Nutrient-Use Efficiency in Sorghum

J.S. Mishra and J.V. Patil

Abstract

Sorghum [*Sorghum bicolor* (L.) Moench] is an important crop of dryland agriculture. With the threat of climate change looming large on the crop productivity, sorghum being a drought hardy crop will play an important role in food, feed and fodder security in semi-arid tropics. With the development of improved sorghum cultivars, the NPK consumption in sorghum has increased from merely 4 kg/ha during 1974 to 47.5 kg/ha during 2003–2004. The nutrient-use efficiency (NUE) of grain sorghum is quite low (7.06–7.22 kg grain/kg NPK applied). Declining factor productivity, soil health, input-use efficiency and profitability and increasing costs of inputs and their timely availability are the major concerns of resource-poor farmers. Soils of the sorghum-growing regions are deficient in organic carbon, N and Zn, besides shallow in depth, low in water holding capacity, alkaline in reaction and prone to degradation. A system approach that includes sorghum cultivars with high NUE, coupled with best management practices, viz. soil health management, conservation tillage, integrated nutrient management including micronutrients, foliar application of nutrients, inclusion of legumes in sorghum-based cropping systems and efficient weed management, will be required for enhancing the NUE in sorghum.

Keywords

Sorghum • Nutrient-use efficiency • NUE • Nutrient deficiency symptoms • INM

1 Introduction

Sorghum, the fifth most important cereal crop on the globe and native to sub-Saharan Africa, is traditionally grown for grain both as food (Africa

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and India) and as animal feed (developed countries like USA, China, Australia, etc.) and stalks as animal fodder, building material and fuel. Sorghum is called various names in different places in the world. In Western Africa, it is called 'great millet', 'kafir corn' or 'guinea corn', which represents a connection with corn or millet. It is called 'jowar' in India, 'kaolian' in China and 'milo' in Spain. It is the dietary staple of more than 500 million people in 30 countries (Kumar et al. 2011). Sorghum grain is mostly used for food purpose (55 %) followed by feed grain (33 %). Of late, sweet sorghum is emerging as a potential feedstock for biofuels. Because of its drought adaptation capability, sorghum is a preferred crop in tropical, warmer and semi-arid regions of the world with high temperature and water stress (Paterson et al. 2009). With the threat of climate change looming large on the crop productivity, sorghum being a drought hardy crop will play an important role in food, feed and fodder security in dryland economy. Sorghum grain has high nutritive value, with 70–80 % carbohydrate, 11–13 % protein, 2–5 % fat, 1–3 % fiber and 1–2 % ash. Protein in sorghum is gluten free, and thus, it is a specialty food for people who suffer from celiac disease, as well as diabetic patients (Prasad and Staggenborg 2009). Sorghum fibers are used in wallboard, fences, biodegradable packaging materials and solvents. Dried stalks are used for cooking fuel, and dye can be extracted from the plant to colour leather (Maunder 2000).

2 Nutrient Use in Sorghum in India

Adequate supply and balance of mineral elements are required for proper growth and development of sorghum plant. Sorghum is generally grown under less favourable conditions, and meagre amounts of fertilizers are applied. Prior to 1950s relatively very little or no fertilizer was used on sorghum. In a survey during 1968–1971, sorghum accounted for 3.5 % of the total fertilizer used with overall nutrient consumption of 4 kg/ha N + P_2O_5 + K_2O (NCAER and FAI 1974). However, with the development of improved sorghum cultivars and other improved production practices, the average nutrient consumption reached to 5.5–22.7 kg/ha during 1978–1980 (Tandon and Kanwar 1984) and 47.5 kg/ha (29.2, 14.2 and 4.1 kg N + P_2O_5 + K_2O) in 2003–2004 as against 60.2 kg/in maize, 119.1 kg/ha in paddy and 136.7 kg/ha in wheat (FAO 2005). Development of better adapted, high-yielding sorghum cultivars has increased the yield potential and the amounts of plant nutrients required by the crop. Consequently, the fertilizer application in sorghum has increased substantially. However, increasing fertilizer prices and decreasing purchasing power of the resource-poor sorghum farmers are the major reasons for less fertilizer use in sorghum. Improving plant efficiency for fertilizer use is important to reduce costs of crop production (Bernal et al. 2002). Policy interventions to reduce fertilizer cost and improve grain marketing efficiency will further enable smallholders to increase fertilizer use for substantial increases in sorghum production.

3 Nutrients Removal by Sorghum

Many factors are involved in determining the mineral requirement of sorghum (Maiti 1996).

1. Amount of available and residual mineral elements in soil.
2. Physicochemical properties of soil.
3. Availibility of soil moisture.
4. Yield and end product desired.

Cultivars producing large amounts of biomass remove greater quantities of soil nutrients. Sorghum crop producing 5.5 t/ha grain removes a total of 335 kg nutrients (149 kg N + 61 kg P_2O_5 + 125 kg K_2O)/ha from soil. High-yielding varieties of sorghum removed 22 kg N, 9 kg P_2O_5 and 30 kg K_2O to produce 1.0 t of grain (Tandon and Kanwar 1984). Sorghum crop yielding approximately 8 t of grain/ha removes about 250 kg N, 40 kg P_2O_5, 160 kg K_2O, 45 kg Mg and 40 kg S/ha from soil (Maiti 1996). Nutrients removed by sorghum hybrid

Table 1 Nutrients removal by rainfed hybrid sorghum

Nutrients	Grain yield (t/ha)	Total uptake by grain and stover
N	4.4	78 kg
P_2O_5	4.4	35 kg
K_2O	4.4	117 kg
Ca[a]	2.6	28 kg
Mg[a]	2.6	17 kg
Fe	4.4	705 g
Mn	4.4	447 g
Zn	4.4	132 g
Cu	4.4	37

[a]Vertisols (CSH 1) (Lakhdive and Gore 1978)

'CSH 5' in Alfisols under rainfed conditions is given in Table 1 (Vijayalakshmi 1979). Further studies revealed that sorghum grown in India removes on an average 22 kg N, 13.3 kg P_2O_5 and 34 kg K_2O to produce one tone of grains (Kaore 2006).

Large quantities of N and P and some potassium are translocated from the other plant parts to the grain as it develops. Unless adequate nutrients are available during grain filling, this translocation may cause deficiencies in leaves and premature leaf loss that reduce leaf area duration and may decrease yields (Roy and Wright 1974). Nitrogen and P accumulation by whole plants increased almost linearly until maturity, but K accumulation was more rapid early in the season. Nitrogen, P and K accumulation rates were higher during the 35th to 42nd day and 70th to 91st day which coincided with the peak vegetative growth period and the grain-filling stage, respectively. In unfertilized plants relatively higher translocation of N and P from the vegetative parts to the developing grain occurred. Little K was translocated. A much smaller percentage of total K was found in the head and more K accumulated in the stem than N and P.

