material. Field trials showed higher NUE with ammonium nitrate compared to urea ammonium nitrate on wheat (Figure 4). The difference was even more marked under drought conditions (no rain for 23 consecutive days after application).

Nutrients promote root growth, which improves moisture uptake from deeper soil layers. It also promotes early canopy development which serves as soil cover and intercepts solar radiation, thereby reducing evaporation. Fertilizer application improves WUE by increasing yield relative to ET. Optimal and timely fertilizer application promotes the rapid expansion of leaf area for higher transpiration and rapid ground cover, hence reducing evaporation from the toil and losses to weeds to increase WUE.

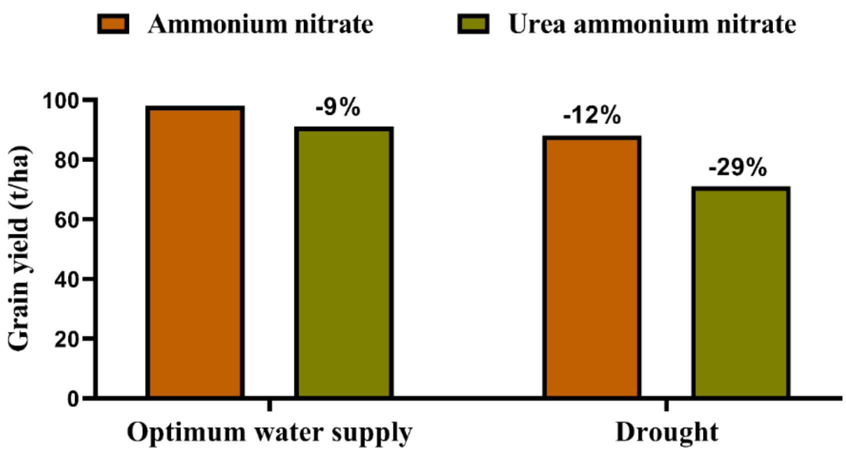


Figure 4. Effect of nitrogen forms and water supply on wheat yield. Adapted from https://www.yara.co.uk/grow-the-future/efficient-farming/water-use-efficiency/

## Improving water use efficiency through nutrient management

One might assume that intensive agriculture uses more water, and low-input agriculture uses less water. The opposite is true. Water demand per unit crop produced decreases with yield. WUE increases with optimal nutrition, and plants grow rapidly to cover the soil surface which reduces the loss of water through evaporation. Adequate N nutrition supply converts available water into maximum growth and yield. WUE is the ratio of yield produced to water applied during the growing period of the plant (Hatfield & Dold, 2019; Brendel, 2021). WUE is a simple means of determining whether crop yield is limited by water or other factors. Good knowledge of the effects of crop management on WUE can enable us to identify and select appropriate management practices to improve WUE (Hatfield & Dold, 2019). In arid regions, efforts to improve agricultural production are limited primarily by water rather than land. Maximizing yield per unit of water (WUE) rather than yield per unit of land (land productivity) is the best technique for dryland cropping systems (Hatfield & Dold, 2019). In such situations, more efficient water management strategies must be adopted (Ali & Talukder, 2008). An increase in WUE is the best strategy to mitigate water deficit and reduce environmental hazards. To enhance WUE through cropping and soil management techniques, practices that take full advantage of natural rainfall and irrigation facilities must be adopted. The primary focus of water-saving agriculture is to increase water utilization rate and WUE to achieve high yields from rain-fed or irrigated fields with less water use. Thus, water-saving agriculture is not simply water-saving irrigation but a comprehensive strategy that uses all possible water-saving measures in a production system to optimize nutrient supply to help crops cope with drought stress. Research shows that irrigation methods such as drip irrigation, fertigation, and sprinklers can help maximize WUE but this must be accompanied by other agronomic techniques (e.g. mulching, organic input, bio-inoculants, crop rotation, tillage, etc.) to achieve optimum results (Wang et al., 2017; Hatfield & Dold, 2019). These practices modify the physicochemical and biological environment of the soil to improve nutrient recovery by crops. Fertilizer recommendations need to be developed for crops and regions where water and nutrient management is required. Adequate nutrition is essential for important physiological processes like light interception by chlorophyll (N, Mg), energy for building carbohydrates (P), and osmotic regulation of stomata (K), etc. Other nutrient elements also follow different pathways to influence WUE. Therefore, a plant that is adequately supplied with nutrients can be expected to produce more biomass per unit of transpired water compared to an under-nourished plant. Research indicates that nutrient status plays a critical role in increasing WUE. Ajouri et al., (2004) reported that priming seeds with limiting nutrients (P and Zn) improved barley establishment under drought conditions. Ali et al., (2013) stated that seed priming increased irrigation water use efficiency of all irrigation regimes and wheat grain yields were linearly increased at 100% ET°, while maximum IWUE was achieved at 80% ET°. Similar results were also reported (Devika et al., 2021). Potassium application mitigates the adverse effects of drought on plant growth (Sangakkara et al., 2001; Xu et al., 2021). N sources have different effects on crop water use. Table 3 shows the effect of different N sources at the root zone level on WUE. Nitrate ($NO_3^-$) is more water-efficient than ammonium ($NH_4^+$), especially in dicotyledonous plants.

