



Nutrient management technologies of millets for higher productivity and nutritional security

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ABSTRACT

Millets are important source of food and livelihood in arid and semi-arid ecologies and covers a significant area in these regions due to their strong abiotic and biotic stress tolerance, particularly their capacity to withstand dry conditions. Since, the grains of these crops have better nutritional qualities compared to other cereals, therefore, to ensure nutritional security in the vulnerable regions, millets can be good option to be included as staple food. The continuous application of high analysis chemical fertilizers without organic manures resulted in reduced water holding capacity, emergence of multi-nutrient deficiencies and consequently lower crop yields. Thus, for long-term ecological and economic sustainability in rainfed millet systems, there is a need to enhance soil organic carbon (SOC) and nutrient buffering capacity of soil by integrated nutrient management through increasing the use of organic sources such as farmyard manures (FYM), biocompost, biofertilizers and legumes inclusion in cropping systems. Efficient nutrient management approaches are among key strategies to realize higher yields in rainfed regions. The systematic information is lacking on nutrient management in different millets, particularly on precision nutrient management. Use of cost effective and locally available organic nutrient sources and biofertilizers in combination with chemical fertilizers, not only enhances yield and soil fertility but also improves grain quality.

Key words: Crop nutrition, Fertilizer, Millets, Nutritional security, Rainfed ecosystems, Sustainability

Millets are small grained cereals, generally termed as “Nutri-cereals” or “Dryland cereals” found to be domesticated around 8000 years ago in the highlands of central China (Amgai *et al.* 2013). In India, different types of millets are grown such as pearl millet, sorghum, finger millet, foxtail millet, proso millet, barnyard millet, kodo millet, and little millet (Table 1). Among these, pearl millet and sorghum have sizeable area under cultivation in the country, whereas the rest of the millets are considered as ‘minor millets’ or ‘small millets’. These crops are well considered as the “Crops of antiquity” mainly due to their inherent drought tolerance capacity and pests and disease resistance mechanism (Devi *et al.* 2014). The grains of these crops have better nutritional qualities compared to other cereals. Millets are good source of Ca, Mg, K, Fe and other micronutrients (Table 2). Millets contains about 10 times more Ca and 2-10 times higher Fe than wheat or rice (Bala *et al.* 2010). The grain protein of these crops is rich in essential amino acids especially sulphur-containing amino acids and phytochemicals such as phytic acid compared to other major cereals. Millets are

gluten-free, thus they could be a good option for patients of celiac diseases. These crops are also beneficial for people suffering from diabetic and cardiac diseases (Coulibaly *et al.* 2011). Since, the malnutrition is a serious emerging threat affects billions of people at global level. At present, approximately 1.9 billion adults are overweight or obese and 462 million are underweight. In India also malnutrition is an acute trouble (WHO 2018). Therefore, to tackle the threats of malnutrition and hidden hunger, inclusion of these nutrient rich crops in staple diet could be a better nutritional security option (Rana *et al.* 2012; Nainwal *et al.* 2018).

On the other hand, cultivation of millets is no longer a priority of Indian farmers, as the area under millets in India have witnessed a significant decline during past 4-5 decades (Table 3). One of the biggest reasons of poor adoption of millets by the cultivators is the low level of productivity of these crops (Bana *et al.* 2013) and consequently poor economic returns. Nutrient and moisture stresses are considered as the greatest constraints in millet productivity (Bana 2014; Bana *et al.* 2018; Mubeena *et al.* 2019). These crops are mainly being cultivated (91%) in rainfed regions and the average crop yield levels of these agro-ecologies are 3 to 4 folds lower than the potential. Therefore, to make millet cultivation remunerative, it is important to achieve the higher productivity of these crops. Efficient nutrient management approaches are among key strategies to realize higher millet yields in rainfed regions (Bamboriya *et al.*

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Table 1 General information of millets