A grain crop of 8.5 t/ha contains (in the total aboveground plant) 207 kg of N, 39 kg of P and 241 kg of K (Vanderlip 1972). Pal et al. (1982) reported that in early stage of crop growth, N and P accumulated slowly compared with the rapid accumulation of K. In later stages, uptake of K decreased relative to that of N and P.

4 Nutrient Deficiency Symptoms in Sorghum

There is a widespread deficiency of nitrogen, phosphorus, iron and zinc under both rainfed and irrigated conditions. Nitrogen, phosphorus, potassium and magnesium are phloem-mobile elements. When a deficiency of these elements occurs, plants tend to withdraw these elements from older leaves and redistribute them to young, actively growing parts of the plant through phloem (Robson and Snowball 1986). Hence, the first and most obvious symptoms of deficiency of these elements occur on lower, older leaves. Elements such as calcium, iron, manganese and boron are phloem-immobile elements and, hence, are not redistributed to any great extent under deficiency conditions (Robson and Snowball 1986). The first and most obvious symptoms of deficiency of these elements occur on young, actively growing parts of the plant, including root tips. The nutrient elements such as sulphur, zinc, copper and molybdenum often have variable mobility in the phloem (Robson and Snowball 1986). Hence, for these elements, symptoms may appear on young or old growth depending on the species, nitrogen supply, etc. However, Grundon et al. (1987) reported that in grain sorghum, only sulphur and zinc exhibited variation in the location of visible symptoms of deficiency and then only when the deficiency was very severe and persisted for some period. The key deficiency symptoms of nutrient elements in sorghum are listed in Table 2.

5 Nutrient-Use Efficiency (NUE)

Nutrient-use efficiency may be defined as 'the mass of nutrient required to produce a given quantity of biomass'. It is estimated that the overall efficiency of applied fertilizer is about or lower than 50 % for N, less than 10 % for P and about 40 % for K (Baligar et al. 2001). The worldwide nitrogen-use efficiency for cereal production including sorghum was approximately 33 %, and the unaccounted 67 % represents a

Table 2 Visible symptoms of nutrient deficiency in sorghum

Nutrients	Deficiency symptoms
Nitrogen	Deficient plants appear pale green to pale yellow in colour, stunted growth and thin and spindly stem and often show delayed flowering and maturity
	Nitrogen is mobile in plants and under conditions of low soil supply; it is easily mobilized from older to younger leaves. Hence, the deficiency symptoms appear first on older leaves and then advance up the stem to younger leaves
	The leaf blades progressively become pale green with pale yellow chlorosis and pale brown necrosis
Phosphorus	Phosphorus deficiency symptoms appear first on the older leaves with purple suffused pigmentation and progress upwards
	Affected plants appear stunted with thin stems and dark green leaves
	Under severe deficiency, plant growth is greatly reduced and dark green older leaves turn purple or purple-red in colour
Potassium	Potassium deficiency symptoms appear first on older leaves with marginal yellow chlorosis and brown necrosis
	Deficient plants lose stalk strength and are prone to lodging
	The internodes are shortened and thin and the older leaves develop a marginal necrosis
Magnesium	Older leaves are pale green to yellow in colour with many brown lesions. The symptoms advance upwards to younger leaves
	In case of severe deficiency, the whole plants appear pale green or pale yellow in colour
Calcium	Young leaves with torn or serrated leaf margins and leaf tips deformed, missing or joined together
	Under severe deficiency, the upper internodes may be very short and the young leaves crowded together to give the appearance of 'rosette'
Sulphur	Sulphur is not easily mobilized from older to younger leaves; the deficiency symptoms appear first on younger leaves
	Young leaves faint yellow interveinal chlorosis and turn pale green in colour, while older leaves remain dark green
Iron	Sorghum is the best indicator plant for iron deficiency
	Prominent pale yellow or white interveinal chlorosis, leaving the veins green and prominent on young leaves
Zinc	Young leaves with broad yellow or white bands between the margins and midvein in lower half leaf. In case of severe deficiency, the chlorosis extends towards the leaf tip and often turns nearly white or pale brown
	Shortening of internodes resulting in stunted plants
	Delayed flowering and maturity
Boron	Young leaves with transparent white interveinal lesions
	Shortening of internodes and stunted plant growth
	Short, erect and dark green leaves
	In case of severe deficiency, apical meristem often dies and tillers develop
Manganese	Plants are pale green to yellow in colour with thin spindly stem
	Young leaves with yellow interveinal chlorosis and red-brown interveinal lesions
Copper	The young leaves and the leaves which are still within the whorl turn pale green in colour
	The whorl of the expanding leaves may remain tightly rolled and become bent to one side
	Young leaves with brown twisted leaf tips
	Stunted plant growth with thin stems and pale green foliage

$15.9 billion annual loss of N fertilizer (Raun and Johnson 1999). The loss of N results from soil denitrification, surface runoff, leaching and volatilization. Continued low NUE in crops could have a drastic impact on land use and food supplies worldwide (Frink et al. 1999). Efficient plants absorb and utilize the nutrients and increase the efficiency of applied fertilizers, reduce cost of inputs and prevent nutrient losses to ecosystems and reduce environmental pollution. The overall NUE of a cropping system can be increased by achieving greater uptake efficiency from applied N inputs, by reducing the amount of N lost from soil inorganic and organic pools or both.

6 Nutrient-Use Efficiency Indices

Nutrient-use efficiency can be expressed in many ways. Prasad (2009) described 4 agronomic indices in relation to nutrient-use efficiency. These are as follows: agronomic efficiency (*AE*), recovery efficiency (*RE*), physiological efficiency (*PE*) and partial factor productivity of fertilizers (*PFPf*). Details of different indices are given in Chap. 1.

7 Factors Affecting NUE in Sorghum

Production practices that lead to affect crop yields will have impact on nutrient-use efficiency. Nutrient requirements and NUE in sorghum vary with soil, climate, cultivar and management practices.

