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REVIEW

IMPROVING FERTILIZATION METHODS AND CROPPING SYSTEMS FOR SUSTAINABLE PRODUCTION OF PEARL MILLET (*PENNISETUM GLAUCUM*) IN WEST AFRICA: A REVIEW

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KEYWORDS

integrated management system, pearl millet, Science and Technology Backyard, West Africa

HIGHLIGHTS

- Constraints in cultivation and production of pearl millet in West Africa are summarized.
- Production systems and fertilization methods in pearl millet production are highlighted.
- Sustainable production needs integrated cropping systems and fertilizer use efficiency.
- A holistic approach is required to establish a strong collaboration among rural actors.

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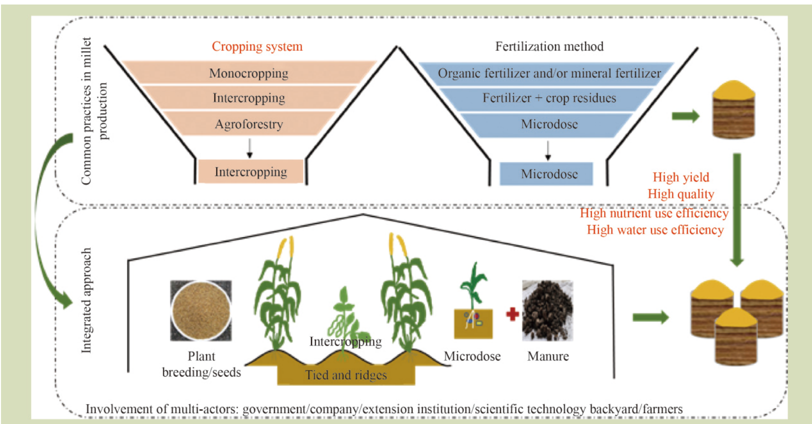
GRAPHICAL ABSTRACT



ABSTRACT

West African countries are among the larger global millet producers but have low yields mainly due to the low quality of their marginal soils. The objectives of this work were to analyze the benefits and constraints of pearl millet production, to summarize the impact of different cropping systems and fertilization modes while proposing a holistic approach for sustainable production. The major constraints on millet yields are low rates or absence of fertilizers, unsuitable cropping systems, and the proliferation of pests and diseases. Intercropping with cowpea is a widely used cropping system in addition to crop rotation, monocropping and agroforestry systems. Microdosing is the best fertilization mode for West African smallholders. It is concluded that integrated systems (breeding new cultivars, intercropping and microdosing) in tied ridges or infiltration pit practices, sustained by the implementation of innovative approaches such as the ‘Science and Technology Backyards’ from China are a promising approach for increasing pearl millet production. In addition, policies such as land protection of the farmers and subsidies of inputs from the government and the effective involvement of farmers and extension officers are necessary in sustaining millet production in West Africa.

1 INTRODUCTION

Agriculture in West Africa is characterized by subsistence agriculture practiced by a majority of smallholders who depend on this practice for their livelihoods. The major challenge of African agriculture is that the smallholders live in extreme poverty and struggle with unproductive soils, unreliable water supplies, low-quality seeds, low application rates of fertilizers and recurring droughts[1]. Cereals are the main crops produced and maize (*Zea mays*), rice (*Oryza sativa*), sorghum (*Sorghum* spp.) and millet (*Pennisetum* spp.) are dominant. Millet is the fourth most important cereal crop in West Africa. It is considered to be a crop for the future but yields remain low compared to other crops[2]. In 2018, the average yield of millet was 0.7 $t \cdot ha^{-1}$ compared to the global average of 0.9 $t \cdot ha^{-1}$[2]. Pearl millet (*Pennisetum glaucum*) is the major staple crop grown in the Sahel region. Its production and area are combined with other millet species such as finger millet (*Eleusine coracana*), foxtail millet (*Setaria italic*), proso millet (*Panicum miliacum*) among others. Global production of millet by region in 2018 was about 51% in Africa, followed by 46% in Asian countries, 1.3% in European countries, 1.1% in American countries (mainly for forage) and 0.1% in Oceania[2]. Major African producer countries are Nigeria, Niger, Mali, Burkina Faso and Senegal in West Africa, Sudan and Ethiopia in East Africa and Chad in Central Africa.

Saharan countries are characterized by severe droughts, low soil fertility, high salinity and high temperatures. These abiotic stress conditions constrain the productivity of pearl millet. Grain yields of pearl millet can be reduced by 40%–49% under terminal drought conditions[3]. Agricultural practices such as low rates or absence of fertilizers, low use or absence of high production pearl millet cultivars and inappropriate cropping systems also hamper millet yields. Weeds like *Striga hermonthica* can infest ⩾ 40% of cereal fields and cause yield losses of ⩾ 90% in some years[4,5]. This damage is exacerbated under low soil fertility, monocropping and drought conditions[6]. According to the Ministry of Agriculture of Burkina Faso, only 3.2% of the total area grown of pearl millet is grown from improved cultivars. Also, only ~ 35% of farmers have adopted improved cultivars of millet in Niger[7].