Crop	Scientific name	Place of origin	Major growing states in India
Pearl millet	<i>Pennisetum glaucum</i>	Africa	Rajasthan, Maharashtra, Uttar Pradesh, Haryana and Gujarat
Sorghum	<i>Sorghum bicolor</i>	North eastern Africa	Maharashtra, Karnataka, Madhya Pradesh, Andhra Pradesh, Gujarat, Rajasthan, Uttar Pradesh and Tamil Nadu
Ragi (Finger millet)	<i>Eleusine coracana</i>	East Africa	Madhya Pradesh, Maharashtra, Orissa, Uttarakhand, Uttar Pradesh and Tamil Nadu
Foxtail/Italian millet/ Kauni	<i>Setaria italica</i>	Central Asia-India	Karnataka, Rajasthan, Madhya Pradesh and Chattisgarh
Proso or common millet (Cheena)	<i>Panicum miliaceum</i>	Central Asia-India	Bihar, North-east India and Maharashtra
Indian barnyard millet (Sawan)	<i>Echinochloa frumentacea</i>	India	Karnataka, Madhya Pradesh, Uttarakhand, Uttar Pradesh and North-east India
Kodo millet	<i>Paspalum scrobiculatum</i>	India	Maharashtra, Tamil Nadu and Chattisgarh
Little millet/Kutki	<i>Panicum sumatrense</i>	India	Karnataka, Madhya Pradesh, Andhra Pradesh, Tamil Nadu, Jharkhand, Odisha, Maharashtra and Chattisgarh

Table 2 Nutritional value of millets (Per 100 g)

Crop	Protein (g)	Carbo-hydrate (g)	Fat (g)	Crude (g)	Mineral (g)	Ca (mg)	P (mg)	Fe (mg)	Zn (mg)
Pearl millet	11.6	67.5	5.0	1.2	2.3	42	296	10.3	3.10
Sorghum	10.4	72.6	1.9	1.6	1.6	25	222	5.29	3.01
Finger millet	7.3	72.0	1.3	3.6	2.7	344	283	4.27	36.6
Proso millet	12.5	70.4	1.1	2.2	1.9	14	206	2.2	4.3
Foxtail millet	12.3	60.9	4.3	8.0	3.3	31	290	3.5	60.6
Kodo millet	8.3	65.9	1.4	9.0	2.6	27	188	3.17	32.7
Little millet	8.7	75.7	5.3	8.6	1.7	17	220	9.3	3.5
Barnyard millet	11.6	74.3	5.8	14.7	4.7	14	121	17.47	57.45

Source: National Academy of Agricultural Sciences, New Delhi (2018)

Table 3 Area, production and yield of millets over the years in India

Year	Pearl millet			Sorghum			Minor millets		
	Area (mha)	Production (mt)	Yield (kg ha ⁻¹)	Area (mha)	Production (mt)	Yield (kg ha ⁻¹)	Area (mha)	Production (mt)	Yield (kg ha ⁻¹)
1950	9.02	2.60	288	15.57	5.50	353	7564	3782	1114
1960	11.47	3.28	286	18.41	9.81	533	7232	3077	1147
1970	12.91	8.03	622	17.37	8.11	466	6931	3972	1297
1980	11.66	5.34	458	15.81	10.43	660	5933	4003	1455
1990	10.48	6.89	658	14.36	11.68	814	3841	3362	1770
2000	9.83	6.76	688	9.86	7.53	764	2736	2598	1766
2010	9.61	10.37	1079	7.38	7.00	949	2320	2443	1951
2018	7.38	9.13	1237	4.96	4.95	998	1864	2292	2207

Source: Government of India, 2018. (Agricultural statistics at a glance, Directorate of Economics and Statistics, 2018) and AICRPSM, 2020, ICAR-All India Coordinated Research Project on Small Millets, Bengaluru

2017a; Bana *et al.* 2016). There is no systematic information available on nutrient management in different millet crops. Therefore, an attempt has been made in the present paper to scientifically compile the current status and constraints in millet production and the available knowledge on approaches of millet nutrition to enhance productivity and grain quality of these cereals in Indian context.

