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Review

A Review of Nutrient Management Studies Involving Finger Millet in the Semi-Arid Tropics of Asia and Africa

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Abstract: Finger millet (*Eleusine coracana* (L.) Gaertn) is a staple food crop grown by subsistence farmers in the semi-arid tropics of South Asia and Africa. It remains highly valued by traditional farmers as it is nutritious, drought tolerant, short duration, and requires low inputs. Its continued propagation may help vulnerable farmers mitigate climate change. Unfortunately, the land area cultivated with this crop has decreased, displaced by maize and rice. Reversing this trend will involve achieving higher yields, including through improvements in crop nutrition. The objective of this paper is to comprehensively review the literature concerning yield responses of finger millet to inorganic fertilizers (macronutrients and micronutrients), farmyard manure (FYM), green manures, organic by-products, and biofertilizers. The review also describes the impact of these inputs on soils, as well as the impact of diverse cropping systems and finger millet varieties, on nutrient responses. The review critically evaluates the benefits and challenges associated with integrated nutrient management, appreciating that most finger millet farmers are economically poor and primarily use farmyard manure. We conclude by identifying research gaps related to nutrient management in finger millet, and provide recommendations to increase the yield and sustainability of this crop as a guide for subsistence farmers.

Keywords: finger millet; nutrient management; nitrogen; phosphorus; potassium; micronutrients; farmyard manure; biofertilizers; organic fertilizer; integrated nutrient management

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1. Introduction

Finger millet (*Eleusine coracana* (L.) Gaertn) is a major food crop of the semi-arid tropics of Asia and Africa and has been an indispensable component of dryland farming systems [1–3]. Its name is derived from the seedhead, which has the shape of human fingers (Figure 1). Locally, the crop is called ragi (India); koddo (Nepal); dagussa, tokuso, barankiya (Ehiopia); wimbi, mugimbi (Kenya); bulo (Uganda); kambale, lupoko, mawale, majolothi, amale, bule (Zambia); rapoko, zviyo, njera, rukweza, mazhovole, uphoko, poho (Zimbabwe); mwimbi, mbege (Tanzania); and kurakkan (Sri Lanka) [4]. The crop was domesticated in the highlands of Ethiopia and Uganda 5000 years ago, but reached India 3000 years ago [4,5]. Today, the crop is ranked fourth globally in importance among the millets, after sorghum, pearl millet, and foxtail millet [6]. It is cultivated in more than 25 countries, mainly in Africa (Ethiopia, Eritrea, Mozambique, Zimbabwe, Namibia, Senegal, Niger, Nigeria, and Madagascar) and Asia (India, Nepal, Malaysia, China, Japan, Iran, Afghanistan, and Sri Lanka) [7,8]. In India, finger millet is primarily grown in the states of Karnataka, Andhra Pradesh, Odisha, and Tamil Nadu [8]. In Eastern Africa, the major producers are Uganda, Ethiopia, and Kenya [9]. Finger millet production data for the last five years in major finger millet producing countries (India, Nepal, and Ethiopia) is listed in Table 1.

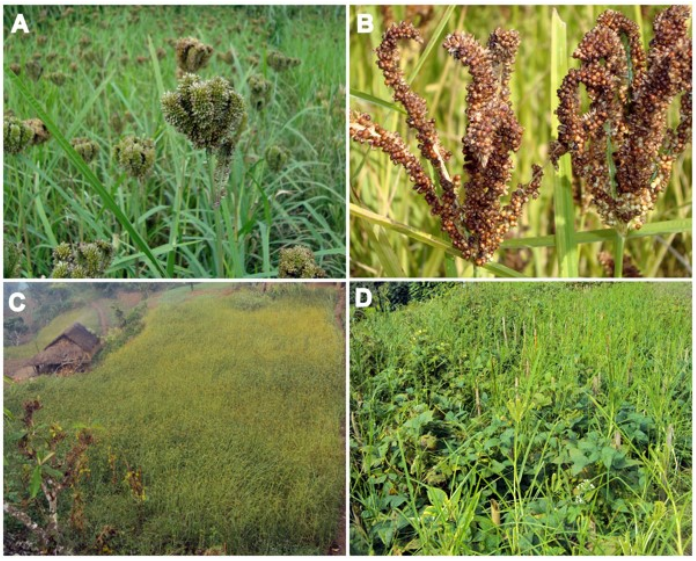

Figure 1. Illustrations of finger millet cultivation. Typical finger millet seed heads at a young stage (**A**) and at maturity (**B**) in farmers' fields in Nepal. The seed heads resemble the fingers of a human hand. (**C**) Finger millet growing in a terraced field on a smallholder farm in Nepal. (**D**) Mixed-cropping of finger millet with soybean in a terraced field of a smallholder farmer in Nepal. Picture sources: LI-BIRD photo bank.

Table 1. Production data for finger millet in selected major finger millet producing nations (2009/2010–2013/2014).

Country	Year	Area under cultivation ('000 ha)	Production ('000 tones)	Average yield (kg ha^{-1})	References
India	2009/2010	1268	1889	1489	[10]
	2010/2011	1286	2194	1705	[10]
	2011/2012	1176	1929	1641	[10]
	2012/2013	1179	1785	1514	[10]
	2013/2014	1138	1688	1483	[11]
Nepal	2009/2010	268.5	299.5	1116	[12]
	2010/2011	269.8	302.7	1122	[12]
	2011/2012	278.0	315.1	1133	[12]
	2012/2013	274.4	305.6	1114	[12]
	2013/2014	271.2	304.1	1121	[12]
Ethiopia	2009/2010	369.0	524.2	1421	[13]
	2010/2011	408.1	634.8	1556	[13]
	2011/2012	432.6	651.8	1507	[14]
	2012/2013	431.5	742.3	1720	[15]
	2013/2014	454.7	849.0	1867	[16]

Nutritionally, finger millet is primarily consumed as a porridge in Africa, but in South Asia as bread, soup, roti (flat bread), and to make beer [4]. Interestingly, new food products made from finger millets are also becoming popular among younger people, including noodles, pasta, vermicelli, sweet products, snacks, and different bakery products [17,18]. In some nutritional components, finger millet is a superior crop compared to some major cereal crops especially polished rice [17]. Among the other millets, finger millet has a high amount of calcium (0.38%), fiber (18%), phenolic compounds (0.3%–3%), and sulphur containing amino acids [17,19–21]. Finger millet also has high amounts of tryptophan, cysteine, methionine, and total aromatic amino acids compared to the other cereals, and thus is an important crop in poor nations to alleviate malnutrition [4]. As a result, unlike many crops grown by subsistence farmers, finger millet remains highly valued in traditional production systems, especially for its nutrient benefits to pregnant women and children for whom it is used as a weaning food [4,18]. As finger millet seeds can be stored for more than five years due to low vulnerability to insect damage [4,20], it provides food security for poor farmers. Although finger millet plays a very important role especially in the diet of rural peoples, it has become a less important cereal crop due to high demand for rice and maize cultivation [17] and lack of adequate male labour [1]. Many of the management practices are conducted by women including land preparation, seeding/transplanting, harvesting, and threshing (Figure 2). Therefore, improvements in productivity of finger millet will benefit the food production systems of Asian and African nations while enhancing local nutrition.

Figure 2. Manual labour associated with finger millet production. (**A**, **B**) Harvesting of finger millet by women in a terraced field of a smallholder farmer in Nepal; (**C**) Hand threshing of finger millet with a wooden pole by women in Nepal; (**D**) Threshing of finger millet with oxen in Nepal. Picture sources: LI-BIRD photo bank.