7.1 Soil Factors

Sorghum is grown on diverse range of soils. This range is so wide that some soils are unusually low in certain nutrients or have excessive quantities of certain nutrients. Nutritional stress problems in soils are often related to the type of parent material and the soil-forming processes characteristic of that soil (Dudal 1976; Clark 1982a, b). Acid soils (oxisols, ultisols and some entisols, alfisols and inceptisols) are usually low in exchangeable bases. Acidity increases the solubility of iron, aluminium and manganese, and hence, these elements may reach to the toxic levels. However, acid soils are deficient in phosphorus, calcium, magnesium, molybdenum and zinc (Clark 1982a). Alkaline soils (mollisols, vertisols and some inceptisols) often contain fairly high concentration of salt in the soil profile. These soils are rich in calcium, magnesium and potassium but deficient in sulphur. The deficiency symptoms of iron, zinc and manganese are the most common in sorghum grown on alkaline soils (Tandon and Kanwar 1984). The nutrient-use efficiency in these soils is greatly influenced by the time and method of fertilizer application. High bulk density, poor soil structure and crust formation, low water holding capacity, water logging and poor soil aeration can also reduce NUE.

Soil management practices like crop rotations and intercropping systems that affect the soil carbon balance will also affect the N balance because the C/N ratio of soil organic matter is relatively constant. In such cropping systems, the overall NUE of the cropping system must include changes in the size of the soil organic and inorganic N pools. When soil-N content is increasing, the amount of sequestered N contributes to a higher NUE of the cropping system, and the amount of sequestered N derived from applied N contributes to a higher NUE. Any decrease in soil-N stocks will reduce the NUE.

7.2 Tillage

After harvest, lots of sorghum stubbles are left in/on the soil. Decomposition of these stubbles prior to planting the next crop is usually desirable. These residues/stalks should be incorporated as soon after harvest as possible. Proper decomposition of residues before planting next crop reduces the problems with tillage and other planting operations. The early decomposition also makes plant nutrients found in residues available for the subsequent crop. Undecomposed stubbles may lead to N immobilization due to high C:N ratio, and N deficiency may occur early in the growth of subsequent crop. A C:N ratio greater than 20 indicates that soil microorganisms feeding on the stubble will require some N from the soil in addition to the

N in stubble for decomposition to occur. The C:N ratio in grain sorghum ranges from 40:1 to 80:1. Nitrogen may be applied to the stubbles to speed up the decomposition and prevent the temporary N deficiency. The amount of N applied usually ranges between 4.5 and 6.8 kg per 450 kg of stubbles produced (Bennett et al. 1990).

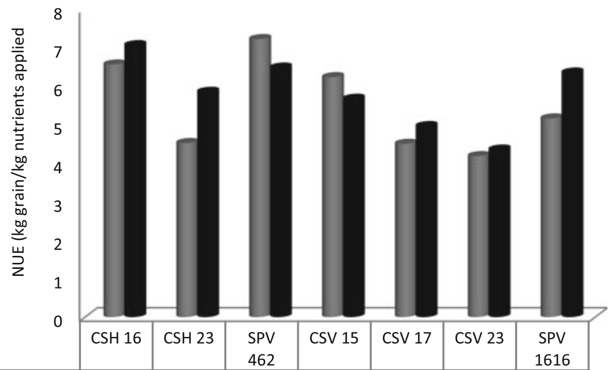
Leaving crop residues on the soil surface is the most cost-effective method of reducing soil erosion. Covering 20 % of the surface with crop residues can reduce soil erosion caused by rainfall and runoff water by 50 % compared to residue-free condition (Shelton et al. 1995). Stubbles also control wind erosion and assists in soil moisture conservation. However, N management becomes even more important in high residue (no-till) farming.

7.3 Climate and Weather Factors

Nutrient availability in soil and the ability of plants to absorb and utilize the nutrients and subsequent yields are greatly influenced by temperature, solar radiation, and rainfall during crop growth (Arkin and Taylor 1981; Baligar and Fageria 1997). The rate of nutrient release from organic and inorganic sources and the uptake by roots and subsequent translocation and utilization in plants is influenced by soil temperature (Cooper 1973). Solar radiation directly affects photosynthesis which in turn influences a plants' demand for nutrients (Baligar et al. 2001). Higher rainfall and humid weather during the growing season favours weed growth and more attack of insect pests and diseases in sorghum, which reduces crop yields and nutrient-use efficiency.

7.4 Cultivars

In semi-arid tropics where sorghum is an important crop, inorganic fertilizer use is limited due to high cost and non-availability and limited soil moisture availability. To reduce the impact of nutrient deficiency on sorghum production, the selection of genotypes that are superior in the utilization of available nutrients either due to enhanced uptake capacity or because of more efficient use of the absorbed nutrients in grain production can be a desirable option. Sorghum cultivars differ in growth, rooting pattern, maturity duration, etc., and hence the nutrient uptake pattern and the efficiency are also likely to differ. Exploiting these differences in nutrient demand and efficiency is a possible alternative for reducing the cost and reliance upon fertilizer. Gardner et al. (1994) demonstrated the genetic diversity for N-use efficiency in grain sorghum and concluded that the differences among sorghum cultivars for higher NUE mechanisms were associated with individual morphological, anatomical and biophysical traits, viz. larger canopies comprised of fewer but larger leaves with low N concentration, thicker leaves, larger leaf phloem transactional area, rapid solubilization and remobilization of N from older to younger leaves and lower dark respiration rates. At low N levels (50 kg N/ha), the improved genotype had the highest nitrogen-use efficiency and the commercial hybrid had the lowest. However, at high levels of N (200 kg N/ha), the commercial hybrid showed the highest NUE (Bernal et al. 2002). Landrace cultivars that have adapted to low N environments may possess different stress-coping mechanisms than do domesticated cultivars developed in contemporary breeding programme (Pearson 1985). Indian improved line M35-1 was found superior in NUE among all environments, and the traits related to high NUE included larger canopies comprised of fewer but larger leaves with low N concentration, thicker leaves, larger leaf phloem transactional area, rapid solubilization and remobilization of N from older to younger leaves and lower dark respiration rates (Gardner et al. 1994). The nutrient-use efficiency of rainy season grain sorghum was influenced by nutrient levels. Hybrid sorghum 'CSH 16' had maximum NUE (7.06 kg grain/kg NPK applied) with 150 % RDF (150:60:60 kg NPK/ha) (Fig. 1), but sorghum variety 'SPV 462' recorded maximum NUE (7.22 kg grain/kg NPK applied) at 100 % RDF (80:40:40 kg/ha) (AICSIP 2010–11).



	CSH 16	CSH 23	SPV 462	CSV 15	CSV 17	CSV 23	SPV 1616
Nutrient-use efficiency 100% RDF	6.56	4.52	7.22	6.23	4.5	4.18	5.16
Nutrient-use efficiency 150% RDF	7.06	5.85	6.48	5.67	4.96	4.35	6.35

Fig. 1 NUE of grain sorghum cultivars

7.5 Fertilizer Management

The nutrient-use efficiency is affected by fertilizer dose, sources of nutrients, method and time of application, interaction of different nutrients, soil moisture, mycorrhiza and others. The availability and recovery efficiency are greatly influenced by addition of organic matter, liming, inclusion of legumes in sorghum-based cropping systems and others.