Status of millet cultivation and major constraints of millet production in India

Millets and particularly small millets are in a position of adversity in India. India has the 3rd largest area under cultivation of small millets in the world. Since 1950 to 2018, the area under pearl millet declined from 9.02 mha to 7.38 mha, in sorghum it came down from 15.57 mha to 4.96 mha, whereas in small millets the area under cultivation came down from 7.56 mha to 1.86 mha (GOI 2018; AICRPSM 2020) (Table 3). Contrarily, the total production of pearl millet has increased from 2.60 mt to 9.13 mt. Whereas, in sorghum and minor millets, total production has seen a decrease from 5.50 mt to 4.95 mt and 3.78 mt to 2.29 mt, respectively (Table 3) (GOI 2018; AICRPSM 2020). Rajasthan is the leading state in both area and production for pearl millet (Table 4), Karnataka leads in minor millets acreage and production (Table 6), whereas Maharashtra has the highest area and production for sorghum (Table 5) (GOI 2018).

As most of the millets are being cultivated in arid and semi-arid ecologies, without any assured supply of irrigation water, therefore environmental and weather-related factors are the biggest limitation in the millet production in India (Bana *et al.* 2013). Inadequate and uneven distribution of rainfall, late onset and early cessation of monsoon rains, prolonged dry spells during the crop growing season and excessive evaporation are some paramount factors which affects millet productivity adversely (Bana *et al.* 2013; Dass *et al.* 2014). Improper varietal selection, poor crop

Table 4 State-wise area, production and yield of pearl millet in India

State	Pearl millet				
	Area (mha)	Area (% to all India)	Production (mt)	Production (% to all India)	Yield (kg ha ⁻¹)
Rajasthan	4.24	57.4	3.75	41.1	886
Uttar Pradesh	0.93	12.5	1.80	19.7	1941
Gujarat	0.40	5.4	0.92	10.0	2312
Madhya Pradesh	0.31	4.2	0.76	8.3	2435
Haryana	0.45	6.1	0.72	7.9	1602
Maharashtra	0.68	9.2	0.61	6.7	903
Karnataka	0.23	3.1	0.29	3.2	1241
Others	0.15	2.1	0.29	3.2	-
All India	7.38	100	9.13	100	1237

Source: Government of India, 2018. (Agricultural statistics at a glance, Directorate of Economics and Statistics, 2018)

Table 5 State-wise area, production and yield of sorghum in India

State	Sorghum				
	Area (mha)	Area (% to all India)	Production (mt)	Production (% to all India)	Yield (kg ha ⁻¹)
Maharashtra	2.17	43.7	1.81	36.5	833
Karnataka	1.09	21.9	1.13	22.9	1040
Madhya Pradesh	0.27	5.4	0.57	11.5	2112
Tamil Nadu	0.39	7.8	0.42	8.5	1089
Andhra Pradesh	0.14	2.8	0.30	6.1	2150
Rajasthan	0.52	10.4	0.30	6.1	583
Uttar Pradesh	0.17	3.4	0.22	4.3	1272
Gujarat	0.09	1.8	0.09	1.9	1022
Others	0.13	2.7	0.11	2.3	-
All India	4.96	100	4.95	100	998

Source: Government of India, 2018. (Agricultural statistics at a glance, Directorate of Economics and Statistics, 2018)

Table 6 State-wise area, production and yield of minor millets in India

States/UTs	Area (000' ha)	Production (000' t)	Yield (kg ha ⁻¹)
Karnataka	733	1198	2042
Madhya Pradesh	181	74.3	1407
Maharashtra	168	124	1419
Uttarakhand	166	225.2	2661
Tamil Nadu	121.3	307.6	4177
Chattisgarh	101.7	16.3	2058
Odisha	71.1	41.0	1121
Andhra Pradesh	51	83	2024
Gujarat	37.0	35.0	1900
Arunachal Pradesh	27.5	27.6	1002
Jharkhand	14.3	9.2	644
Rajasthan	13.9	6.7	482
West Bengal	13.3	14.2	1869
Nagaland	9.0	10.1	2092
Bihar	8.7	11.2	2185
Uttar Pradesh	8.0	5.0	625
Assam	6.6	4.4	674
Sikkim	6.5	6.5	2022
Himachal Pradesh	6.1	4.9	1755
Jammu & Kashmir	5.9	2.3	395
Meghalaya	2.9	2.8	950
Others	2.1	2.8	-
India	1864	2292	2207