Currently, progress in terms of suitable production techniques, optimum nutrient and soil management (cropping systems and fertilization modes) and improved cultivars have been made available to farmers to increase pearl millet production. Intercropping systems reduce the risk of harvest loss[8]. Microdosing techniques allow maximum exploitation of soil nutrients due to early lateral root proliferation within the topsoil, leading to increasing pearl millet yields[9]. High yields of pearl millet grains have been achieved through the combined use of organic and mineral fertilizers in Senegal[10], Burkina Faso and Niger[11]. Thus, appropriate cropping systems are recommended combined with efficient nutrient management with fertilization mode to increase soil quality and pearl millet production by smallholders in West Africa.

The use of fertilization methods and cropping systems for millet production in West Africa has been addressed by other studies[8–11]. However, the improvement of millet production practices based on experiences from model countries is inadequately addressed. In addition to giving brief comments of practices on pearl millet production in West Africa, here we propose an integrated and realistic approach based on the use of suitable practices from East Africa and China. From this, research organizations and rural development agencies can obtain new information to improve their interventions in rural areas.

2 GENERAL PRODUCTION AND BENEFITS OF PEARL MILLET IN AFRICA

Pearl millet is globally the sixth most important cereal in terms of the planting area after rice, maize, barley (*Hordeum vulgare*), wheat (*Triticum aestivum*) and sorghum[2]. West Africa is often considered as its origin where the greatest number of wild ancestors or cultivated races are found[12,13]. It has spread to other countries through trade where it has been domesticated due to its extreme tolerance to drought. West Africa accounts for ~ 95% of total millet production globally. Pearl millet is an important staple food incorporated into a wide variety of dishes in semiarid areas of Africa and Asia. It helps with food shortages and in meeting the nutritional demands of an increasing human population. It is important to note that 85% of the production of pearl millet, sometimes mixed with sorghum, is used mainly in the self-consumption of agricultural households[14]. Millet stover is also used as animal fodder. Also, the stems are used for a wide range of purposes such as construction of hut walls, fences and thatches and the production of brooms, mats, baskets and sunshades[15]. However, the production and most of the consumption of millet have decreased in several countries in favor of crops such as maize and legumes. This decline in consumption is due to a lack of awareness of the nutritional quality of millet which is often considered as food for poor people. Pearl millet often has good nutritional value and health-promoting potential for humans mainly because of its high contents of protein (especially tryptophan and threonine)[16], starch, lipid, vitamins and minerals (Table 1)[17–19]. Also, dietitians and many health professionals recommended pearl millet because of its various health benefits[20]. It is therefore useful to promote the consumption of this cereal in West African countries where child malnutrition is unacceptably common.

In Sahelian Africa, where 97% of the agricultural land is rainfed and crop yields are ~ 0.5–1 $t \cdot ha^{-1}$[21], pearl millet covers more than 21 Mha with a production level of 15.9 Mt[2]. Nearly 500 million people depend on pearl millet for their survival thanks to its high nutritional value[22]. Considered as a tolerant plant species grown predominantly in sandy soils low in organic matter and nutrients in West Africa, pearl millet is grown during the wet season. Generally, it is planted as a continuous crop intercropped with sorghum, cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogaea*) or in rotation. Sowing of early millet is in April or May and of late millet in June or early July. Average grain yield ranges from 0.6 to 0.8 $t \cdot ha^{-1}$ in dry regions and 3–3.5 $t \cdot ha^{-1}$ with improved cultivars under favorable conditions[23].

In 2018, the top 10 millet producing countries worldwide were India, Niger, Sudan, Nigeria, Mali, mainland China, Burkina Faso, Ethiopia, Chad, and Senegal (Fig. 1(a)). West African countries had low yields and Niger recorded the lowest yield with only 0.5 $t \cdot ha^{-1}$ (Fig. 1(b)). In fact, in Africa, pearl millet yield has not shown a significant increase from 2009 to 2018 (effectively stable at ~ 0.7 $t \cdot ha^{-1}$). This is unlike other continents such as America, Europe and Asia which have recorded significant millet yield increases (~ 1.9–2 $t \cdot ha^{-1}$; 1.2–1.4 $t \cdot ha^{-1}$ and 0.8–1.3 $t \cdot ha^{-1}$, respectively) (Fig. 2). China has the highest yield increase from 1.6 to 2.5 $t \cdot ha^{-1}$ over that period[2]. The low yields in West African countries are partly due to the low fertilizer use (3% of global agriculture fertilizer used in 2017)[24], the low use of improved cultivars[25] and the lack of adoption of soil management practices.