A balanced nutrient supply increases the osmotic pressure in plant cells, resulting in high WUE and better resistance to drought (Osakabe et al., 2013; Malik et al., 2021; Tavakol et al., 2022). In addition, synchronizing fertilization and irrigation at critical growth stages of plants may be a more useful approach to increase crop WUE than other methods of irrigation, e.g., feel and appearance, soil moisture depletion, and irrigation at different cumulative pan evaporation.

Table 3. Influence of nitrogen sources on water use efficiency

| Crops | Order of decreasing WUE |
|---|---|
| Maize | $NO_3^- > NH_4^+$ |
| Wheat | $NH_4NO_3 = NO_3^- = NH_4^+$ |
| Beans | $NO_3^- > NH_4^+ > N_2^+$ |
| Groundnut | $NO_3^- > N_2^+$ |
| Tomato | $NO_3^- > NH_4^+$ |
| Sunflower | $NO_3^- > NH_4^+$ |

$N_2^+$ is atmospheric fixed nitrogen by legume. Adapted from: https://www.fertilizer.co.za

## Research accomplishments, gaps, and future needs

Increasing global demand for food, underground water depletion, and climate change have led many scientists to investigate the relationship between plant nutrition (soil nutrients) and water in agricultural production systems. Freshwater shortage and fertilizer pollution have drawn attention to such studies. Several research reports and management strategies have been developed to improve the functions and interaction of plant nutrients and water. Some achievements have been made in many countries in both rainfed and irrigated farmlands, e.g., water-saving irrigation(Yang & Gao, 2021; He et al., 2022); fertilization/fertigation (Bandyopadhyay et al., 2020); INM approach (Kahsay & Hansen, 2016; Mugwe et al., 2019, Descheemaeker et al., 2020); fertilizer micro-dosing technology (Saidia et al., 2019); split application (Olfati et al., 2014; Belete et al., 2018; Kabir et al., 2021); bio-inoculants (Kyei- Boahen et al., 2017; De Rosa et al., 2018; Lv et al., 2018); tillage and mulches (Diaz et al., 2005; Mohammad & Adam, 2010; Farahani et al., 2016; Wolka et al., 2018); nutrients seed priming (Wildman, 2016; Banerjee et al., 2022), nutrient efficient crops and many others to give a better understanding of the interaction of water and nutrients but some critical issues need to be explored.

We have highlighted the need to: identify signaling cascades that regulate water and nutrient transport, and target analyses of physiological traits that influence water and nitrogen movement and uptake; apply modern phenotyping, breeding techniques, and agronomic measures to increase crop yield in nitrogen- and water-limited cropping systems. The technologies do not stand alone and should be integrated. There is also the need to divide the drylands into different regions and identify the priority problems in each region and, link conventional and mulch tillage practice in drylands with water and nutrient management and strategies.

The optimum efficient growth stage of plants and the timing of water and nutrient inputs have been determined but the degree of deficiency that plants can tolerate or the extent to which they can tolerate it remains an open question. This is critical to allow farmers to regulate water and nutrient supplies at appropriate levels during the plant’s most efficient growth phase. In addition, there is the need to apply interactive mechanisms of water and nutrients, especially nutrients in improving WUE. Most studies are limited narrowly to water-improving nutrient uptake. There is a need to understand the impact of nutrient deficiency on plant water uptake and the water retention capacity of plants.

## Conclusion

Increasing challenges in the forthcoming years lie in the debate that agriculture must meet the growing food needs of the population which exceed 4 billion tons annually. To meet this huge food demand annually, more crops must be grown per drop of water and high yields must be achieved per unit of land. This means that water and nutrients should be used efficiently through proper soil water conservation practices, water-saving irrigation techniques, proper choice of fertilizers, amount, method, and time of application. As long as the soil remains the largest growth medium for plants, it will always be necessary to improve water and nutrient conditions for crop productivity. The purpose of enhancing inputs utility will be defeated if the soil is so impoverished that supplied water and nutrients are easily lost below the root zone or off-field. Water conservation strategies must be synchronized with nutrient-efficient techniques. Approaches such as drip irrigation, fertigation, mulch tillage, mulching, integration of organic and mineral fertilizers (INM), split fertilizer application, fertilizer micro-dosing, foliar fertilization, use of coated fertilizers, use of microbial bio-inoculants, soil erosion, and leaching control measures, and among others must be synchronized in production systems for maximum water and nutrient use efficiencies. Integrating water and nutrient supply is a good option and an economical choice to streamline the supply of these inputs to plants at optimum rates to achieve potential yields and create a favorable soil environment. Since water and nutrient efficiencies are interrelated, the supply of these inputs should be based on the soil's nutrient-supply capacity and water status. Therefore, we need to think about nutrients when supplying water and about water when applying nutrients. Farmers must take advantage of soil- and plant-management technologies that increase plant productivity and minimize soil productivity losses.

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