The striking feature of finger millet is its ability to adjust to different agro-climatic conditions [22]. Once adequate moisture is available (minimum water requirement is 400 mm) and the temperature is above 15 °C, finger millet can be grown throughout the year [22]. It is well adapted to higher elevations and is grown in the Himalayas up to an altitude of 2400 m [4]. Finger millet is drought tolerant [8,22], disease resistant [1], effective in suppressing weed growth [23], and able to grow on marginal lands with poor soil fertility. Finger millet varieties are primarily grouped into two types based on crop duration: early maturity (90–100 days) and late maturity (110–120 days) [22]. It can be established either by broadcasting the seeds or transplanting, where the yield is higher when transplanted in rows compared to broadcasting [22,24].

Though finger millet is valued by traditional farmers as a low fertilizer input crop [4], under these conditions, it suffers from low yields [20,22]. Most of the soils in the semi-arid tropics, where finger millet is grown, are deficient in major and micronutrients, mainly due to continuous cropping, low use of mineral fertilizer, poor recycling of crop residues, and low rates of organic matter application which can limit yield potential [25]. Therefore, it is important to optimize nutrient management practices and other related factors affecting finger millet cultivation in order to attain better yields under the comparatively marginal local growing conditions. Unfortunately, compared to the major cereal crops, the recommendations available for nutrient management in finger millet are scarce, limiting the ability of agricultural extension officers to assist subsistence farmers.

The land available for agriculture is declining especially in the semi-arid tropics mainly due to increases in population. On the other hand, the food productivity of staple food crops in these regions (e.g., finger millet) has to be increased in order to meet food demand. Although many research findings suggest that increased application rates of inorganic fertilizers improve finger millet yield and productivity, it is not a practical option for many poor finger millet farmers in South Asia and Africa, as they cannot afford inorganic fertilizer. Therefore, integrated nutrient management (INM) may be a sustainable option for finger millet farmers in these regions. The main objectives of INM are improvements in plant performance and resource use efficiency while minimizing negative environmental impacts [26,27]. These can be achieved through use of all possible sources of nutrients to meet crop demand, matching soil nutrient availability with crop demand (spatially and temporally), and minimizing nitrogen losses [26,28]. The major advantages of INM are increases in yield, water use efficiency, grain quality, economic return, and sustainability [26].

The objective of this paper is to review the literature concerning nutrient management of finger millet in the semi-arid tropic regions of Asia and Africa, including the use of inorganic fertilizers (macronutrients and micronutrients), farmyard manure, green manures, organic by-products, and biofertilizers. The review further discusses the benefits and concerns of INM as well as different cropping systems, and reviews the limited data that exists on varietal effects. The review concludes with identifying gaps and recommendations for improving productivity of this crop.

2. Current Literature Concerning Inorganic and Organic Nutrient Management

As illustrated below, most of the major inorganic fertilizer studies related to finger millet have focused on testing the effects of N, P, and NPK together (Table 2). Most of the studies related to micronutrients have focused on zinc (Zn) and boron (B). In addition, significant attention has been paid to measuring the effects of different organic fertilizers on finger millet growth and yield, including the use of FYM, green manures, and bio-fertilizers (Table 2).

Table 2. Effect of different fertilizer management practices on finger millet growth, yield, and soil nutrition.

Area/Country	Soil properties	Cropping system	Nutrient treatments	Key results	References
			NPK + FYM		
Bangalore, Southern India	Alfisol soil Soil organic carbon (SOC) = 0.30%−0.45% Available soil N = 163–204 kg N ha^{-1}	Finger millet	Control 100% NPK (50:50:25 kg N, P_2O_5, K_2O ha^{-1}) FYM at 10 t ha^{-1} FYM at 10 t ha^{-1} + 50% NPK FYM at 10 t ha^{-1} + 100% NPK Control Maize residues (MR) at 5 t ha^{-1} MR at 5 t ha^{-1} + 50% NPK MR at 5 t ha^{-1} + 100% NPK	Higher grain yield was found with FYM (10 t ha^{-1}) + 100% NPK (3167 kg ha^{-1}) and MR (5 t ha^{-1}) + 100% NPK (2518 kg ha^{-1}) compared to the recommended NPK fertilizer (1826 and 1965 kg ha^{-1} respectively). Similar trend was found for soil NPK.	[29]
Bangalore, Southern India	Alfisol soil SOC = 0.46% Available soil N = 302 kg N ha^{-1}	Finger millet monocropping under rainfed conditions	Control (no NPK fertilizer or organic amendments) FYM 10 t ha^{-1} + 50% NPK FYM 10 t ha^{-1} + 100% NPK FYM 10 t ha^{-1} Recommended dose of NPK (50:50:25 kg N, P_2O_5, K_2O ha^{-1})	Higher grain yield (mean grain yield of 3281kg ha^{-1}) and sustainable yield index were achieved with integrated nutrient management (INM) (FYM at 10 t ha^{-1} + 100% NPK) than recommended NPK. Application of FYM improved soil C stock (35% of soil C buildup after 27 years).	[30]
Tamil Nadu, Southern India	Fine Montmorillonitic, isohyperthermic SOC = 4% (control) and 0.62% (NPK + FYM)	Finger millet-maize rotation	50% NPK (90:45:17.5 kg N, P_2O_5, K_2O ha^{-1}) 100% NPK 150% NPK 100% NPK + hand weeding 100% NP 100% N 100% NPK + FYM at 10 t ha^{-1} 100% NPK (-S) Control	Application of 100% NPK + FYM increased soil organic C level (6.2 *vs*. 5.3 g kg^{-1} soil), CEC (34.4 *vs*. 28.9 cmol (p+) kg^{-1} soil), available soil N (197 *vs*. 165 kg ha^{-1}), P (26.2 *vs*. 16.8 kg ha^{-1}), K (650 *vs*. 596 kg ha^{-1}), and micronutrients (Cu, Mn, Fe, Zn) compared to NPK fertilizer alone. 100% N and control treatments resulted in lowest soil organic carbon level.	[31,32]

Table 2. *Cont.*

Area/Country	Soil properties	Cropping system	Nutrient treatments	Key results	References
Karnataka, India	Alfisol, sandy loam soil SOC = 0.42% Available soil N = 302 kg N ha^{-1}	Finger millet-groundnut rotation	No fertilizer FYM (10 t ha^{-1}) 100 % NPK (50:21.8:20.7 kg N, P, K ha^{-1}) FYM + 50% NPK FYM + 100% NPK	Higher grain yield was achieved with NPK + FYM treatment (3957 kg ha^{-1}) compared to the recommended NPK (2578 kg ha^{-1}). SOC increased by 41% with INM after 13 years of crop rotation.	[33]
Bangalore, India	Red sandy loam SOC = 0.34% Available soil N = 172 kg N ha^{-1}	Finger millet-groundnut	NPK (100:50:50 kg N, P_2O_5, K_2O ha^{-1}) NPK + FYM (7.5 t ha^{-1})	Application of FYM + NPK improved finger millet yield, soil NPK content, and microbial biomass. INM maintained neutral pH, where the recommended NPK treatment caused acidic conditions.	[34]
Karnataka, India	Red sandy loam Available soil N = 329 kg N ha^{-1}	Finger millet	Recommended NPK (50:40:25 kg N, P_2O_5, K_2O ha^{-1}) through fertilizer Farmer practice (20 N, 21 P_2O_5 kg ha^{-1}) 50% N through FYM + 50% NPK through fertilizer Recommended N + P and K through FYM	Application of 50% N through FYM + 50% NPK produced slightly greater yield (30.3 quintiles ha^{-1}) than recommended NPK through fertilizer (28.7 quintiles ha^{-1}). In comparison to recommended NPK, the above treatment had slightly high/similar plant height (77 *vs*. 75 cm), straw yield (36.2 *vs*. 35.0 quintiles ha^{-1}), and benefit/cost ratio (3.2 *vs*. 3.0).	[35]
Bangalore, India	Fine, mixed isothermic Kandic Paleustalfs	Finger millet	50% NPK 100% NPK 150% NPK 100% NPK + HW (not defined) 100% NPK + Lime 100% NP 100% N 100% NPK + FYM 100% NPK (S-free) 100% NPK + FYM+ Lime Control	In comparison to 100% NPK, INM treatments (100% NPK + FYM + lime and 100% NPK + FYM) showed increased root biomass (10.7 *vs*. 9.2 quintiles ha^{-1}), root N (0.53–0.54 *vs*. 0.51%), K (1.04–1.05 *vs*. 0.9%), Ca (0.54–0.58 *vs*. 0.48%), Mg (0.31–0.34 *vs*. 0.26%), and micronutrient content (Fe, Cu, Zn, Mn).	[36]