Source: AICRPSM, 2020, ICAR-All India Coordinated Research project on Small Millets, Bengaluru and Government of India, 2018. (Agricultural statistics at a glance, Directorate of Economics and Statistics, 2018)

establishment, weeds and several biotic stresses also influences the millet yield negatively. In addition, soil and land related constraints such as poor soil organic matter content, low moisture retention, macro and micronutrients deficiencies, alkalinity and undulated topography in the millet growing region of India makes millet cultivation and nutrient management in millets challenging (Venugopal *et al.* 2015).

Nutrient management in millets

To obtain a good yield, recommended dose of fertilizer (RDF) for sorghum is 80-100:40-50:40::N:P₂O₅:K₂O kg ha⁻¹. To match the crop N demands, the N fertilizers are applied in 2-3 splits. Nutrilization by sorghum crop increases rapidly after crop reaches five leaf stages, whereas P and K nutrients are required throughout the crop growth period. Moreover, N is prone to volatilization, denitrification and leaching losses. Therefore, half dose of N and full dose of P and K are recommended to be applied at planting and placed below the seed. Remaining N in sorghum is applied at 35 days after sowing (DAS) as side dressing (Cothren *et al.* 2000). For pearl millet RDF is 60-100:40-50:40-50::N:P₂O₅:K₂O kg ha⁻¹ wherein half dose of N and full doses of P and K are placed below the seed at planting time. Remaining N is recommended at 25-30 days after sowing (DAS) as side dressing (Cothren *et al.* 2000). In finger millet the general RDF 40-60:20:20::N:P₂O₅:K₂O kg ha⁻¹ where N is applied in two splits, first as basal placement along with full doses of P and K, and second split is applied as side dressing at late tillering stage. Other millets well respond at moderate application of nitrogen and phosphorus RDF (40:20:00::N:P₂O₅:K₂O kg ha⁻¹) and response to K has not been observed (Prakash *et al.* 2008). Generally, as compared to irrigated crops, almost half doses of fertilizers are applied for rainfed crops (Rana and Bana 2012). Likewise, nutrient requirement depends on various other factors like soil type, cultivar, source of nutrients etc. Research information and region-wise general recommendation of fertilizer doses in millets are available but information on precision nutrient management on localized basis is lacking for most of the millet growing zones of India.

EFFECT OF DIFFERENT SOURCES OF NUTRIENTS ON MILLETS

Effect of different types of compost

Various field studies were carried out on application of compost in millets and their beneficial effect on crop and improvement in soil microbial activity, moderation of soil temperature and increase in water holding capacity. Bana *et al.* (2012) in a field experiment on sandy loam soils of New Delhi observed that vermicompost @10 t ha⁻¹ along with *Azospirillum* and PSB, biofertilizer treatment enhanced the crop growth and yield of pearl millet by 35-43% as compared to control. Application of vermicompost supplied all essential nutrients higher than other organic sources and secondly, vermicompost had incorporated some earthworms

in the field which helped in improving the physical conditions of the soil thus increasing aeration for root development and more availability of nutrients. Vermicompost also improved soil physical, chemical and biological properties of soil and improved the grain yield (2.04 t ha⁻¹) as compared to control (1.40 t ha⁻¹). This improved growth of pearl millet by vermicompost along with biofertilizer treatment increase the dry matter accumulation (58.63 g plant⁻¹) than control (39.79 g plant⁻¹), test weight increased from 6.26 g to 6.46g was also attributed by the increased uptake of nitrogen and phosphorus to the pearl millet crop due to the use of *Azospirillum* and PSB. In addition of increased nutrient availability in soil, *Azospirillum* and PSB also affected the plant growth through the production of growth hormones like IAA, GA and Cytokinin. The superiority the organics might be due to increased photosynthetic activity of pearl millet resulted in higher accumulation of photosynthates. Earhead length (cm) and no. of tillers of pearl millet increased from 23.3 to 30.4 cm and 17.3 to 25.0 tillers m⁻¹ row length, respectively. Further, these have translocated to sink due to better development of source-sink channel resulting in to improved grain protein and nutrient content (nitrogen 1.61% to 1.92%) of pearl millet (Bana and Gautam 2009).