7.5.1 Nitrogen

The availability of nitrogen is a primary factor limiting the growth of sorghum plant. Nitrogen is one of the most abundant mineral nutrients required for sorghum growth. The level of nitrogen fertility has more influence on the growth and yield of grain sorghum than any other single plant nutrient. The amount of fertilizer N required will vary depending on the yield potential of the cultivar and the amount of residual N available in the soil prior to planting. Preplant soil analysis can be very useful in estimating the nitrogen need of the crop. Most of the sorghum-growing soils contain low amount of nitrogen and hence require supplemental nitrogen applied in the form of fertilizer for optimal productivity. The previous studies have shown that most crop plants utilize less than half of nitrogen added to the soil. According to Maiti (1996), only about 50 % of the N applied to soil is taken up and used by plants. The reminder is left for microbial use, leaching, denitrification or incorporated into the organic fractions through immobilization and many other reactions and processes occurring in the soil. It has been estimated that 1.95–3.2 t soil/ha is lost annually due to wind and water erosion in sorghum belt (ICRISAT 1986). This eroded soil carries away precious nutrients and reduces topsoil depth. Alfisols, vertisols and red lateritic soils where sorghum is prominently grown are prone to soil erosion (Sharda and Singh 2003). Therefore, appropriate nutrient management strategies need to be adopted for improving soil health, N-use efficiency and productivity. Vitousek (1982) reported that the nitrogen-use efficiency decreased with increasing nitrogen availability. In sweet sorghum N-use efficiency defined as theoretical ethanol yield per unit of N taken up decreased with increasing total N uptake (Wiedenfeld 1984). Sawargaonkar et al. (2013) observed that in sweet sorghum NUE increased with N application rate up to 90 kg N/ha and then NUE decreased as N application rate increased.

7.5.1.1 Nitrogen Concentration in Plant Tissues

Nitrogen accumulation in sorghum plants usually continued until maturity of the crop (Srivastava and Singh 1971). The young plants accumulate relatively high concentration of N, and the N content decreases in the various plant parts with age. Most of the plant N is absorbed during the vegetative and by early grain filling stages. Singh and Bains (1973) observed a continuous decline

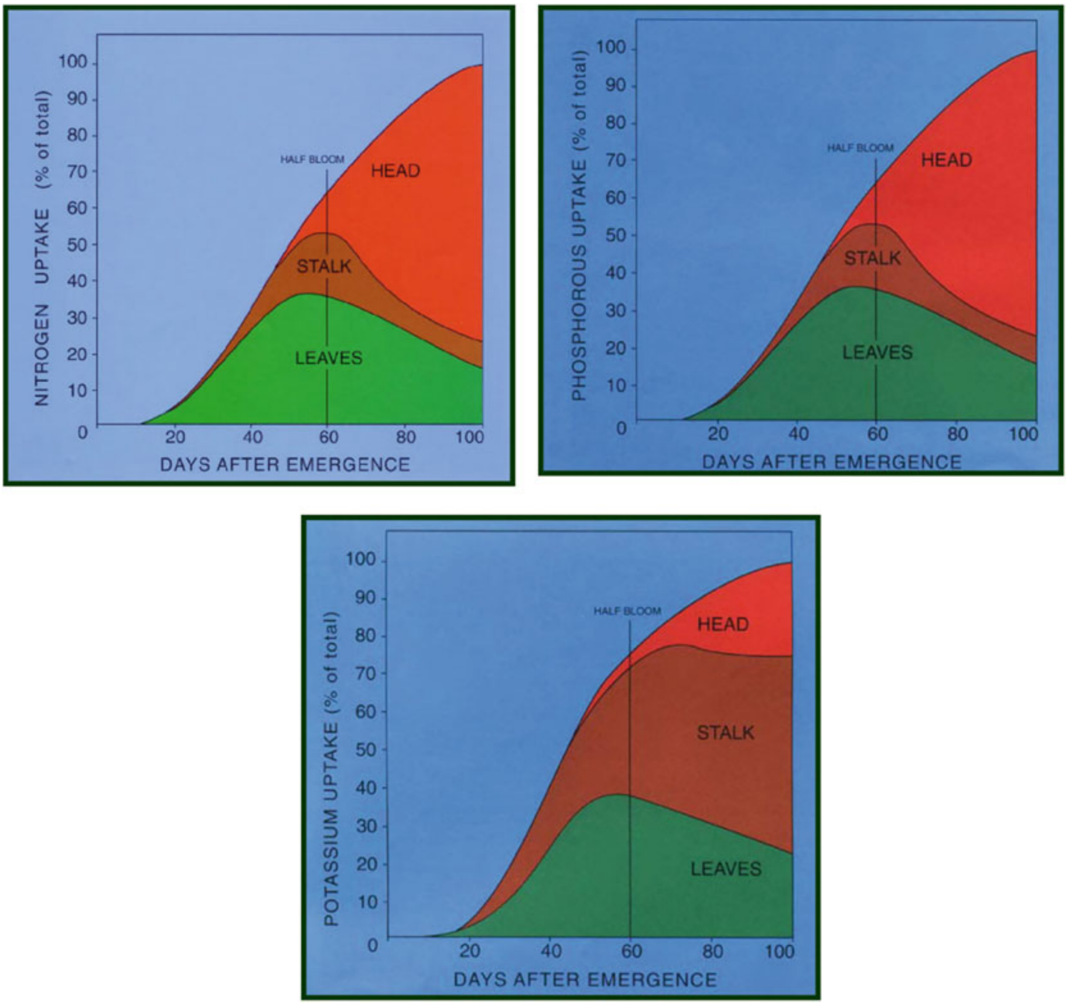


Fig. 2 NPK uptake pattern in grain sorghum (***Source:*** R. L. Vanderlip, *How a Sorghum Plant Develops*, Kansas State University, January 1993. (http://www.nasecoseeds.com/products/sorghum/47.html))

in N content in whole plant tissues until 75 days after planting followed by increased N content up to maturity. This late season increase in N content in whole plant after boot leaf stage was the result of the build-up of N in grains. The N content in plant tissues is influenced by the dose and time of fertilizer application, plant population, variety, irrigation and other management practice. There was a strong association between N content in whole plant at 30 and 60 days after sowing and grain yield (Hariprakash 1979). Jones (1983) reported that the N concentration in sorghum grain ranged from 1.02 to 3.20 % (mean 1.67 %) and in stover 0.36–1.26 % (mean 0.80 %).