3 MILLET PRODUCTION IN CHINA AS A MODEL

Foxtail millet and broomcorn millet are considered as Chinese millets. They were initially domesticated in northern China and became the predominant traditional grain crop[26,27]. The production area of millet in China has decreased and is now restricted to certain regions due to a shift to the cultivation of major crops with much higher yields such as maize, rice and wheat[27,28]. Nevertheless, China still has the highest millet yields globally with 2.5 $t \cdot ha^{-1}$ in 2018[1] due to effective farming practices in semiarid regions. For example, high grain yields of proso millet were obtained in a ridging treatment with hills and furrows and plastic film mulching as a result of increased soil water contents and water use efficiency[29]. Combined use of basal fertilizers and suitable planting densities together with elite cultivars has increased plant biomass and yields of summer millet[30]. In fact, integrated techniques such as plastic film mulching, mechanized production and agronomy have been recommended to increase foxtail millet production[31]. Millet yields have reached 13 $t \cdot ha^{-1}$ compared to 0.5 $t \cdot ha^{-1}$ using conventional management[31]. In addition, intercropping proso millet with mung bean (*Vigna radiate*) has increased millet yields by 5.6%–21%, 7.9%–54% and 28%–75% in the first, second and third years, respectively[32]. These practices might be applicable to millet production in West Africa provided that they can be adopted and implemented effectively.

Table 1 Nutrient content in 100 g of selected cereals

Crop	Calcium (mg)	Energy (kcal)	Iron (mg)	Lipid (g)	Niacin (mg)	Protein (g)	Riboflavin (mg)	Thiamine (mg)
Maize	3	368	1.3	1	1.0	9.4	0.08	0.26
Pearl millet	22	341	3	4	1.7	10.4	0.22	0.3
Rice	4	361	0.5	1	1.5	6.5	0.02	0.08
Sorghum	26	345	4.5	3.2	3.3	10.7	0.15	0.34
Wheat	15	341	1.5	1.3	0.7	9.4	0.03	0.10

Note: Data sourced from Latham[17].

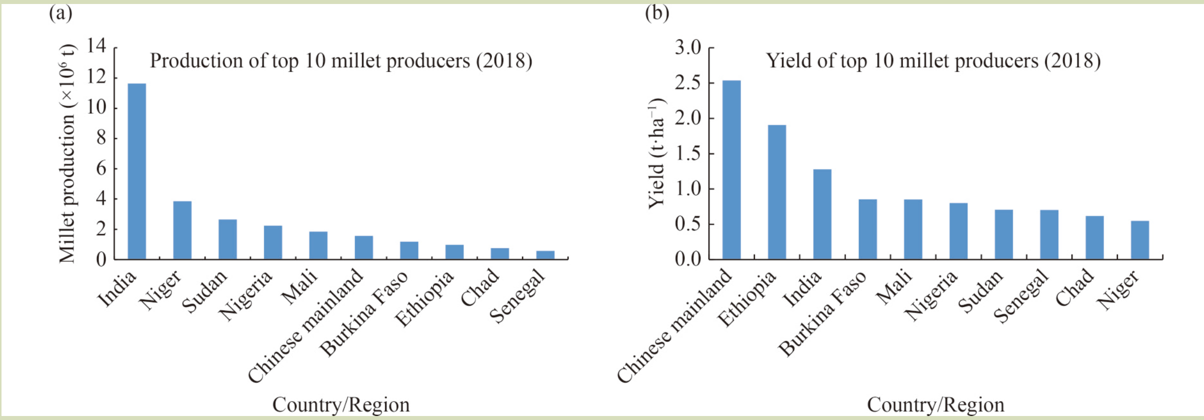


Fig. 1 Top 10 millet-producing countries/regions: (a) millet production and (b) millet yields. Data sourced from FAOSTAT 2019[2].

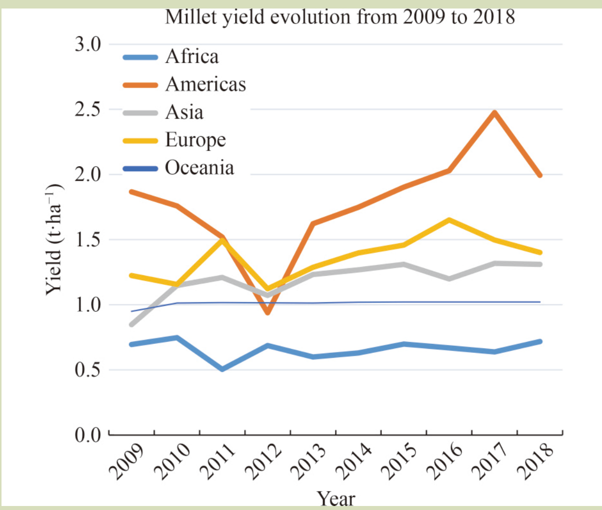


Fig. 2 Global pearl millet yield evolution from 2009 to 2018. Data sourced from FAOSTAT 2019[2].