Higher yield (grain yield 2.40 t ha⁻¹ and stover yield 4.73 t ha⁻¹) and better quality of finger millet was recorded with 75% RDN (40 kg N ha⁻¹) + 25% N poultry manure and 100% RDF (40:20:20::N:P₂O₅:K₂O kg ha⁻¹) over control (grain yield 1.58 t ha⁻¹ and stover yield 3.40 t ha⁻¹) which was increased 48.4% and 47.7%, respectively (Pallavi *et al.* 2016). The combined use of organic and inorganic sources has good effect on physiological process of plant metabolism and growth, leading to higher yield. The better availability of nitrogen due to mineralization of organics thereby influence the shoot and root growth favoring absorption of other nutrients also (Basavaraju and Purushotham 2009).

Bana *et al.* (2016) in an experiment at New Delhi observed that application of leaf compost (LC) @10 t ha⁻¹ resulted in improved plant growth, higher Fe, Zn and protein content in grain and enhanced yield of pearl millet (3.11 t ha⁻¹), followed by FYM @ 10 t ha⁻¹, leaf compost mixed cow dung compost (10 t ha⁻¹) and 100% RDF, respectively. The pearl millet grain yield improvement with LC and FYM were 40% and 38.3% over control; and 10.7% and 9.3%, respectively, over 100% RDF. Organic sources resulted in balanced supply of macro and micronutrients improving biochemical properties of the soil, improve the water holding capacity, thereby reduced moisture stress in plant tissues sufficient enough to be regulated optimum photosynthetic activity for greater accumulation of photosynthates and maintaining cordial source-sink relationships (Choudhary and Suri 2014).

Thesiya *et al.* (2019) also found that yield attributes and yield of little millet were significantly higher with application of 100% RDF (40:20:00:: N: P₂O₅: K₂O kg ha⁻¹) resulting in grain yield of 2.05 t ha⁻¹ and stover yield 5.85 t ha⁻¹ which remained at par with 75% RDN through chemical fertilizer + 25% RDN through vermicompost (grain yield 1.94 t ha⁻¹

and stover yield 5.63 t ha⁻¹). Adequate availability of NPK in soil solution improved root growth, thereby increasing uptake of nutrients. Higher yield due to combined application of chemical fertilizers and organic manures might have attributed to sustained nutrient supply and also as a result of better utilization of applied nutrients through improved micro environmental conditions, especially the activities of soil microorganisms (Chaudhari *et al.* 2011)

Effect of NPK

Raundal and Patil (2017) observed that highest yield of little millet (grain yield 1.34 t ha⁻¹ and stover yield 1.61 t ha⁻¹) was recorded with 150% RDF which was on par with 125% RDF and significantly superior over 100% RDF (40:20:00:: N: P₂O₅: K₂O kg ha⁻¹). Tillers per plant were higher due to luxuriant availability of nutrients for growth and development of auxiliary buds from which tillers are emerged. The panicle length increased with 150% RDF (23.87 cm) as compared to 100% RDF (19.21 cm) due to availability of nitrogen and phosphorus to plants resulted in higher accumulation of photosynthetic assimilates might be responsible for higher length of panicle. The test weight increased with 150% RDF (2.63 g) as compared to other treatment (2.01 g) due to better source-sink relationship. The grain yield increased due to high chlorophyll synthesis and dehydrogenase activity, also it affects source-sink relationship which reflects in higher yields. The straw yield increased due to better root activity and high physiological activities (Anonymous 2015).