7.5.1.2 Nitrogen Uptake

The N-uptake curve is generally similar to sigmoidal growth curve in sorghum (Fig. 2). Nitrogen accumulation rate by the whole plant was usually slower in the early growth stage, became faster in the log phase of crop growth and again slowed down at maturity (Table 3) (Srivastava and Singh 1971). Upon reaching the maximum accumulation in the vegetative plant parts, coinciding mostly with heading stage, nitrogen from vegetative parts starts getting translocated

Table 3 N accumulation rates by sorghum (CSH-1)

Growth stages (days after sowing)	N accumulation rates (mg N/plant/day)
0–30	4.05–5.14
30–45	17.24–21.75
45–60	18.53–23.75
60–75	20.00–21.10
75–90	6.47–6.71
90-full maturity	0.40–2.10

into the panicles (Singh and Bains 1973a, b). More N is translocated from leaves than from stem. Earheads contain the major portion of the N accumulated by the whole plant. Only 12–47 % of applied N is utilized by sorghum (Pal et al. 1982). The recovery of N influenced by the rates and method of N application, soil types, variety, soil moisture and management practices. The results from a study with 15_N labeled urea at ICRISAT, 1982 and 1983, revealed that sorghum recovered 62.5 % of added N in the alfisol and 55.0 % in the vertisol. About 27.1 % of applied N was distributed in the alfisol profile and 38.6 % in the vertisol profile accounting to 89.6 % and 93.6 % N by the soil + crop system. In alfisols crop recovery of N varied from 46.3 to 51.1 % as N levels increased from 40 to 160 kg N/ha. At the highest N level tested, soil + crop system could account for 78.9 % of added N, as compared to 93.2 % at 40 kg N/ha. Although considerable fertilizer N was present in the soil profile after the harvest of rainy season sorghum, this residual N was of limited value either for safflower grown in the post-rainy season or for sorghum grown in the following rainy season (Moraghan et al. 1984). The N response (kg grain/kg nitrogen applied) of rainfed sorghum to optimum or near optimum levels of N during rainy season varied from 21.7 kg in alfisols, 18.32 kg in vertisols 11.9 kg in molisols and 20.15 kg in entisols (Tandon and Kanwar 1984). A significant positive interaction between nitrogen and moisture has been well established in sorghum, and this interaction is stronger in an alfisol than in a vertisol (Kanwar 1978). Nitrogen uptake was also improved by P and Fe fertilization in calcareous soils (Patil 1979).

7.5.1.3 Nitrogen × Moisture Interaction

Moisture availability, moisture use and nutrient supply to the plants are closely interacting factors influencing plant growth and yield production (Viets 1972). There is a significant and positive correlation between fertilizer N and soil moisture for sorghum grain yield. The response was more in alfisols than that of vertisols (Kanwar 1978). Water application in the alfisols probably compensates for it comparatively shallow depth and low moisture storage, as compared with the vertisol. With 58 or 120 kg N/ha, grain yield in nonirrigated vertisol was similar to those in the alfisol irrigated at 50 % moisture depletion (Tandon and Kanwar 1984).

7.5.1.4 Nitrogen × Genotype Interaction

Sorghum genotypes greatly influence the nutrient accumulation in plants due to variation in rate of absorption, translocation and accumulation of nutrients in plant tissues. Genotypic difference in N uptake partitioning and NUE (unit dry matter per unit N in dry matter) has been reported for grain sorghum (Maraanville et al. 2002). The varietal differences for N and P uptake might be due to additive gene action for N and nonadditive for P (Krishna et al. 1985). In general hybrids deplete greater amount of nutrients than that of varieties. Sorghum genotypes vary significantly for various root characteristics which may affect the nutrient uptake (Seetharama et al. 1990). Sorghum genotypes, viz. CSH 1, CSH 5 and CSV 3, were highly responsive to phosphorus (7.8 kg grain/kg P) compared to CSV 5 (3.5 kg grain/kg P) (Krishna 2010). Long-term studies conducted in vertisols indicated that sorghum absorbs mere 5 % of the total N during first 5 weeks followed by rapid N uptake. The crop accumulated 88 kg N/ha in 40–70 days, at the rate of about 3 kg N/ha/day (ICRISAT 1986).

7.5.1.5 N × P Interaction

Long-term studies have indicated positive interaction between N and P in sorghum. The response to N may subside, if sufficient levels of P are not maintained on vertisols and alfisols. The positive N × P interactions have resulted in net advantage of 300–500 kg grains/ha (ICRISAT 1986). N × P interactions may contribute up to 48–50 % of total response of sorghum to nutrient supply (Tiwari 2006).

7.5.2 Phosphorus

Phosphorus is important in plant bioenergetics. As a component of ATP (adenosine triphosphate), phosphorus is needed for the conversion of light energy to chemical energy during photosynthesis. There is widespread deficiency of phosphorus in soils of semi-arid tropics. It is estimated that only about 10 % of the P added to the soil is absorbed by plants and remaining 90 % become unavailable in the soil by adsorption or fixation by various soil fractions. Phosphorus accumulates extensively in the kernels (as phytin). A small fraction (16–22 % of total P uptake) of P is accumulated during early growth of the crop (42 days after sowing) owing to slower accumulation rate, whereas the major portion of the P is accumulated during later stages of crop growth (Roy and Wright 1974).

Phosphorus uptake is enhanced by P fertilization. Excess P can interact with other nutrients (especially, Fe, Zn and Cu) and depress plant growth but causing deficiency of other plant nutrients. The response of phosphorus (kg grain/kg P_2O_5 applied) varies with soil types in order of alfisols (17–32 kg) > entisols (11–34 kg) > vertisols (7–27 kg). In post-rainy crop, a response of 11 kg grain/kg P_2O_5 was obtained in vertisols. Vertisols may require higher P application than other soils because of their high clay content and greater reactive surfaces/components (Rao and Das 1982). On calcareous soils, P uptake by hybrid sorghum was highest when phosphatic fertilizers were applied on the surface, followed by 5 and 10 cm deep placement, but the reverse was the case in non-calcareous soils (Venkatachalam et al. 1969). Apart from soil types, response to P is strongly affected by the yield potential of the cultivars, level of N applied, available soil P and favourable environment. The residual response of P applied to sorghum on succeeding wheat crop is small and not consistent (Tandon and Kanwar 1984). In general, 40–50 kg P_2O_5/ha is recommended for rainfed *kharif* sorghum and 20–30 kg/ha for *rabi* sorghum grown in medium and deep soils. In irrigated *rabi* sorghum, 40–50 kg P_2O_5/ha is recommended.