Table 2. *Cont.*

Area/Country	Soil properties	Cropping system	Nutrient treatments	Key results	References
Bangalore, India	Red sandy loam soil SOC = 0.34% Available soil N = 172 kg N ha^{-1}	Finger millet under irrigation	NPK (100:50:50 kg N, P_2O_5, K_2O ha^{-1}) NPK + FYM (7.5 t ha^{-1})	Application of 100% NPK + FYM increased millet yield (3086 kg ha^{-1}) by 9.5% compared to NPK alone (2946 kg ha^{-1}). INM also increased the number of tillers per hill, ear length, ear weight, 1000 grain weight, threshing percent, and number of fingers per ear head.	[37]
Pakhribas and Dordor Gaun, Nepal	Sandy loam and silt loam Organic matter and N% = 1.33, 0.08% (Pakhribas) and 0.82, 0.08% (Dordor Gaun)	Maize-finger millet cropping system	No inputs Farmer practices for fertilizer-T1 Farmer practices for FYM-T2 50% (T1 + T2) 50% T1 50% T2 25% (T1 + T2)	Highest millet yield was associated with the FYM applied to previous maize crop than inorganic fertilizer treatment. FYM application reduced the rate of C and N losses.	[38]
Pakhribas and Dordor Gaun, Nepal	Sandy loam and silt loam SOC and total N at top 25 cm soil = 1.32, 0.08% (Pakhribas) and 0.82, 0.08% (Dordor Gaun)	Maize-finger millet	No fertilizer NPK fertilizer (90:30:30 kg ha^{-1}) FYM alone (90 kg N ha^{-1}) NPK + FYM (different ratios)	A trend of high yield was found in finger millet plots, which were previously manured, compared to inorganic fertilizer applied plots. Recovery of fertilizer applied to maize by subsequent finger millet crop was very low (3%).	[39]
Dhankuta, Eastern Nepal	Dystochrept (sandy clay loam texture) Organic matter = 1.9%	Maize/millet rotation	NPK FYM (0, 15, 25 t ha^{-1}) NPK + FYM Lime	Millet yield increased following maize treated with FYM (by 705 kg ha^{-1}) or FYM + inorganic fertilizer (by 631 kg ha^{-1}), compared to inorganic fertilizer alone.	[40]

Table 2. *Cont.*

Area/Country	Soil properties	Cropping system	Nutrient treatments	Key results	References
Micronutrients					
Karnataka, India	Alfisols and Inceptisols SOC = 0.37%	Finger millet under rainfed	Farmers' inputs (FI) + NP (60:130 kg N, P_2O_5 ha^{-1}) FI + S, B, Zn (30:0.5:10 kg S, B, Zn ha^{-1}) FI + NP + S, B, Zn (60:130:30:0.5:10 kg N, P_2O_5, S, B, Zn ha^{-1}).	In comparison to FI, combined application of FI + NP + S, B, Zn fertilizers enhanced grain yield (3350 *vs.* 2150 kg ha^{-1}), straw yield (6650 *vs.* 4630 kg ha^{-1}), and uptake of N (31 *vs.* 20 kg ha^{-1}), P (7.5 *vs.* 5.2 kg ha^{-1}), K (17 *vs.* 11 kg ha^{-1}), S (2.9 *vs.* 1.8 kg ha^{-1}), and Zn (49 *vs.* 36 kg ha^{-1}).	[25]
Karnataka, India	Vertisol and Alfisol (sandy, loam, clay) SOC = <0.5% Available soil N = <280 kg N ha^{-1}	Finger millet under rainfed conditions	Farmer practice (N + P) Farmer practice + Zn, B, S (10:0.5:30 kg Zn:B:S ha^{-1})	In comparison to farmers' practice, farmer practice + Zn, B, S increased finger millet grain yield (3354 *vs.* 2142 kg ha^{-1}), stover biomass (6654 *vs.* 4630 kg ha^{-1}), total biomass (10008 *vs.* 6772 kg ha^{-1}), and plant uptake of Zn (322 *vs.* 193 g ha^{-1}), B (21 *vs.* 17 g ha^{-1}), and S (16 *vs.* 10 kg ha^{-1}).	[41]
NPK + FYM + Bio-fertilizers/Green manures					
Wakawali, India	Terraced upland	Finger millet	Recommended fertilizer (RF) (80:40:00 kg N, P_2O_5, K_2O ha^{-1}) FYM at 5 t ha^{-1} + RF FYM at 5 t ha^{-1} + 75% RF + bio-fertilizers (*Azospirillum* + PSB) FYM at 10 t ha^{-1} + bio-fertilizers FYM at 15 t ha^{-1} + bio-fertilizers	Higher grain yield obtained with FYM at 5 t ha^{-1} + 75% NPK + bio-fertilizers	[42]
Karnataka, India	Red sandy loam soil Available soil N = 59 kg N ha^{-1}	Finger millet under rainfed conditions	Recommended NPK (50:37.5:25 kg NPK ha^{-1}) RF + *Azotobacter* (1 kg ha^{-1} root dipping) RF + gypsum (500 kg ha^{-1}) RF + *Azotobacter* + $ZnSO_4$ (10 kg ha^{-1}) RF + *Azotobacter* + gypsum RF + $ZnSO_4$ + gypsum RF + *Azotobacter* + $ZnSO_4$ + gypsum	In comparison to RF treatment, INM (RF + $ZnSO_4$ + gypsum + *Azotobacter*) had higher number of tillers (8 *vs.* 4 plant^{-1}), ear head (8 *vs.* 3 plant^{-1}), number of fingers (43 *vs.* 25 plant^{-1}), yield (61 *vs.* 49 quintiles ha^{-1}), and benefit:cost ratio (2.5 *vs.* 2.2).	[43]