Mubeena *et al.* (2019) found that the application of 100% RDF (60:30:20::N: P₂O₅: K₂O kg ha⁻¹) recorded significantly higher yield of foxtail millet (2.14 t ha⁻¹) and it was on par with 125% RDF. Better availability of nitrogen and phosphorus results in higher yield of foxtail millet. Nitrogen and phosphorus having beneficial effects of on growth and yield contributing characters like number of tillers, dry matter production, ear head weight and ear head length. Application of RDF increased the concentration of nutrient ions in the soil solution and availability of sufficient nutrients might have helped in higher nutrient uptake (Nigade and More 2013).

Effect of combined application of organics + NPK

Many significant studies have been conducted to analyze the effect of farmyard manure applied with RDF on growth and yield of millets. Generally, application of FYM + NPK fertilizer increased the yield of millets and soil fertility. Govindappa *et al.* (2009) studied that application of FYM (7.5 t ha⁻¹) applied with the recommended dose of NPK improved the dry matter production, grain weight, grain yield and straw yield of finger millet. Venugopal *et al.* (2015) studied that integrated nutrient management practice by applying optimum NPK fertilizers along with FYM (NPK+FYM) or crop residues (NPK+CR) increased the sorghum yield (grain yield 3.26 t ha⁻¹ and stover yield 3.37 t ha⁻¹) significantly over application of only 100% NPK fertilizers (grain yield 2.57 t ha⁻¹ and stover yield

3.08 t ha⁻¹). Super optimal dose of fertilizers (50% NPK) did not increase the yield. Continuous application of only nitrogen resulted in reduced yields due to the imbalanced fertilizer use (Srilatha *et al.* 2014).

Ojha *et al.* (2018) found that the highest yield of foxtail millet (2.46 t ha⁻¹) was obtained from FYM @6 t ha⁻¹ + 60:30:20 kg NPK/ha which was statistically at par with 60:30:20 kg NPK ha⁻¹. The higher grain yield could be attributed to the favorable effect of more tillers, increased panicle length, more number of grains per panicle and higher test weight. The balanced supply of FYM and NPK had increased the growth parameters, yield attributing characters which ultimately contributed to increase in yields. Nitrogen nutrition increased LAI, chlorophyll content and nutrient uptake. Phosphorus supply increases cytokinin synthesis and supply of photosynthates for flower formation. Ultimately it increases the grain yield. The application of P in combination with N contributed to translocation of dry matter and physiological attributes towards yield (Sarita and Singh 2016).

Kumara *et al.* (2014) reported that finger millet-groundnut rotation gives higher yield with NPK + FYM treatment (3.95 t ha⁻¹) compared to the recommended NPK (2.57 t ha⁻¹). Finger millet monocropping under rainfed conditions resulted in higher grain yield of 3.28 t ha⁻¹ and sustainable yield index with integrated nutrient management (INM) (FYM at 10 t ha⁻¹ + 100% NPK) than recommended NPK (Sankar *et al.* 2011). Under finger millet-pigeon pea rotation, INM resulted in better yield (2.66 t ha⁻¹) with a 29% increase compared to 100% N supply through urea (2.06 t ha⁻¹) as well as INM improves tiller number (5.8 vs. 4.9 plant⁻¹). The response of application may be attributed to the better nutrient availability and its favorable effect on soil physical and biological properties, resulting in higher yields (Pushpa *et al.* 2013).

Effects of biofertilizers

Kumar and Gautam (2004) conducted a field experiment at dryland research farm of New Delhi, India. Study showed that the application of FYM@5 t ha⁻¹ + biofertilizer (*Azospirillum* and PSB) + 60 kg N ha⁻¹ brought out a significant variation in growth and yield of pearl millet (grain yield 3.0 t ha⁻¹ and stover yield 10.22 t ha⁻¹). Organic sources improved soil properties and thus overall vegetative growth of the crop. N is the structural component of protein and thus has a positive correlation with N content in grain. *Azospirillum* and PSB also affected the plant growth through the production of growth hormones like IAA, GA and Cytokinin (Gautam 2000).