7.5.3 Potassium

Among the essential plant nutrients, potassium assumes greater significance since it is required in relatively larger quantities by plants. Besides increasing the yield, it largely improves the quality of the crop produce. Potassium regulates the opening and closing of stomata. Since stomata are important in water regulation, adequate potassium content in plants is associated with higher tolerance to drought and higher resistance to frost and salinity damage and resistance to fungal diseases.

Potassium deficiency may not be a serious problem for sorghum in Indian soils. In general, black soils with higher clay and CEC showed high levels of exchangeable K and medium to high non-exchangeable K content; alluvial soils with higher contents of K-rich mica with light texture showed medium in exchangeable K and high in non-exchangeable K content; and red and lateritic soils with kaolinite as a dominant clay mineral and light texture showed low in exchangeable as well as non-exchangeable K content (Srinivasarao et al. 2011). However, recent studies indicated an application of 40–50 kg K_2O/ha in rainfed *kharif* and irrigated *rabi* sorghum.

Similar to N and P, K content in plant tissues also decreases as the crop advances from seedling stage (2.16–2.26 % in the leaves) to maturity (1.33 % in the leaves), and the earheads contain less K than the leaves (Gopalkrishnan 1960). At harvest, the K content in grain declined from 0.41 to 0.39 % and increased in stover from 1.24 to 1.29 % (Venkateswarlu 1973). The potassium accumulated in sorghum plants rapidly during the early growth period and slowly at later stages (Roy and Wright 1974). They further observed that 50–60 % of the total K uptake was completed before heading and around 68–78 % of total K was contained in the vegetative parts and 22–32 % in the heads.

7.5.4 Micronutrients

Among micronutrients, deficiency of zinc is more widespread in sorghum-growing areas. Of the 2,51,660 soil samples analyzed for micronutrients, 49 % were deficient in Zn and 12 % in Fe content (Singh 2001). Most Zn in sorghum is taken by the early grain-fill stage. Next to Zn, iron nutrition to sorghum has importance in some soils. Sorghum is sensitive to iron stress and is less efficient in its absorption and translocation. Since Fe uptake decreases with increased $CaCO_3$ content of the soil, the problem of Fe deficiency is more on calcareous soils. Soils containing more than 1.2 ppm Zn and 3–5 ppm Fe (critical limit for sorghum) did not respond to Zn/Fe application (Tandon and Kanwar 1984). Application of 20 ppm Fe as $FeSO_4$ increased the grain yield by 0.9 t/ha (Babaria and Patel 1981). Koraddi et al. (1969) observed complete recovery from lime-induced chlorosis and obtained higher sorghum yield with spraying of $FeSO_4$. Singh and Vyas (1970) reported 5.1 % and 13.9 % increase in grain yields application of manganese and zinc, respectively, in Jodhpur. Joshi (1956) reported significant increase in yield of sorghum due to $CuSO_4$ application in Maharashtra. Kanwar and Randhawa (1967) observed 35 % and 40 % increase in the yield of sorghum due to application of boron and boron (B) + manganese (Mn). Foliar application of $MnSO_4$ @ 10 kg/ha was found to increase the sorghum grain yield by 24–35 % (Gill and Abichandani 1972). Experiments conducted under All India Coordinated Sorghum Improvement Project (AICSIP) revealed that deficiency of Zn and Fe can be corrected either through soil application of respective sulphate forms or through foliar application (Table 4).

An antagonistic relationship was reported with Fe and Cu, Zn and Mn, whereas Cu showed antagonism with Fe and Zn and synergism with Mn in sorghum shoot (Singh and Yadav 1980)

7.5.5 Biofertilizers

A biofertilizer is a substance which contains living microorganisms which, when applied to seed, plant surfaces or soil, colonizes the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant (Vessey 2003). Biofertilizers add nutrients through nitrogen fixation, solubilizing phosphorus and stimulating plant growth through the synthesis of growth promoting substances. Biofertilizers can be expected to reduce the use of chemical fertilizers and pesticides. Through the use of biofertilizers, healthy plants can be grown while enhancing the sustainability and health of soil. Biofertilizers form an important component in the integrated nutrient management. A number of biofertilizers, *viz. Azotobacter*, *Azospirillum*, vermicompost, etc., are now commercially available for cereals.

Field research on using microorganisms on increasing nutrient-use efficiency was started during 1970s. Various strains of microorganisms like *Azotobacter*, *Azospirillum*, *Phosphobacterin* and *Mycorrhiza* were found promising. Senthil Kumar and Arockiasami (1995) reported that arbuscular mycorrhizas (AM) inoculated sorghum seedlings contained 11.5 mg Zn/g dry root but non-mycorrhizal seedlings had 7.5 mg Zn/g dry root. Sorghum genotypes also vary with regard to AM mycorrhizal colonization in roots and P uptake (Seetharama et al. 1988). The net advantage from AM symbiosis to sorghum seems to be 10–20 kg P/ha (Krishna et al. 1985). Studies conducted at TNAU, Coimbatore, revealed that fertilizer-N application could be reduced by inoculating with *Azospirillum* (TNAU 2003). In sorghum-chickpea system, biofertilizer [*Azospirillum* and phosphate-solubilizing bacteria (PSB)] gave significantly higher grain and fodder yields (Gawai and Pawar 2006).

7.5.6 Method and Time of Fertilizer Application

Nitrogen fertilizers should be applied in a method that ensures a high level of N availability to the crop and high N-use efficiency. It should be placed as close to planting as possible. Fertilizer placement below the soil surface should be more effective than broadcasting or banding on the soil surface, both in ensuring quick

Table 4 Effect of iron and zinc on grain and dry fodder yield of sorghum (AICSIP 2011)

Treatment	Grain yield (kg/ha)					
	Coimbatore	Parbhani	Akola	Dharwad	Surat	Mean
RDF + $ZnSO_4$ 25 Kg (soil application)	1,833	2,737	3,178	2,462	3,045	2,651
RDF + $FeSO_4$ 25 Kg (soil application)	1,502	2,312	3,114	2,862	3,491	2,656
RDF + 0.2 % $ZnSO_4$ foliar spray at 15 and 30 DAS	1,730	2,328	2,609	2,289	2,955	2,382
RDF + 0.5 % $FeSO_4$ foliar spray at 15 and 30 DAS	1,553	2,197	2,525	2,466	3,024	2,353
RDF + $ZnSO_4$ 15 kg (soil application) + 0.20 % as foliar spray at 15 and 30 DAS	1,936	2,662	3,136	2,882	2,826	2,689
RDF + $FeSO_4$ 15 kg (soil application) + 0.50 % as foliar spray at 15 and 30 DAS	1,562	2,009	3,093	2,598	2,971	2,447
RDF + soil application of 15 kg $ZnSO_4$ + 15 kg $FeSO_4$	1,636	2,793	4,798	2,953	3,676	3,171
RDF + foliar application of 0.20 % $ZnSO_4$ + 0.50 % $FeSO_4$	1,698	2,036	2,925	3,184	3,367	2,642
RDF (80:40:40 kg NPK/ha) alone	1,438	1,847	2,883	2,939	2,868	2,395
Mean	1,567	2,252	3,072	2,509	3,028	2,486
C.D. (P = 0.05)	160	437	643	355	228	482
CV%	5.94	11.3	12.2	8.24	4.38	15.1