Table 2. *Cont.*

Area/Country	Soil properties	Cropping system	Nutrient treatments	Key results	References
Odisha, India	Red lateritic sandy loam	Finger millet	Farmers' input (FI) (FYM at 2 t ha^{-1} + 17:12:0 kg N, P_2O_5, K_2O) RF (40:20:20 kg N, P_2O_5, K_2O ha^{-1}) FI + 2.5 kg ha^{-1} each of PSB and *Azotobacter* FI + *Gliricidia* at 5 t ha^{-1} 50% RF + 2.5 t ha^{-1} FYM + 2.5 kg ha^{-1} each of PSB and *Azotobacter* 50% RF + 2.5 t ha^{-1} *Gliricidia* + 2.5 kg ha^{-1} each of PSB and *Azotobacter*	In comparison to FI, INM (50% RF + 2.5 t ha^{-1} *Gliricidia* + 2.5 kg ha^{-1} each of PSB and *Azotobacter*) treatment increased shoot and root growth (10.9, 3.5 *vs*. 9.7, 2.8 g $plant^{-1}$), yield parameters, grain yield (4.0 *vs*. 3.5 t ha^{-1}), benefit:cost ratio (2.4 *vs*. 2.1), soil moisture, SOC (0.46 *vs*. 0.41%), soil available N (278 *vs*. 240 kg ha^{-1}), available P (14.7 *vs*. 12.1 kg ha^{-1}), and available K (307 *vs*. 279 kg ha^{-1}).	[8]
Bangalore, Southern India	Red sandy clay loam SOC = 0.36% Available soil N = 175 kg N ha^{-1}	Finger millet-pigeon pea rotation	100% N through urea 50% N through urea + 25% N through FYM + 25% N through *Gliricidia* 50% N through FYM + 50% N through *Gliricidia*	INM had higher grain yield (2666 kg ha^{-1}) with a 29% increase compared to 100% N supply through urea (2067 kg ha^{-1}). In comparison to sole organic N treatment, INM had higher tiller number (5.8 *vs*. 4.9 $plant^{-1}$), grain yield (2666 *vs*. 1665 kg ha^{-1}), and benefit:cost ratio (3.23 *vs*. 1.71).	[44]
Bangalore, Southern India	Sandy and gravel soil SOC = 0.44% Available soil N = 307 kg N ha^{-1}	Finger millet	Recommended FYM + 100% NPK Recommended FYM + 100% N through Pongamia cake Recommended FYM + 100% N through Mahua cake Recommended FYM + 100% N through Neem cake	Recommended FYM + Neem cake equivalent to 100% N increased finger millet yield (2454 *vs*. 2175 kg ha^{-1}), soil available N (391 *vs*. 315 kg ha^{-1}), available P (50 *vs*. 30 kg P_2O_5 ha^{-1}), and available K (391 *vs*. 260 kg K_2O ha^{-1}) compared to the 100% NPK + recommended FYM.	[45]
Karnataka, India	Sandy loam SOC = 0.57% Available soil N = 205 kg N ha^{-1}	Finger millet following potato	100% NPK 100% N as FYM 100% NPK + FYM (10 t ha^{-1}) 25%–50% N as composted weeds	In comparison to 100% inorganic fertilizer, 100% N as FYM had higher finger millet grain yield (4.77 *vs*. 4.13 t ha^{-1}), soil N (133 *vs*. 107 kg ha^{-1}), soil P (27 *vs*. 21 kg ha^{-1}), and soil K (174 *vs*. 142 kg ha^{-1}).	[46]

Table 2. *Cont.*

Area/Country	Soil properties	Cropping system	Nutrient treatments	Key results	References
Bangalore, India	Red sandy loam Soil organic matter = 0.48% Available soil N = 268 kg N ha^{-1}	Horse gram in the previous season	FYM Biogas slurry Poultry manure City waste compost Agrimagic Green manure 100% RF (50:40:25 NPK kg ha^{-1}) 100% RF + FYM 100% NK	100% RF + FYM at 7.5 t ha^{-1} had higher grain yield (3660 kg ha^{-1}) compared to other treatments (1400–3200 kg ha^{-1}). Finger millet supplied with poultry manure produced higher grain yield (2970 kg ha^{-1}) than FYM or green manure treatments (2200–2300 kg ha^{-1}).	[47]
Tamil Nadu, India	Not available	Rice-Finger millet	Recommended fertilizer + FYM (12.5 t ha^{-1}) RF + composted coirpith (12.5 t ha^{-1})	Finger millet yield was higher under FYM + RF (2816 kg ha^{-1}) and composted coirpith + RF (2739 kg ha^{-1}).	[48]
Tamil Nadu, Southern India	Not available	Finger millet	Control (no organics) FYM at 12.5 t ha^{-1} Pressmud at 12.5 t ha^{-1} Composted coirpith at 12.5 t ha^{-1} Gypsum at 500 kg ha^{-1}	Application of pressmud and composted coirpith significantly improved finger millet yield (3316, 3385 *vs*. 2593 kg ha^{-1}), soil N (135, 136 *vs*. 120 kg ha^{-1}), soil P (6.18, 10.3 *vs*. 5.7 kg ha^{-1}), soil K (134, 138 *vs*. 116 kg N ha^{-1}) macro and micronutrients (Zn, Cu, Mg, Fe), soil organic carbon (0.45, 0.46 *vs*. 0.25%), pH (8.33, 8.27 *vs*. 8.45%), EC (0.25 *vs*. 0.41 dSm^{-1}), and microbial population (bacteria, fungi, actinomycete) compared to the control.	[49]

Abbreviations: FYM: farmyard manure; MR: maize residues; FI: farmers' inputs; RF: recommended fertilizer; PSB: phosphorus solubilizing bacteria; SOC: soil organic carbon; INM: integrated nutrient management.

2.1. Nitrogen (N)

Finger millet responds well to N application [6,22,50], since many of the soils in the semi-arid regions of Asia are deficient in N [25]. Studies concerning N management in finger millet are mainly focused on the amount of N applied, timing of application, and varietal responses to N. Rao *et al.* [51] reported increases in yield and grain protein content in finger millet due to N fertilizer application rates of up to 40 kg N ha^{-1} in Andhra Pradesh, India. The authors claimed that the economic optimum rate of N fertilizer for finger millet was 43.5 kg ha^{-1} under rainfed conditions. Hegde and Gowda [22] reported that finger millet grain yield was 23.1 kg per kg N at 20 kg N ha^{-1}, while the yield benefit declined to 19.9 kg per kg N at 60 kg N ha^{-1}. These results suggest that application of the correct dose of N fertilizer is important in order to maximize the profits of poor finger millet farmers. It is also important to note that the application of inorganic N fertilizer can delay flowering and physiological maturity by 1–2 weeks [24], which can affect the final yield. The latter study also found that application of inorganic N alone (22.5–45 kg N ha^{-1}) did not increase the grain yield compared to the no fertilizer application under conditions of seed broadcasting and row planting. Therefore, the authors claimed that N application alone is not economical in finger millet cultivation. Based on a long-term field experiment with finger millet, Hemalatha and Chellamuthu [32] found that continuous application of inorganic N fertilizer alone reduced the soil organic carbon level due to low dry matter production and reduced return of crop residues to the field (Table 2).

In addition to the amount of N supplied, the timing of N application is also important for finger millet. The importance of applying N starts with seed germination, a challenge for small seed crops like finger millet especially under nutrient deficient conditions. The application of inorganic N fertilizer at the time of planting stimulates better crop emergence especially in N deficient soil [20]. Hegde and Gowda [22] also claimed that incorporation of N fertilizer during seeding enhanced finger millet yield by 30% compared to broadcasted fertilizer. Synchronizing N supply with crop N demand is essential to maximize yield and N use efficiency. Hegde and Gowda [22] reported that application of N on sandy loam soils at 50 kg ha^{-1} produced a finger millet grain yield of 2430 kg when applied at planting, whereas the yield increased to 2650 kg ha^{-1} when the application time was split (at planting and 25–30 days after planting). Therefore, split application of N fertilizer enhances finger millet yield production and possibly reduces N losses as well.

2.2. Phosphorus (P)

Although P is one of the major macronutrients required by finger millet, limited research has been conducted to evaluate the significance of P on finger millet growth and yield. Nevertheless P is one of the highly limited nutrients in farmers' fields in semi-arid regions of Asia [25]. Based on multi location field experiments conducted in Eastern Uganda, Tenywa *et al.* [24] found that application of P fertilizer (20–40 kg P_2O_5 ha^{-1}) increased the growth and yield of finger millet compared to the no fertilizer control under row planting conditions. However, Hedge and Gowda [22] reported a reduction in finger millet grain yields from 16.3 to 14.7 kg per kg P_2O_5 when the P application rate was increased from 30 to 60 kg ha^{-1} P_2O_5. Similar to inorganic N, this result suggests that application of excess P does not improve yield, but rather that application of balanced fertilizer is crucial.