Prabudoss *et al.* (2014) reported that among the various treatments, application of 125% RDF (55:27.5:0 kg NPK ha⁻¹) + soil application of *Azospirillum*@ 2 kg ha⁻¹ + vermicompost @2 t ha⁻¹ + foliar application of 1% polyfeed (micronutrient fertilizer) at tillering and flowering significantly increased yield of transplanted kodo millet (grain yield 3.86 t ha⁻¹ and stover yield 8.84 t ha⁻¹). The yield attributes have contributed to increased yield potential of the

crop by improved plant growth, translocation, assimilation and storage of photosynthates from source to sink might have resulted in higher grain and straw yield. The higher level of N and P resulted in the significant increase in yield. Vermicompost contains macro and micronutrients which might have influenced the grain yield. In respect of *Azospirillum* inoculated treatments, a well-developed root system coupled with increased availability of nutrients could have promoted greater uptake of nutrients resulting in higher grain yield, likewise, Polyfeed contains micronutrients which might have influenced the grain yield (Salem *et al.* 2011).

Nemade *et al.* (2017) while working on sorghum-chickpea cropping system observed that yield of sorghum (grain yield 3.16 t ha⁻¹ and stover yield 13.15 t ha⁻¹) significantly increased with the application of 75% RDN through inorganic fertilizer+25% RDN through FYM+ seed treatment with microbial fertilizers PSB+ *Azospirillum*. However, it was at par with 75% RDN through inorganic fertilizer+25% RDN through vermicompost+ seed treatment with microbial fertilizers PSB+ *Azospirillum*. The response of application may be attributed to the better nutrient availability and its favorable effect on soil properties, resulting in higher yields (Wu and Ma 2015).

Roy *et al.* (2018) observed that grain and straw yield of finger millet significantly differed with varying level of inorganic fertilizers in association with FYM and biofertilizers over control. Maximum grain yield (3.77 t ha⁻¹) and straw yield (6.98 t ha⁻¹) was recorded with FYM (10 t ha⁻¹) + Biofertilizers (*Azospirillum brasilense* + *Bacillus* spp. + *Pseudomonas fluorescens* @20 g kg⁻¹ seed each) + ZnSO₄ (12.5 kg ha⁻¹) + Borax (5 kg ha⁻¹) + 75% RDF treatment. Organic manure improved environment for microorganism, i.e. *Azospirillum* which fixes atmospheric nitrogen available to plants. Also, PSB is one of the most important nutrient solubilizing microorganisms, which convert insoluble phosphate into soluble forms by secreting several organic acids, resulting into better crop growth and development (Khan *et al.* 2012).

Effect of foliar nutrition of micronutrients

Rani *et al.* (2017) at Andhra Pradesh found that the growth characters and yield attributes of finger millet were significantly influenced with different nutrient management practices. They found that highest yield (grain yield 3.37 t ha⁻¹ and stover yield 7.81 t ha⁻¹) was observed with 150% RDF + ZnSO₄ 0.5% foliar spray + FeSO₄ 0.2% foliar spray which was however on par with 150% RDF + ZnSO₄ soil application + FeSO₄ 0.2% foliar spray as well as 150% RDF and these were significantly better compared to all the other treatments. Zong *et al.* (2011) showed that foliar application of Zn @ 1.5 kg of ZnSO₄·7H₂O ha⁻¹ resulted in 5.54% improvement in yield of pearl millet as compared to control. It could be due to important role played by Fe in maintenance and synthesis of chlorophyll in plants and Zn in synthesis of IAA, metabolism of gibberellic acid and synthesis of RNA (Rurinda *et al.* 2014). Suruthi *et al.* (2019) reported application of integrated (RDF + organic

+ foliar spray of 0.5% ZnSO₄ + 1% Urea) nutrition gives significantly highest plant height of barnyard millet (173.82 cm), dry matter production (270.39 g plant⁻¹), leaf area index (13.72), number of productive tillers (7.4 tillers plant⁻¹) and seed yield per plant (18.9 g). This might be owing to effective absorption and translocation of both macro and micro nutrients to the developing panicle as a result of foliar application at critical stages of the barnyard millet.