4 CONSTRAINTS ON PEARL MILLET PRODUCTION IN WEST AFRICA

Millet production in West Africa is subject to both abiotic and biotic stresses[33]. Drought, low soil fertility, *Striga hermonthica*, head miner, birds and downy mildew are the main factors[34]. Socio-economic factors can also constrain pearl millet production[35].

4.1 Abiotic constraints

Abiotic constraints include the prevalence of drought conditions due to insufficient soil moisture and rainfall, to heat and light stress (high irradiation), to atmospheric drought (dry weather), and to low soil nutrient status and high soil salinity. Drought is the most important constraint in most millet producing areas of the world[35].

● **Drought:** West African agriculture is mainly rainfed, making it vulnerable to climate change due to the high variability of climate factors (rainfall and temperature). This variability leads to water scarcities and extreme events such as droughts which affect agricultural productivity and hence rural household food security[36]. In West African countries, despite irregular rains, pearl millet is not grown with other water sources such as supplementary irrigation[37]. This is due to the lack of irrigation resources and the low status given to millet compared with other crops by farmers. Indeed, semiarid areas show a significant variation in climatic factors (rainfall, temperature, insolation, wind speed and number of rainy days) that reduce the soil available water content. In most pearl millet growing regions the annual rainfall range is 150–800 mm[3]. However, the water demands of millet increase over the growing period (345 mm over 75 days, 420 mm over 90 days and 600 mm over 120 days)[4]. A drought period of 5–7 days can lead to drastic yield losses of the non-resistant millet cultivars. Drought or water stress can occur in pearl millet production across all growth stages, e.g., at the seedling stage, during the vegetative stage or at the time of grain filling. However, post flowering at the end of the season is more important and more sensitive to moisture deficit. Under terminal drought conditions the yield loss can range from 40% to 49%[3]. New techniques for soil water conservation such as the use of plastic mulch coupled with irrigation systems may reduce the impact of drought on millet production.

● **Low soil quality and low fertilizer inputs:** Low soil nutrient content and low organic carbon content are also limiting factors in most soils in the semiarid zones of West Africa. Soils are degraded as a result of nutrient-mining agriculture without sufficient minerals or organic nutrient inputs[38]. Millet is mostly grown in sandy soils that are poor in nutrients with average soil organic matter content of 1.4%, total nitrogen of 446 mg·kg^{-1}, available phosphorus of 8 mg·kg^{-1} and potassium of 78.2 mg·kg^{-1}[39] and low in water holding capacity. In addition, farmers seldom practice crop rotations or apply fertilizers[35].

In terms of fertilizer inputs the average fertilizer (N + P) consumption in Africa is 16.2 kg·ha^{-1}[40], only one-sixth of the world consumption (98 kg·ha^{-1}). In fact, despite poor soils, millet crops are rarely given enough inputs. This is associated with the high cost and unavailability of inputs at the farmer level and with the high adaptation of pearl millet to various production conditions. For example, in Burkina Faso, only 24% of millet areas have received NPK fertilizers over the four years from 2014 to 2017[41].

4.2 Biotic constraints

Pest and disease pressure is one of the main constraints to millet production. Millet is damaged by various kinds of biotic stress: diseases, insects, weeds and birds[34]. The relative overall impacts of pearl millet diseases are downy mildew 45%, *Striga hermonthica* 32%, smut 9%, ergot 7%, rust 3%, viruses 1% and other diseases 3%[42].

● **Diseases:** Significant yield losses are caused by a range of diseases due to viruses, fungi, bacteria, nematodes and others, and of which the most important are fungal diseases. Downy mildew caused by *Sclerospora graminicola*, millet smut caused by *Tolyposporium peniciluriae* and ergot by *Claviceps fusiformis*[34,43] are economically important diseases[42] (Table 2). The yield losses are in the range 20%–40% and 30% for downy mildew and millet smut, respectively[48,50].

● **Pests:** Compared to other cereals, millet is damaged by only a limited number of insects and weeds[20]. The main insect pests are classified into five groups: seedling pests, stem borers, leaf-eating insects, spike or candle pests and stock insects. Weeds and birds are also major problems in millet production in the Sahel region of West Africa. *Striga hermonthica* infests ⩾ 40% of cereal fields here. This is an important factor involved in the decline in millet yields in West Africa with a yield loss of ⩾ 90% in some years[5]. The monocropping system and the lack of organic matter application lead to the proliferation of this weed. The most common diseases and pests and their damage in pearl millet growing regions in West Africa are summarized in Table 2.