Organic practices have been shown to be important for P nutrition in finger millet. Based on a long-term field study at Tamil Nadu, India, Hemalatha and Chellamuthu [31,32] found that continuous application of 100% NPK + FYM increased P availability (Table 2), which agrees with previous findings by Govindappa *et al.* [47]. This could be due possibly to the solubilisation of P by organic acids released during organic matter decomposition. An earlier study by Subramanian and Kumaraswami [52] also reported that application of NPK, along with FYM increased the uptake of P by finger millet. This highlights the importance of applying FYM along with inorganic fertilizer to improve P availability for finger millet. With respect to lessons learned from crop rotations, in Eastern Uganda, Ebanyat *et al.* [53] found that application of P to legume crops generally enhanced the yield of the subsequent finger millet crop; six different legumes were tested in parallel including cowpea, pigeonpea, and groundnut (peanut). Addition of P increased the amount of N fixed by legume crops, resulting in a positive effect on yield of the subsequent finger millet crop. In addition to the benefit provided by N, residual P may have also had a positive effect on finger millet yield. Generally the yield response of finger millet to the addition of P to the previous legume crop was higher in fields with low soil fertility. The authors also found that P supplied to the previous legume crops increased the N use efficiency in finger millet, but the results were not consistent across the different legume species or soil fertility types tested. Although the application of P to legumes increased the yield of the subsequent finger millet crop, it may not be profitable due to the extra cost associated with P fertilizer [53].

2.3. Nitrogen, Phosphorus, and Potassium (K)

NPK has been shown to be important for early establishment of finger millet. Based on a well-planned, three-year study conducted in farmers' fields in Eastern Zimbabwe, Rurinda *et al.* [20] found that finger millet emergence was low without inorganic NP fertilizer or with manure (<15%) compared to fertilization with either NP fertilizer or manure + fertilizer (>70%). The data suggests that application of manure alone may not be beneficial to finger millet, perhaps because the nutrients are not readily available to the seedling. This result highlights the importance of supplying starter NPK mineral fertilizer for better finger millet establishment. The authors also found that agronomic N use efficiency (kg grain yield produced per kg N applied) decreases at high NPK rates, thus identification of the optimum fertilizer requirement is very important in order to maximize crop productivity. Hegde and Gowda [22] reported that the required application rate of NPK fertilizer depends on whether the conditions are wet or dry, with a higher rate of fertilizer required under irrigated conditions (100, 50, 50 kg N, P_2O_5, K_2O) compared to dryland conditions (50, 37.5, 25 kg N, P_2O_5, K_2O) in order to achieve their respective yield potentials (*i.e.*, there is more biomass produced under wet conditions). Similarly Sankar *et al.* [29] found that the benefit of applying inorganic fertilizer increased under high moisture availability compared to low moisture availability (<500 mm).

Application of the major macronutrients to finger millet alone does not necessarily provide better yields, rather the application of balanced nutrients is important as already noted above. Using a soil management study in Eastern Uganda, Tenywa *et al.* [24] found that application of N or P alone did not increase finger millet growth and yield compared to non-fertilized plants. However, they found that application of N + P and manure + P produced better growth and yield in finger millet compared to N or manure alone, highlighting the importance of balanced nutrient management. Based on a two year field trial, Bhoite and Nimbalkar [54] reported that application of 60 kg N ha^{-1} and 20 kg P_2O_5 produced the best finger millet yield in Maharashtra, India. Based on a 25 year long term experiment conducted under rainfed conditions on alfisols in Bangalore (Southern India), it was observed that application of N:P_2O_5:K_2O at 50:50:25 kg ha^{-1} increased finger millet yield and soil fertility status compared tonon-fertilized plants [29]. The authors further observed that application of FYM and maize residues along with NPK enhanced the yield and soil fertility status. Long term application of 100% NPK along with FYM (10 t ha^{-1}) also increased the available soil nutrients (N, P, K, Ca, Mg) [32].

2.4. Micronutrients

Soil micronutrients are commonly deficient in South Asia [25,41] and Sub Saharan Africa [55]. Most of the micronutrient studies related to finger millet have concentrated on zinc (Zn) and boron (B). Based on soil tests with 1617 farmers in the semi-arid tropics of India, Srinivasarao *et al.* [41] found that Zn and B deficiency ranged from 2%–100% and 0%–100% respectively in farmers' fields, depending on the geographic region. The authors considered the following minimum levels to be critical for available Zn and B in farmers' fields, respectively: 0.75 mg Zn kg^{-1} soil (DTPA extractable), 0.58 mg B kg^{-1} soil (hot water extractable). Similarly, based on surface soil testing (802 soil samples), Rao *et al.* [25] also found that farmers' fields were deficient in Zn (34%–88% of fields tested) and B (53%–96%) in the semi-arid regions of Karnataka, India. Srinivasarao *et al.* [41] found that application of Zn, B, and sulfur (S) along with N and P, enhanced finger millet grain yield (56%), stover biomass (44%), total biomass (48%), and plant uptake of Zn (66%) and B (22%) compared to the addition of N and P alone (Table 2). Based on a three-year experiment, Rao *et al.* [25] found that application of B and Zn along with farmer inputs (farmers chose their fertilizer types and application rates), N, P, and S fertilizer increased grain yield, straw productivity, and nutrient uptake (N, P, S, B, and Zn) of finger millet compared to the farmers' traditional inputs (Table 2). Similarly Maury and Verma [56] claimed that application of Zn along with NPK fertilizer favored the uptake of NPK, but reduced the Zn content, but further methodological details were not available to explain this result. Ramachandrappa *et al.* [57] reported that soil application of $ZnSO_4$ (12.5 kg ha^{-1}) and borax (10 kg ha^{-1}) along with the recommended NPK increased finger millet yield in B and Mo deficient soils.

Other than micronutrient fertilizers, FYM may be a good source of essential micronutrients for millet growth. Based on a long-term field experiment in Tamil Nadu, India, it was found that continuous application of 100% NPK + FYM (10 t ha^{-1}) increased some of the available micronutrients (Fe, Zn, Mn, and Cu) in a finger millet-maize cropping system [32] (Table 2).

2.5. Farmyard Manure (FYM) + Inorganic Fertilizer

2.5.1. Yield Response of FYM + NPK

A significant number of studies have been conducted to evaluate the effect of farmyard manure along with recommended inorganic fertilizer on finger millet growth and yield (Table 2). Some of these studies have been noted above. Generally application of FYM along with recommended NPK fertilizer enhances finger millet yield and soil fertility [25,29,30,34,37,42,58]. Kumara *et al.* [37] found that application of FYM along with the recommended NPK fertilizer increased yield parameters of finger millet under an irrigated system in Bangalore, India (ear length, 1000 grain weight, number of fingers per ear head, ear weight per plant, and grain weight per plant). The same trend was observed by Govindappa *et al.* [47], where application of FYM (7.5 t ha^{-1}) along with the recommended NPK increased dry matter production, grain weight, grain yield, and straw yield of finger millet (Table 2). The authors also found that poultry manure was a better source of manure than FYM or green manure for finger millet to achieve better growth and yield. Based on a very long-term comprehensive study (1984–2008), Sankar *et al.* [29] found that application of FYM and maize residues increased millet yield as well as sustainability in rainfed semiarid tropical alfisols (Table 2). Furthermore, based on a long-term field experiment, Pushpa *et al.* [36] found that application of FYM along with 100% NPK + lime increased root growth and root nutrient content (major, secondary and micro nutrients) compared to plants treated with 100% NPK alone (Table 2). Based on an eight year field experiment, Sherchan *et al.* [40] found that finger millet yield and plant NPK uptake increased when potato, as the preceding crop, was supplied with 100% FYM or when 50% of N was supplied by lantana (*Lantana camara*, a weedy green manure).