RDF: Recommended Dose of Fertilizers
Source: (AICSIP 2010–2011)

availability and in enhancing N-use efficiency. In no-till grain sorghum, Lamonds et al. (1991) reported higher yields with knifed UAN (urea-ammonium nitrate) than broadcast. Placement of urea or diammonium phosphate with or near the seed is not recommended due to the risk of seedling injury due to ammonia toxicity. Nitrogen utilization by sorghum plant is quite rapid after the plant reaches to five-leaf stage, with 65–70 % of the total N accumulated by the bloom stage of growth (Cothren et al. 2000). Apparent N recovery was also markedly improves when N is applied in 2 or 3 splits in a high rainfall year (Venkateswarlu et al. 1978). Sorghum yields are adversely affected if the dose of N at planting is either reduced to less than 50 % of the total dose or the top dressing is delayed beyond the flower primordia initiation stage (Tandon and Kanwar 1984). Application of half amount of N at planting and half at 30 days after sowing produced significantly higher yields of hybrid sorghum (Lingegowda et al. 1971; Sharma and Singh 1974; Turkhede and Prasad 1978). However, in light soils and in high rainfall areas, three splits of N fertilizer, 50 % at sowing, 25 % at floral primordial initiation and 25 % at flowering, has been found beneficial (Choudhary 1978). In heavy black soils of Maharashtra, Bodade (1964, 1966) concluded that the application of 50 % N through foliar application was as effective as the full dose of N through soil application. Choudhary (1978) recommended 2 equal splits of N for foliage application: first at floral primordial initiation and second at mid-bloom stage of crop. Narayana Reddy et al. (1972) reported 6 % concentration of urea solution as the best for foliar spray. It is generally recommended that all phosphatic and potassium fertilizers should be applied as basal and deep placed.

7.5.7 Integrated Nutrients Management (INM)

Continuous application of only mineral fertilizer ultimately results in yield declines. However, with a combination of mineral and organic sources of nutrients yield levels can be maintained (Bationo and Buerkert 2001). It is widely accepted that addition of organic is essential to maintain soil health. Importance of the use of organic sources of nutrients along with chemical fertilizers for maintaining soil health has been emphasized by Katyal (2000). The use of chemical fertilizer or biofertilizer has advantages and disadvantages in the context of nutrient supply, crop growth and environmental quality. The advantages need to be integrated in order to make optimum use of each of the fertilizers to achieve balanced nutrient management for crop growth (Jen-Hshuan 2006). Combined use of inorganic and organic manures improves physical and chemical properties of soils. At a dose equivalent to 40 kg N/ha, crop yield was better secured with organic N than with urea N. Combining organic and mineral sources of nutrients do not have only additive effects but real interaction, which significantly affect crop yield and water-use efficiency (Ouedraogo and Mando 2010). Application of sorghum stubbles, sun hemp and *Gliricidia* has recommended dose of fertilizer resulted in maximum response with only 50 % under rainfed condition. Application of 75 % recommended dose of fertilizer (RDF) + farmyard manure (FYM) + biofertilizer [*Azospirillum* and phosphate-solubilizing bacteria (PSB)] gave significantly higher plant height, dry mater, yield attributes and grain and fodder yields of sorghum and was on a par with application of 100 % RDF through inorganics alone showing 25 % saving of nutrients (Gawai and Pawar 2006; Patil et al. 2008). Incorporation of FYM, wheat straw and *Gliricidia* leaves for 25 or 50 % N substitution in conjunction with balanced dose of NPK fertilizers increased infiltration rate, water stable aggregates and organic matter, the values of which ranged from 0.88 to 0.92 cm h^{-1}, 0.82 to 0.96 mm and 1.10–1.27 %, respectively, whereas bulk density decreased from 1.32 to 1.22 Mg m^{-3}. The soil reaction and electrical conductivity remained unaffected while the organic carbon content increased appreciably and ranged from 0.68 to 0.74 %. The available N, P_2O_5 and K_2O status improved after harvest of both the crops due to integrated nutrient management by the application of 50 % recommended dose of fertilizers and 50 % N equivalent with FYM to sorghum in *kharif* and recommended dose of fertilizers to wheat in *rabi* than the continuous application of recommended dose of fertilizers to both the crops (Bhonde and Bhakare 2008). Crop residue recycling is a vital aspect of sorghum cultivation as it reduces run-off induced soil and nutrient loss (Dhruvanarayan and Rambabu 1983). Among the residues, prunings from *Leucaena* and *Gliricidia* enhance carbon sequestration better than cereals residue. Integration of vermicompost at 2 t/ha + 50 % RDF was found on a par with RDF in sorghum – chickpea/field pea/lentil system (AICSIP 2007). Similarly, integration of organic and inorganic sources of N to supplement N requirement of sorghum significantly improved the productivity of succeeding chickpea crop as compared to applying 100 % N through inorganic fertilizer (AICSIP 2014). Minimum tillage with 80:40:40 kg NPK/ha or conventional tillage with 60:30:30 kg NPK/ha, of which 75 % through inorganic + PSB + *Azospirillum* + *dhaincha* incorporation/mulching at 30 DAS were found promising (Mishra et al. 2012a). In *rabi* sorghum, studies were conducted three consecutive years under All India Coordinated Sorghum Improvement Project (AICSIP) to see the effect of INM practices on N-use efficiency. Results revealed that growing cowpea/green gram/*dhaincha* in preceding *kharif* season (Fig. 3) significantly improved the productivity of succeeding *rabi* sorghum and could save 20–40 kg N/ha as compared to *kharif* fallow. Growing short duration legume crops during *kharif* season significantly improved the NPK content (Fig. 4) and population of soil microflora (Table 5).