4.3 Technical and socioeconomic constraints

The low yields of pearl millet are also related to the lack of adequate technology infrastructure such as irrigation and soil water conservation facilities in rainfed agricultural ecosystems. Although improved production technologies such as better cultivars, quality seeds, and up-to-date information on crop management practices, may be available at the institutional level, they often do not reach farmers on time. In the latter case the problem is related to a lack of strategic organization that may be financial or at extension services level. The low yields are also due to a lack of highly productive cultivars including hybrids and the poor adoption of few open pollinating cultivars[34]. According to a survey conducted by the *Harnessing Opportunities for Productivity Enhancement* project in Burkina Faso, Mali and Niger, the main explanations for non-adoption of improved cultivars are: low seed availability, no insect resistance, late maturity, low yields, low drought

Table 2 Important pests and diseases in pearl millet and their damage in West Africa

Pests and disease		Impact on millet production	Reference
Pests	Millet stem borer	Yield losses ranged from 15% to total poor harvest	[44,45]
	Millet spike worms	Causes up to 85% losses in grain yield	[46]
	Weeds	It is one of the significant factors responsible for the decline in millet yields It also infests more than 40% of cereal production areas and causes a loss of yield of between 90% and 100% in some years	[5,47]
	Birds	These species are polyphages and the percentages of damage on millet vary from 10% to 30% and sometimes more, especially on early cultivars that ripen before others.	[41]
Diseases	Downy mildew	Disease incidence up to 90% is often recorded in farmers' field depending on location and specific cultivar Yield losses in the range of 20%–40%	[48,49]
	Millet smut	Yield losses amount to 30%	[50]
	Millet ergot	Its infection causes loss in seed yield, seed quality, germination, and seedling emergence. Grain yield loss has been estimated to be as high as 58%–70% in hybrids	[51]

resistance and high seed costs[37,52]. In Burkina Faso and Niger, low seed availability and late maturity are the two limiting factors, accounting for ~ 50% and 16% of the poor adoption of improved cultivars, respectively (Table 3).

Other constraining factors include low prices and inadequacy of demand for the processed products and a lack of technical know-how among farmers and processors about processing methods. The main obstacle to the marketing of local cereals is the weakness of marketable surpluses. Also, the involvement of many intermediaries in the marketing system inflates the cost of buying cereals. Furthermore, the lack of awareness by people about the nutritional value of millets, the general perception that millets are crops for poor people and the difficulty of the execution of certain processes (e.g., harvesting and pounding) limit production to the level of food needs.

5 CROPPING SYSTEMS FOR PEARL MILLET PRODUCTION IN WEST AFRICA

Millet cropping systems in West African countries are predominantly traditional and result in low productivity. In general, monocultured and intercropped (with cowpea) pearl millet are the dominant cropping systems[53]. Pearl millet is often grown in agroforestry systems[54] or intercropped with or rotated with grain sorghum, groundnut or maize[55].

5.1 Monocropping system

In most of the West African countries, pearl millet is grown in the lands near the concessions called box fields (without fenced) in monocrop or monoculture systems. This practice leads to rapid soil degradation and a proliferation of diseases, such as smut and downy mildew, insect attacks and weeds, such as *Striga hermonthica*. The reason why millet is grown as monocultures in these box fields are among other things damages caused by rambling animals on legumes such as cowpea grown in associated crops[56]. This cropping system, although it is practiced by many producers, would not contribute to an improvement in millet yields, unless a system of management of the fertility of the soils is integrated.

5.2 Intercropping system

The combination of millet and cowpea is the predominant farming practice[57]. The seeds of pearl millet and cowpea are mixed and sown on the same hill but other farmers are shifting the sowing date of the two species, with millet the main crop and sown first, and cowpea or other legume plants sown at the first weeding, e.g., 3–4 weeks after the sowing of millet[56,58]. Intercropping is practiced to maximize yields, for better use of resources, to reduce the risk of insect and weed attacks, crop diversity and increased farm income, and to take advantage of the beneficial effects of legumes (residual nitrogen) on other crops[56]. Similarly, biological and economic advantages of intercropped pearl millet and cowpea on increasing millet yields have been evidenced in the field[55].

5.3 Crop rotation system

Crop rotation is an ancient practice widespread in Saharan zones of West African countries. However, rotations between cereals and legumes occur at low frequencies and the rotation cycle is poorly defined on most traditional farms[56]. Furthermore, pearl millet yield does not usually increase with traditional millet-cowpea rotations unless inorganic fertilizer N and P and/or manures are added[59]. Indeed, this rotation system needs to be improved at the farmer level by the promotion of adapted legume crops like soybean and mung bean (*Glycine max*) which have a high nutritional value, higher symbiotic nitrogen fixation rate and the capacity to reduce pest

Table 3 Percentage of main constraints of non-adoption of pearl millet improved cultivars in Burkina Faso, Mali and Niger

Main constraints	Percentage of main constraints per country		
	Burkina Faso	Mali	Niger
Low seed availability	50%	8%	49%
No insect resistance	13%	8%	–
Late cultivar maturity	11%	15%	16%
Low cultivar yield	9%	12%	18%
Low drought resistance	2%	17%	–
High seed costs	1.66%	–	7%

Note: Data sourced from Badolo and Ilboudo[37], Silim S and Okwach G[52].

pressure (e.g., *Striga hermonthica*).