Application of integrated nutrient management practices can reduce the amount of inorganic fertilizer used for finger millet without compromising yield. It was found that application of 50% recommended N through FYM + 50% recommended NPK fertilizer can produce a slightly higher yield than 100% of recommended NPK fertilizer alone [35] (Table 2). The authors also claimed that the benefit/cost ratio was higher with the above treatment than the traditional farmer practices and in par with the recommended NPK at 100%. Sankar *et al.* [29] also found that application of FYM at 10 t ha^{-1} + 50% recommended NPK fertilizer produced a much higher yield than the recommended NPK application at 100% (Table 2).

2.5.2. Effects of Manure + NPK on Soil Carbon

In the arid and semi-arid regions of the tropics and subtropics, soil organic carbon (C) is a limiting factor (<0.5%) [41], thus the retention capacity of nutrients is low, especially N. Therefore, improvement of the soil carbon pool through different organic manures helps to improve soil fertility and sustain yields. Based on long-term field experiments, Srinivasarao *et al.* [30,33] and Hemalatha and Chellamuthu [32] found that application of FYM along with 100% NPK inorganic fertilizer increased the grain yield of finger millet as well as the soil organic C level. Also, Srinivasarao *et al.* [30,33] found a strong correlation between soil C levels and a sustainable yield index (an approach to evaluate the sustainability of long-term cropping systems), highlighting the importance of maintaining the soil C pool in order to attain sustainable yields. It appears that sustainable finger millet production is achievable if appropriate amounts of both inorganic fertilizers and organic materials are applied together. On the other hand, application of balanced NPK along with low amounts of FYM is an alternative solution to maintain the soil C levels under limited manure availability [33]. However, application of FYM to maintain the soil C level may not be economical in the short term in the absence of compensating for C sequestration [38]. In this situation application of inorganic fertilizer may be economical for farmers.

2.5.3. Other Benefits and Challenges of Combining Manure with Inorganic Fertilizers

The application of organic manure can minimize the negative effect of continuous application of inorganic fertilizer to finger millet. Organic manure helps to maintain soil C levels [30,32,33], which minimizes N losses from the cropping system while increasing the sustainability of the system. Furthermore Hemalatha and Chellamuthu [32] found that application of FYM with NPK increased the cation exchange capacity (CEC) of the soil, possibly due to buildup of soil humus by FYM. Based on a simulation model used to explore the long-term impact of different fertilizer management scenarios for maize-millet systems in Nepal, Matthews and Pilbeam [38] observed that application of FYM reduced the decline in rates of soil C and N compared to the application of inorganic fertilizer alone (Table 2). Based on a two-year field study conducted under irrigated conditions, Kumara *et al.* [34] found that application of organic fertilizer helped to improve the microbial biomass and maintain soil pH at a neutral level compared to the application of inorganic fertilizer alone (Table 2).

It is also important to consider the extra cost involved in purchasing manure and its transportation, because in reality it may be more economical to apply inorganic fertilizer rather than organic fertilizer [58]. On the other hand, farmers in some nations are in favor of applying inorganic fertilizer rather than organic fertilizer when government subsidies are available for inorganic fertilizers (e.g., India), and also due to the ease of application, ease of transportation, ready availability, and consistency of results.

2.6. Alternative Sources of Organic Fertilizer: By-Products, Biofertilizers, and Green Manures

The availability of organic fertilizer is becoming a limiting factor for farmers, thus alternative and local organic fertilizer sources need to be explored to meet demand. Research has been conducted to evaluate the possibility of using different organic byproducts as organic fertilizers in finger millet production: composted coirpith, a by-product of the coconut coir industry [48,49,59]; neem oil cake, a by-product of bio-fuel production from neem trees [45,60]; *Pongamia* and mahua cake, by-products of biofuel production from *Pongamia* and mahua legume trees, respectively [45]; and pressmud, a by-product of industrial sugar production from sugarcane [49]. Parasuraman and Mani [48] reported that FYM can be substituted with composted coirpith, wherein the finger millet yield under recommended NPK + composted coir pith (at 12.5 t ha^{-1}) was in par with NPK + FYM (at 12.5 t ha^{-1}). Shivakumar *et al.* [45] found that application of neem cake equivalent to 100% N, along with the recommended FYM, increased finger millet yield (12.8%) and available NPK in soil compared to the addition of inorganic NPK fertilizer + FYM alone (Table 2). However, the experiment was conducted for only one season, whereas long term trials are needed in order to evaluate the organic fertilizer effect on soil. Subbiah *et al.* [60] also claimed that neem cake treated with $(NH_4)_2SO_4$ and urea significantly increased grain yield and NP uptake of finger millet. Based on a two-year field study, Rangaraj *et al.* [49] found that application of different agro-industrial wastes (composted coirpith, FYM, and pressmud) could improve finger millet yield, soil fertility (macro and micro nutrients), soil microbial population (bacteria, fungi, and actinomycetes), and soil chemical and physical properties (Table 2).

Green manures and bio-fertilizers are also becoming valuable organic sources in finger millet production. Research conducted on green manure is mainly focused on *Gliricidia* (a leguminous tree fodder) [8,44], which is rich in nutrients and decomposes rapidly [8]. Different bio-fertilizer products have been tested in finger millet such as *Azotobacter* [8,43,61,62], *Azospirillium* [61], phosphorus solubilizing bacteria (PSB) [8,62], and mycorrhizae fungi [61,63]. Based on a three year field study at Odisha, India, Dass *et al.* [8] found that finger millet supplied with 50% of the recommended inorganic fertilizers, *Gliricidia* green leaf manure (2.5 t ha^{-1}), and *Azotobacter* and PSB, produced the highest grain yield (3.95 t ha^{-1}) compared to 1.76 t ha^{-1} using the farmers' traditional practice (2 t ha^{-1} FYM + 17 kg ha^{-1} P_2O_5 + 12 kg ha^{-1} K_2O); the combined organic treatment also increased soil moisture, organic C, and NPK content (Table 2). Furthermore, the study found that treatments with *Gliricidia* (5 t ha^{-1}) combined with the above farmers' practice increased the available P and K in the soil, compared to the farmers' traditional practice alone. Based on a two-year field study, Vijaymahantesh *et al.* [44] also found that greater finger millet yield can be achieved by combining FYM (25% N), *Gliricidia* (25% N) and urea (50% N) compared to 100% N added using urea alone (Table 2). Based on a three-year field experiment, Sridhara *et al.* [43] found that application of *Azotobacter*, $ZnSO_4$, and gypsum along with recommended NPK fertilizer enhanced the growth, yield parameters, yield and profitability of finger millet compared to the recommended fertilizer application alone (Table 2). Based on pot experiments with soil as the growing medium, Ramakrishnan and Bhuvaneswari [61] found that finger millet treated with *Azospirillium* + arbuscular mycorrhizal (AM) fungi + PSB increased plant growth and N, P uptake. Uptake of macro (N, P) and micronutrients (Zn, Cu) by plants was also enhanced when finger millet was treated with AM fungi compared to non-inoculated plants [63]. Based on a single year field experiment, Apoorva *et al.* [62] found that application of *Azotobacter* and PSB along with fertilizer (based on soil testing) and FYM (10 t ha^{-1}) increased finger millet yield by 2000 kg ha^{-1} compared to the recommended fertilizer application alone.