7.6 Weed Management

Sorghum is grown on marginal lands with poor fertility. Weeds compete with the sorghum for available nutrients and make the crop deprive of the essential nutrients resulting in poor crop growth and lower NUE. Uncontrolled weeds in sorghum removed 29.94–51.05, 5.03–11.58 and 30.38–74.34 kg/ha NPK, respectively, from soil (Satao and Nalamwar 1993; Mishra et al. 2012b). Effective management of weeds is therefore

Fig. 3 Showing the effect of preceding legume crops on succeeding *rabi* sorghum

	Preceding *kharif* crops (Greengram, *Dhaincha*)
	Green manuring with *Dhaincha*
	Succeeding *Rabi* sorghum

very essential for increasing the NUE. Kondap et al. (1985) reported that increasing levels of nitrogen decreased the population of *Cyperus rotundus* and *Panicum emeciforme* in sorghum. This study revealed the possibility of saving 30–90 kg N/ha by adopting either chemical or manual weed control. Okafor and Zitta (1991) observed that reduction in grain yield due to weed competition by 51.0, 37.8 and 32.2 % at zero, 60 and 120 kg N/ha, respectively, indicating that yield reduction due to weeds decreased at higher N levels.

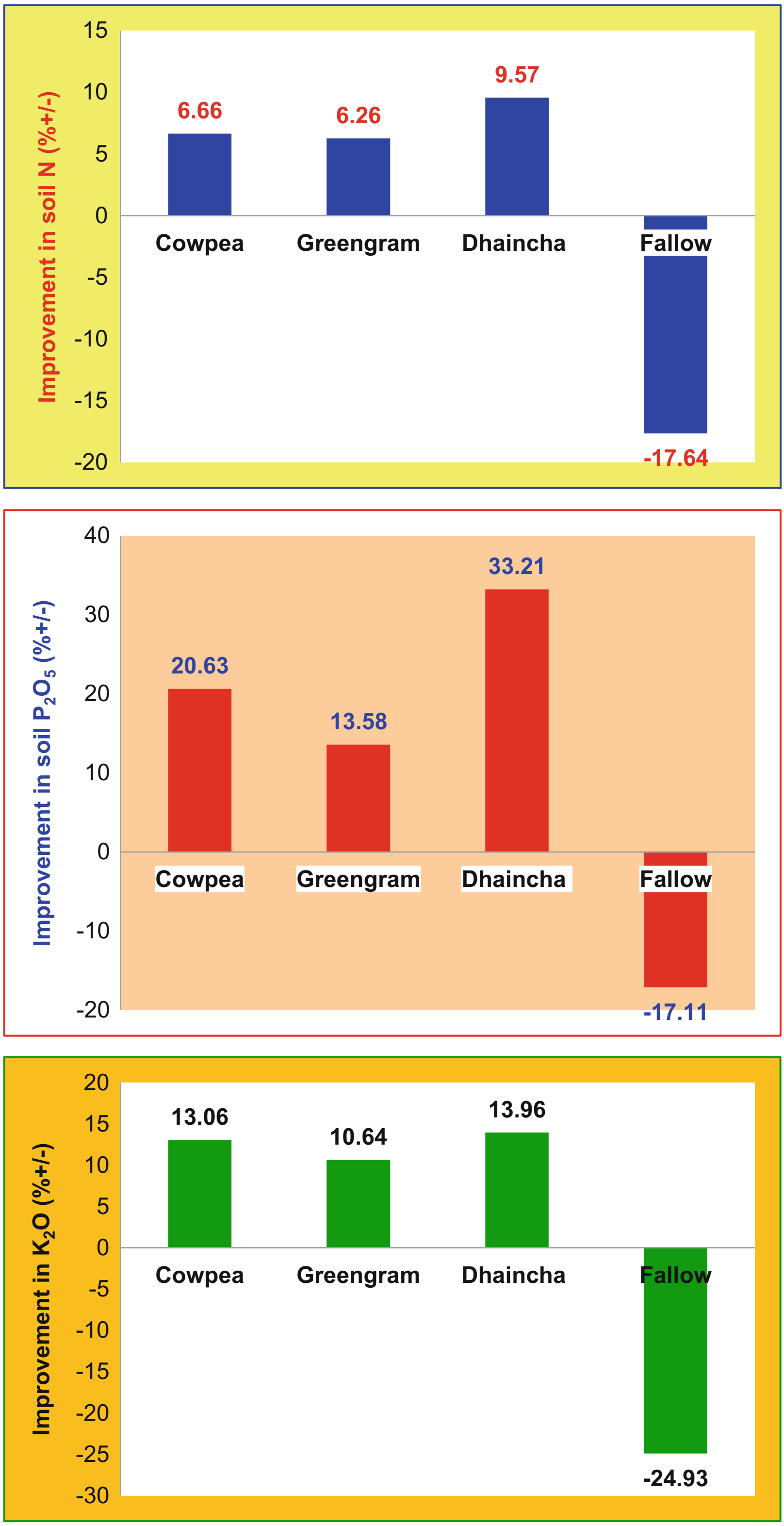


Fig. 4 Changes in nutrient status of soil after 3 years of INM treatment

Table 5 Effect of INM treatments on soil microflora after 3 years (2013–2014)

Treatment	Actenomycetes (10^4 CFU g^{-1} soil)	Bacteria (10^6 CFU g^{-1} soil)	Fungi (10^2 CFU g^{-1} soil)
***Kharif* season (main plots)**			
Cowpea fodder-*rabi* sorghum	216.42	153.17	35.92
Green gram/black gram-*rabi* sorghum	198.50	121.17	36.75
Dhaincha-rabi sorghum	290.83	164.42	46.25
Fallow-*rabi* sorghum	126.92	58.33	31.00
LSD (P = 0.05)	7.92	4.45	4.77
***Rabi* season [N levels (kg/ha)]**			
0	249.33	124.25	47.17
20	226.25	132.25	39.75
40	176.42	118.67	34.67
60	144.67	121.92	28.33
LSD (P = 0.05)	7.59	8.20	4.34
Initial value (2011–2012) before start of the experiment	132	72	47

Conclusion

With the increasing cost of chemical fertilizers and decreasing nutrient-use efficiency, it is very important to find out the solutions to address this problem either through developing nutrient efficient genotypes to effectively utilize supplemental nitrogen added to the soil or through developing alternative crop and soil management practices that will minimize the nutrient loss. Genotypes and management conditions can significantly influence nutrient-use efficiency in sorghum. Post flowering drought-tolerant genotypes have been reported to have improved nitrogen-use efficiency over senescent genotypes. Some plant morphological attributes such as leaf thickness and specific leaf weight have been shown to be positively related to nitrogen-use efficiency. While such information are useful for better targeting the problem in future research, most of the results so far generated are based on a small set of entries with relatively narrow genetic backgrounds. Evaluation of larger set of genotypes representing an array of genetic backgrounds having contrasting characteristics for traits assumed to be related to nitrogen-use efficiency may help generate more robust information.

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