5.4 Agroforestry system

This type of intercropping is practiced in some of the West African countries. Indeed, pearl millet is sometimes grown under trees, especially *Faidherbia albida*, a perennial nitrogen-fixing acacia species (average 180–220 kg·ha^{-1} N) indigenous to Africa and widespread throughout the continent[60]. This tree is a multipurpose, deep-rooted, leguminous tree species with reverse phenology, as it has leaves present during the dry season that drop during the wet season[61]. It creates high soil fertility, high water availability, improved microclimate and better soil physical properties for millet[62]. Millet yields can be increased by 36%–169%[40,63].

In some regions, millet gown under areas where farmers allow natural regeneration of shrubs such as *Guiera senegalensis* and *Piliostigma reticulatum* has shown an increase in yield by ⩾ 41%[64]. This system is of great potential benefit to producers as it integrates agroecological parameters.

6 PEARL MILLET NUTRIENT MANAGEMENT IN WEST AFRICA

6.1 Fertilizers recommended for pearl millet production

Phosphorus is considered to be the most limiting element followed by nitrogen in the majority of West African soils[65]. Pearl millet is generally unmanaged and does not receive any fertilizers. Also, nutrient balances are negative for most crop systems with a larger output relative to input. For example, in Mali pearl millet the deductions are ~ 47 kg·ha^{-1} N, 3 kg·ha^{-1} P and 37 kg·ha^{-1} K per year, respectively, because no fertilizer is applied[66]. More realistic fertilization taking into account agroecological zones in West Africa is recommended to solve this problem. For example, the fertilizer recommendation for pearl millet is 100 kg·ha^{-1} NPK (1:2:1) as basal fertilizer and 40–80 kg·ha^{-1} urea as a top dressing[67]. In Burkina Faso, the fertilizer rate is 100 kg·ha^{-1} NPK (14:23:24) at plowing or after thinning and first weeding and 50 kg·ha^{-1} urea at the development stage[68]. In some African countries a range of types and amounts of fertilizers are recommended for millet production (Table 4). However, farmers generally do not use these fertilizers as recommended due to a lack of financial resources.

6.2 Fertilization modes for pearl millet production

Appropriate fertilization techniques are now available for farmers to increase millet production. These fertilization modes are:

- **Crop residues combined with fertilizers:** Use of crop residues increases soil water use over the control by, on average, 57–68 mm in a season and facilitates the trapping of windblown soil. In addition, crop residues reduce the export of plant nutrients (Ca, K and Mg)[71]. For example, a combination of 0.3 t·ha^{-1} millet stover and 2.7 t·ha^{-1} manure without

Table 4 Recommended fertilizers for pearl millet production in Mali and Nigeria

Country	Formulation process or agroecological zone	Nutrients recommended (kg·ha^{-1})	Material or fertilizer formulations that should be applied to achieve the nutrient levels of the main recommendation	Source
Mali	Field trials	31 N, 8.5 P_2O_5, 8.5 K_2O	NPK 17:17:17 (50 kg·ha^{-1}) + urea (50 kg·ha^{-1})	[69]
	Field trials	31 N, 8.5 P_2O_5, 8.5 K_2O, 2 S	NPK 17:17:17 + 4 S (50 kg·ha^{-1}) + urea (50 kg·ha^{-1})	
	Field trial	7.35 N, 16.1 P_2O_5	DAP microdosing (35 kg·ha^{-1})	
	Optimization function for maximum profit per hectare	8.5 N, 3.9 P_2O_5, 3.9 K_2O	NPK 15:15:15 in microdosing (26 kg·ha^{-1}) + urea (10 kg·ha^{-1})	
Nigeria	Sahel	60 N	NPK 20:10:20 (300 kg·ha^{-1}) or urea (131 kg·ha^{-1}) or CAN (261kg·ha^{-1})	[70]
	Sudan	30 P_2O_5	SSP (167 kg·ha^{-1})	
	Northern Guinea	30 K_2O	MOP (50 kg·ha^{-1})	
	Southern Guinea	30 N	urea (65 kg·ha^{-1}) or CAN (115kg·ha^{-1}) or NPK 20-10-10 (150 kg·ha^{-1})	
	Savanna and forest	15 K_2O	MOP (25 kg·ha^{-1})	

Note: P_2O_5, phosphorus fertilizer; K_2O, potassium fertilizer; N, nitrogen; NPK, combined fertilizer of nitrogen phosphorus and potassium; DAP, diammonium phosphate fertilizer; SSP, single superphosphate fertilizer; MOP, muriate of potash fertilizer.

mineral fertilizer increases yield by 95%, and a combination of 0.9 t·ha^{-1} millet stover, 2.7 t·ha^{-1} manure and 15 kg·ha^{-1} N + 4 kg·ha^{-1} P as fertilizer leads to an average increase in grain yield of 132%[72]. Use of crop residues in Africa faces competing interests due to their extensive use as fuel and building materials as well as an important source of animal feed[73]. Encouraging plant stover return to the soil by farmers would increase soil fertility and increase yields of cereals like millet. This might be possible with the implementation of new policies such as the introduction of fodder plants (*Andropogon gayanus, Bracharia brizantha* and *Stylosanthes hamata*) and the promotion of millet cultivars with high fodder potential in order to reduce this conflict.