3. Crop Rotations

Finger millet based crop rotations or relay cropping are common cropping practices in South Asian countries, involving maize-millet [39,40], potato-millet [46], and groundnut-millet [30,34]. In Africa (eastern Uganda), finger millet based crop rotations are beans-cassava-cowpeas-groundnuts-cotton, beans-cotton-cowpeas, and beans-cotton-maize [24]. Crop rotation is important as residual fertility from the previous crop contributes to the next crop. It was observed that finger millet benefits more from residual fertilizer from the previous crop when the fertilizer is supplied as organic fertilizer compared to inorganic fertilizer [38,40,58] (Table 2). Based on a well-planned study conducted in eastern Uganda, Ebanyat *et al.* [53] found that finger millet yields following legume crops (cowpea, green gram, groundnut, mucuna, pigeonpea, and soybean) were higher compared to continuous finger millet cropping. However, the N benefits derived from the legume crop residues decreased as the season progressed [53]. Although, there are N benefits to finger millet following legume crops, farmers were reluctant to use some of the legumes in their crop rotations, as they were not aware of their potential marketability or usefulness as fodder (mucuna) [53]. However, the residual N benefit to finger millet was shown to be low when the previous crop was a non-legume [39]. In particular, the authors found that recovery of N applied to maize by the following finger millet crop was only <3%, possibly due to most of the applied N being taken up by maize combined with a slow N turnover rate from maize residues. Therefore, selection of appropriate crops in finger millet based crop rotations is very important in order to utilize the residual nutrients and to obtain N credits for finger millet from the previous crop.

4. Intercropping/Mixed-cropping

Intercropping/mixed-cropping of finger millet with different legume crops such as pigeon pea, soybean, green gram, horsegram, common bean, and groundnut are also common farming practices [64–68] (Figure 1). As legumes fix atmospheric nitrogen through symbiotic N fixation, finger millet obtains N benefits from neighboring legumes. Based on a two-year field experiment in West Bengal, India, Maitra *et al.* [66] claimed that finger millet yield increased under intercropping with pigeon pea and groundnut rather than sole cropping with finger millet. However, it was reported that intercropping is beneficial only under low fertilizer input systems [22]. However, intercropping of finger millet with grain legumes can reduce legume yields due to competition, thus transplanting of finger millet after a legume is established can be beneficial [22]. Also the application of balanced inorganic fertilizer is important to minimize competition under intercropping. Maitra *et al.* [66] reported that application of NPK at a rate of 60:13.3:25 kg ha^{-1} maximized productivity and net return under finger millet-grain legume (pigeon pea and groundnut) cropping systems.

Other than nutrient benefits, intercropping has been shown to enhance finger millet yield through disease control [9,69]. Based on a multi season field trial in Western Kenya, it was observed that intercropping of finger millet with green manure legumes (leaves of *Desmodium*, a ground-cover legume) increased finger millet yield compared to mono-cropping, mainly by controlling pests associated with finger millet (*Striga hermonthica* and cereal stem borer) [9]. The authors also evaluated the economic benefits of intercropping of finger millet over monocropping, wherein the former resulted in greater economic returns although the labor cost was higher under intercropping [9]. Similarly intercropping of finger millet with mungbean has been shown to reduce *Cercospora* leaf spot and leaf curl disease [69].

One of the key factors of successful intercropping is proper plant density, which depends on the plant species as well as the particular varieties used [65,67]. Padhi *et al.* [65] reported that intercropping of early duration pigeonpea with finger millet at a row ratio of 2:4 had greater productivity and economic return than a medium duration variety. In a study conducted in Bangalore, India, intercropping of finger millet with pigeonpea at an 8:2 row ratio and field bean at 8:1 also resulted in better yield and a higher net return over sole cropping [67].

5. Varietal Effects

Finger millet has high genetic diversity [3]. All finger millet varieties do not respond to nutrients in the same manner. Genotypic variability among different finger millet cultivars has been reported for responsiveness to N and P [54]. Gupta *et al.* [6] evaluated the N use efficiency (ratio of grain yield to N supply) and N utilization efficiency (ratio of grain yield to total N uptake) of three finger millet genotypes under different N inputs (0, 20, 40, 60 kg N ha^{-1}, and 7.5 t FYM ha^{-1}) under pot conditions. They found that there was genotypic variability among the finger millet genotypes' responses to different N inputs, wherein some varieties were highly responsive to N. Therefore, identification of genotypes with higher N use efficiency and N utilization efficiency especially under low available soil N levels will benefit farmers who cannot afford N fertilizer or who do not have access to N fertilizer sources.

With respect to biofertilizers, finger millet plants treated with different strains of arbuscular mycorrhizal (AM) fungi showed significantly different effects on plant growth and yield [63]. Furthermore, the authors found variability for plant growth responses to inoculation with AM fungi by different finger millet varieties. Combined, these results highlight the importance of considering the finger millet cultivar effect as well as the strain effect of AM fungi.

Unfortunately, there is little literature available regarding development of new finger millet varieties with high yield potential under low or high nutrient input conditions, although more papers have appeared in recent years [3]. For example, in Nepal there are only three finger millets varieties that have been released after 1990 for commercial purposes [70]. Finger millet varieties suitable for different seasons and different parts of India are listed in Hegde and Gowda [22].

6. Research Gaps and Recommendations for Improving Nutrient Management in Finger Millet

Based on our literature review it is clear that limited attention has been paid to soil nutrient management issues related to finger millet compared to the other cereals like maize, rice, and wheat. Some of the research reports are restricted to a single growing season (non-replicated), lack appropriate controls, and/or the controls are not well defined (e.g., "farmer practice"). Furthermore, the majority of studies have been conducted in South Asian countries while there is a paucity of research in African countries where finger millet is a major crop. As summarized in this review, finger millet farmers have available to them different nutrient management options (Figure 3). In general, in the context of subsistence farmers, an integrated nutrient management approach appears to have the best potential to reduce the yield gap between potential yield and actual yield of finger millet farmers. This section highlights specific gaps and recommendations as follows:

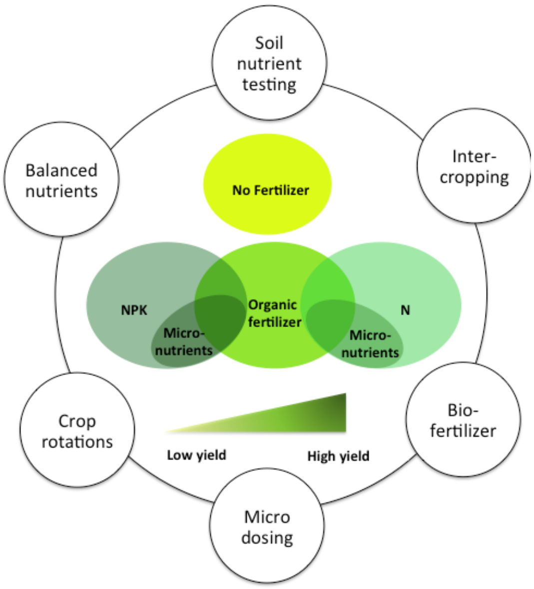

Figure 3. Nutrient management strategies that can be applied to maximize finger millet yield in farmers' fields. The internal Venn diagram (green) demonstrates the effects of integrated nutrient management on finger millet yield. The outer ring represents other nutrient management options that can be incorporated. Finger millet yield can be maximized through application of balanced NPK, farmyard manure (FYM), and micronutrients together, compared to no fertilizer, N alone or farmyard manure alone. Furthermore, a variety of management strategies can be applied together based on resource availability under different cropping systems.

6.1. Nitrogen Management

It is clear that one of the key nutrients that limits finger millet yield is N, since most of the soils under finger millet growing areas have medium to low soil N availability (75–330 kg N ha^{-1}) (Table 2). However, being a highly mobile nutrient, N is easily lost from cropping systems. There is a lack of information available regarding N fertilizer recovery by finger millet. Therefore, research needs to be conducted to evaluate and improve N use efficiency rather than a simple focus on increasing the amount of inorganic N applied. This is also important, as N is expensive for many subsistence farmers, particularly in Africa where there is a lack of fertilizer subsidies.