Site specific nutrient management (SSNM) or precision nutrient management approaches

SSNM is based on need of crops for nutrients and identify the inherent spatial variability which helps to improve the crop productivity, profitability and nutrient use efficiency. Plant analysis-based SSNM considering crop demand using several modern gadgets like green seeker, chlorophyll meter (SPAD) or leaf color chart (LCC) helps in nitrogen scheduling in cereal crops. Soil-cum-plant analysis based SSNM on the basis of availability of nutrient in soil, plant demand for a higher target yield (not <80% of Y_{max}), and apparent recovery efficiency of applied nutrients can also be good tools for precision nutrient management in millets. Computer-based decision support tool for nutrient recommendations for an individual farmer field are now becoming popular in rice, wheat and maize. All these approaches help to efficient utilization of nutrients by crop plants and increase crop yields by >15%. In Indian context, systematic studies and information in millets on many of these aspects is not available.

Future prospects

Based on above, we can conclude that less research attention has been given towards nutrient management in millets as compared to rice, wheat and maize. The research focus has remained on doses and time of application of various nutrient sources. Therefore, precise management of individual nutrients or an integrated nutrient management approach emerges as the good potential to reduce the yield gap between potential and actual yield of millets. It is evident that most of the soils under millet growing areas have medium to low soil N availability. Thus, N management research orientation should be towards higher N fertilizer recovery, improved N use efficiency, use of modern gadgets for precision N management and developing new N management protocols for changing climatic and socio-economic conditions. Availability of phosphorus to plants mainly depends on soil pH (optimum pH of 6.5) and moisture availability. As majority of Indian millet tract falls in low rainfall areas, where soils are alkaline in nature with low moisture retention capacity. Thus, low phosphorus availability for plant uptake is a serious constraint in millets. Therefore, research should focus on how to maintain favorable soil pH, P solubility in soils using various mycorrhizal interactions, P solubilizing bacteria while maintaining optimal soil moisture using bioresources and modern era polymers. Likewise, due to lack of K fertilizer application methods and improper management of crop residues, the soil K content has seen a

declining trend in recent decades. Therefore, designing K management protocols for higher fertilizer K use efficiency in cropping system mode and its effect on crop stress tolerance may be a good future work. Likewise, among micronutrients, most of studies in millets have been conducted on Zn and B only. It is needed to evaluate the other micronutrients (Fe, Mn, Cu, Mo) responses through seed treatments and foliar nutrition options.

A significant research should be conducted to evaluate alternative sources of organic matter and need to explore different locally available organic manures and amendments to sustain soil health. Different microbial bio-fertilizer can be used in millet such as *Azospirillum*, phosphate solubilizing bacteria (PSB), *Trichoderma*, *Bacillus*, vascular arbuscular mycorrhizal fungi (AMF), and plant growth promoting rhizobacteria (PGPR). Incorporation of selected legume crops in cropping system can help in minimizing inorganic fertilizer requirements, addition of soil organic matter, and improvement in overall yield and sustainability of ecosystem.

Conclusions

Millets have potential for tackling the hidden hunger caused by micronutrient deficiencies. These energy rich crops are good source of Ca, Mg, K, Zn, Fe and other micronutrients along with relatively better-quality grain protein. To enhance productivity of millets, efficient crop nutrition among other management strategies could be an option. Balance nutrition involving principles of integrated nutrient management practice by applying organic nutrient sources along with optimum NPK and micronutrients fertilizers increases the millet yield over the application of only fertilizers. Application of NPK and organic manures also improves the grain nutrient and protein content while improving soil health, water holding capacity and root proliferation. Millet nutrition research should be focused to enhance nutrient use efficiency through developing scale-neutral nutrient and moisture smart INM protocols and system-based precision nutrient management using modern gadgets/tools and computer-based models.

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