● **Combinations of organic manures and mineral fertilizers:** Several types and forms of fertilizers are used for pearl millet production in many West African countries and numerous studies have reported increasing yields. In Senegal, high grain yield has been obtained with a combination of organic manure (5 t·ha^{-1}) and mineral fertilizer (75 kg·ha^{-1} NPK + 50 kg·ha^{-1} urea)[10]. Also, 2 t·ha^{-1} poultry manure recommended for pearl millet production in Niger has increased grain yields by 56% and stover yields by 53%[74]. Although these experiments have given satisfactory results, it is very difficult to see any impact in agricultural fields. Thus, close support for farmers on methods of efficient use of these fertilizers and participatory evaluation of their benefits on soil and crops could reverse the trend in the smallholder environment.

● **Microdosing technique:** This has been developed by the International Crops Research Institute for the Semi-Arid Tropics and consists of a small intake of mineral fertilizers. The microdosing technique has emerged as a method that may be interesting to smallholders[75,76] as it provides higher yields compared to current practices. It contributes to reduced cost of investment in fertilizers and might promote the intensification of agriculture in Sahelian West African countries. A microdosing rate of 20 kg·ha^{-1} NPK gave the best result in southern Mali[77]. Another study revealed an increase in millet grain yield of 76% (0.33–0.57 t·ha^{-1}) in Niger, of 180% (0.20–0.55 t·ha^{-1}) in Burkina Faso, and 27% (1.11–1.45 t·ha^{-1}) in Mali[78]. Also, stover yields increased by 61% (1.57–2.63 t·ha^{-1}) in Niger, 72% (0.93–1.59 t·ha^{-1}) in Burkina Faso, 66% (1.55–2.56 t·ha^{-1}) on sandy soil in Mali, and by 50% (2.50–3.75 t·ha^{-1}) on heavy soils in Mali. According to a survey in Mali, microdosing fertilizers provide higher grain yields (80%), lower mineral fertilizer costs (86%), reduced farm weeding period (86%) and higher producer incomes (33%)[79]. The extension to and adoption of this efficient use of fertilizers by farmers will help to solve the fertilizer access issues in under-developed countries. Also, it is important to note that *zai* pits system, half-moon and stone bund technologies are used in most Sahelian West African countries (Burkina Faso, Mali and Niger) to address issues of land degradation, soil fertility, and soil moisture for water use efficiency. If these technologies are combined using organic and/or mineral fertilizers, millet yields can attain 1–2 t·ha^{-1} in some areas where current yields are commonly ⩽ 0.5 t·ha^{-1}[80].

7 PERSPECTIVE FOR IMPROVING PEARL MILLET PRODUCTION IN WEST AFRICA

7.1 Integrated system (intercropping and microdosing) in tied ridges or infiltration pits

Intercropping has been used to increase crop production as well as a strategy to mitigate the risk of loss of harvests. In addition, farmers can harvest one of the associated crops if others have been negatively impacted by some factor such as drought[8]. In intercropping, complementarity is the general term used to describe the positive effects. In addition to the complementarity effects the practice might contribute to reducing many of the constraints of pearl millet production in West Africa, e.g., soil fertility and low use of fertilizers, pest and disease attacks, and reduce non-point source pollution by decreasing nitrogen losses.

Despite the advantages of intercropping on cereal yields, this practice alone cannot meet expectations at farmer level in West Africa. However, an integrated practice as a package combined with other practices may help to achieve spectacular results. The microdosing technique turns out to be the one best suited to West African conditions. The implementation of both intercropping and microdosing has great potential to increase millet yields.