6.2. Phosphorus Management

Phosphorus is limited in most Asian and African soils [71]. One of the major constraints related to soil P is its low availability for plant uptake [72]. Little research has been conducted to evaluate the importance of P in finger millet and how to improve P availability in finger millet cropping systems. As P availability depends on soil pH (optimum pH of 6.5), it is important to maintain soil pH at a favourable level for nutrient uptake rather than adding extra fertilizer. Therefore, research on how to increase P solubility in soil using different P solubilizing bacteria, endophytes, and mycorrhizae may be beneficial, in addition to efforts to breed varieties that secrete organic acids from roots. Finding alternatives to inorganic P is very important such as different animal manures and green manures, as they may be locally available at low cost for subsistence finger millet farmers.

6.3. Potassium Management

There has been limited attention paid to K management in finger millet. Lack of K fertilizer application and removal of crop residues by farmers have decreased soil K levels [73]. Most of the finger millet growing areas are located on marginal lands, which suffer from drought stress. As K improves the drought resistance of plants [74], finger millet can benefit from K fertilizer. Furthermore, application of K along with N fertilizer can also improve N use efficiency [75].

6.4. Micronutrients

Most micronutrient studies on finger millet have focused on Zn and B. There is a need to evaluate the effects of other micronutrients (Mn, Cu, Mo) and secondary macronutrients (e.g., Fe) on finger millet growth and yield. As micronutrients are expensive compared to the major macronutrients, research on micronutrient seed treatments may be beneficial.

6.5. Organic Manure

A significant amount of research has been conducted to evaluate the importance of FYM and alternative sources of organic matter on finger millet growth (Table 2). However, most of the studies are restricted to Asia, whereas there is a need to explore different sources of organic manure for finger millet farmers in Africa, as soil and climatic conditions are unfavorable for crop growth in most of Sub-Saharan Africa.

6.6. NPK + FYM + Soil Testing

Typically, farmers in South Asia and Africa apply N as the sole fertilizer to their crops, as N fertilizer is subsidized by the government. However, an optimal nutrient balance is necessary to obtain higher yields of finger millet. The current literature suggests that application of NPK along with micronutrients and FYM (7.5–12.5 t ha^{-1}) increases finger millet yield. As soil fertility varies from field to field, fertilizer recommendations based on a soil test will be ideal in order to maximize yield while enhancing fertilizer use efficiency. Best-management fertilizer practices, which involve the identification of the right source, right place, right timing, and right application method [76] will also lead to more efficient management of fertilizers in finger millet systems.

6.7. Green Manures, Organic Byproducts, and Bio-fertilizers

Where fertilizer subsidies are not available, the application of alternative organic fertilizers may be beneficial for subsistence finger millet farmers due to the high costs associated with inorganic fertilizers. As discussed above, different organic options can be used to minimize the amount of inorganic fertilizer required (Table 2). Possible microbial bio-fertilizer options for finger millet include

Azospirillum, PSB, *Trichoderma*, *Bacillus*, arbuscular mycorrhizal fungi (AMF), and plant growth-promoting rhizobacteria (PGPR).

6.8. Crop Rotations and Intercropping

Subsistence farmers already grow a diversity of crops to meet their needs. Inclusion of carefully selected legume crops in finger millet based crop rotations can help to minimize inorganic N fertilizer requirements, as symbiotically fixed N can be transferred from previous legumes to a subsequent finger millet crop. Similarly, intercropping of finger millet with legumes also improves the overall yield and sustainability of the system, however selection of suitable legume crops and optimization of finger millet:legume sowing densities are critical to minimize competition.

6.9. Fertilizer Micro-Dosing and Split Applications

Micro-dosing is a strategy wherein fertilizers are applied in small quantities close to the seed or plant by digging a small hole [77]. Compared to the traditional farmer method of broadcasting fertilizers, micro-dosing minimizes the amount and cost of fertilizer as it is targeted to where roots are positioned, thus preventing leaching. Micro-dosing is an appropriate strategy to increase the yield and fertilizer use efficiency under marginal lands with low moisture availability [78]. Micro-dosing can also be practiced with organic fertilizers in areas limited to manure. In East and Sothern Africa, it was found that the grain yield of finger millet can be increased by 20%–40% by micro-dosing N fertilizer at a rate of 20 kg N ha^{-1} compared to much higher rates using traditional broadcasting [77]. As N is vulnerable to losses especially through leaching and volatilization, split application of inorganic N fertilizer (and other mobile nutrients) is an alternative management approach. The concept is to synchronize nutrient supply with plant demand, resulting in increased nutrient use efficiency. As a recommended practice, N fertilizer can be applied at the time of planting and again at 25–30 days after planting.

6.10. System of Ragi Intensification (SRI method)

With the success of the system of rice intensification (SRI), a similar method has also been introduced to finger millet, which in India is known as ragi, and hence this strategy uses the same acronym (SRI). This method involves transplanting seedlings at the two-leaf stage with some soil attached to the root, at a distance of 30 × 30 cm in a square pattern. Weeding between the rows is performed three times at an interval of 10–15 days by using a cycle hoe or hand weeder [79]. Application of the SRI method has been shown to improve finger millet grain yield significantly while reducing the cost. Therefore, the SRI method may hold significant potential for subsistence finger millet farmers in Asia and Africa.

6.11. Varietal Breeding

As already noted, there appear to be limited efforts to breed new varieties of finger millet that are adapted to low or high nutrient conditions. The development of high-yielding finger millet varieties for the arid and semiarid regions is a high priority. In particular, breeding is required to adapt finger millet to deficiencies of specific nutrients, and on the opposite end of the spectrum, to adapt this crop to high doses of synthetic fertilizers, analogous to the selection of semi-dwarfs in rice and wheat during the Green Revolution. Given recent changes in rainfall, there is a particular need to improve the yields of short duration varieties of finger millet grown under high or low input conditions. There are also opportunities to breed finger millet to be more compatible with companion crops (e.g., legumes) that improve nutrient availability to finger millet. Unfortunately, multiple years are required to release a new variety, since station trials, multi location trials, and adaptive research trials need to be conducted to compare a new variety with previously recommended varieties [80]. Therefore, a long-term funding commitment is required to enable developing countries to develop high-yielding, locally-adapted finger millet varieties. The yield evaluation of currently available local millet varieties is also important in order to provide appropriate varietal recommendations to local farmers. As an example, large numbers of Nepalese finger millet cultivars have been evaluated for yield and agro morphological characteristics [81]. Local farmers in Nepal select their own seeds for the next growing seasons using extensive seed selection procedures, and extension work can play a positive supporting role as has been previously shown [82].

7. Conclusions

Although the world's food supply depends on approximately 150 plant species, the majority of cereal based calories comes from three major sources: maize, wheat, and rice. However, due to its high nutritional quality, finger millet still plays a vital role in supplying staple food mainly to poor peoples of the world, especially in Sub-Saharan Africa and South Asia. Due to its longer storability, finger millet provides food security for poor people in these regions. Land degradation due to poor crop management practices, and low land availability for cultivation due to increased population have limited global finger millet production. Therefore, there is a need to improve finger millet productivity in order to improve the nutritional status of vulnerable poor rural people. Farmer-friendly proper nutrient management practices along with rational cropping systems can play a key role in achieving this goal. It is hoped that this review will help to better inform agricultural extension officers and other groups who make recommendations to subsistence farmers.

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Author Contributions

Both Malinda S. Thilakarathna and Manish N. Raizada conceived of the manuscript. Malinda S. Thilakarathna analyzed the literature and wrote the manuscript, and Manish N. Raizada edited the manuscript. Both authors read and approved the final manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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