Intercropping in this integrated package should include legumes with high potential for dinitrogen fixation such as soybean and mung bean. In some areas with high forage demand for livestock integration between millet and legumes with high potential of both fodder and grain yields could reduce the conflict of fodder utilization (e.g., fencing, energy and animal feed). Hence, legumes such as groundnut and cowpea are likely to be adopted due to their high fodder quality for livestock. The microdosing system integrated into such a package has to combine the use of both well decomposed organic manures and chemical fertilizers to maintain soil fertility. Microdosing is applicable only to chemical fertilizers while organic fertilizers must be applied and incorporated into the soil prior to the sowing of both millet and legumes. The maximum efficiency of such technology is achieved when sufficient water is available. Therefore, in order to increase efficiency, use of fertilizers and soil water, crops (millet and legumes) could be sown using the tied ridge soil management system (in humid zones with rainfall > 500 $mm \cdot yr^{-1}$) or infiltration pits (dry zones with rainfall < 500 $mm \cdot yr^{-1}$). For example, compared to flat cultivation at 30 cm depth after 10 days of rainfall, tied ridge systems and infiltration pits conserve soil water by 38% and 45%, respectively. Also, pearl millet and groundnut yields were increased significantly[81]. In Ethiopia, millet grain yield was increased by 65% with prolonged storage of soil water[82,83]. An integration of microdosing, tied ridge and intercropping of pearl millet with mung bean produced the highest grain yield (3.7 $t \cdot ha^{-1}$) compared to the integration of no fertilizer application and flat beds (2.1 $t \cdot ha^{-1}$)[84]. Also, intercropping of pearl millet and groundnut along with tied ridges and infiltration pits with microdosing rates (from 25% to 75% of recommended rate) provided a financial return of around 650–1000 $USD \cdot ha^{-1}$ higher than monocropped pearl millet in flat cultivation without fertilizer application in Tanzania[81].

7.2 Contribution of 'Science and Technology Backyards' to sustainable millet production in West Africa

The Science and Technology Backyard (STB) is an integrated platform developed by China Agricultural University over more than a decade to transfer technology to farmers. This platform is located in rural areas and links students, researchers, extension agents and smallholders (also including local government and private enterprises) in order to facilitate information exchange and technological innovation in agriculture. In the STB, agronomy professionals (experts) including researchers and postgraduate students live in the backyards of smallholdings and work together with farmers and extension agents. In this process the role of the scientists is no longer solely that of a teacher but also as a participant. Farmers are trained and knowledge is transferred through the multiactors innovation platform consisting of farmer field schools, participatory on-farm research, new technology demonstrations and farmer interest group or clubs. Through this platform they identify the problems that limit sustainable agriculture and provide smallholders systematic, integrated and holistic solutions without time lags, limitations, fees or distances[85]. Indeed, it is an effective approach to connect research/graduate students and farmers and to work together to identify key limiting factors, develop sustainable site-specific double high (high yield and high efficiency) technology, and help farmers adopt and implement double high technologies.

The STB has been very successful. Indeed, close training sessions in villages have significantly changed many farmer perceptions and increased the adoption rate of technologies, thus increasing smallholder production and nitrogen use efficiency. From 2009 to 2017, more than 200 technologies have been developed to increase the sustainability of crop production and 30,000 farmers in Quzhou County, Hebei Province on the North China Plain have been trained in the STB. These includes individual householders and also farming community at large[85]. According to Zhang et al.[86], grain yields increased by 20% without any increase in chemical fertilizer use after farmers adopted the technology recommended by the STB staff on the North China Plain. Across Quzhou County grain yields increased to 8 $t \cdot ha^{-1}$ without any increase in N fertilizer use in 2011, primarily due to the dissemination of innovative technology developed in the STBs[87]. Also, compared with conventional farming practice, nitrogen use efficiency by STB farmers increased by 11% and wheat yield increased by 23%. Similarly, maize yields increased by 10% and economic benefits by 20%[88].

It is a common consensus that the only way to increase food production and achieve food self-sufficiency in African countries is to empower smallholders to increase grain yields. This would require close collaboration among different stakeholders for farmer capacity building. Taking into account the constraints of agricultural production in Africa, STB is envisaged to build an effective approach that would facilitate promoting sustainable pearl millet production in West Africa. However, each African country should adapt and adjust this approach to its own realities, politics and challenges for positive outcomes.

7.3 Proposed solution for promoting pearl millet production: case study in Burkina Faso

In the context of climate change and land degradation, pearl millet is positioned to be the future crop for semiarid zones and many policies must be pursued to promote millet production. In the case of Burkina Faso, solutions may be effective at different levels where each partner (government, extension service agents, researchers and farmers) interacts to work closely together. Strategies must focus on the development of positive attitudes toward the adoption of improved pearl millet technologies and integrated management of water and soil fertility. Also, an adapted STB approach could act as an effective exchange and action platform for different stakeholders.

Government role: Government is responsible for the implementation of the policy in agricultural matters. These policies must take into account land transactions that are becoming increasingly recurrent in Burkina Faso. Farmers are deprived of agricultural lands for the benefit of agribusinesses that do not use this land for real agriculture production. In turn, these farmers, who are forced to borrow the land for their agricultural activities, cannot make sustainable investments in soil conservation and restoration techniques. Also, these policies need to strengthen the promotion of improved cultivars, agroforestry (*Faidherbia albida*), fertilizer subsidies and irrigation systems for smallholders, as well as training sessions for millet producers. To be sustainable, government is encouraged to implement projects to promote traditional cereals with top pearl millet which is considered a future crop for semiarid regions and for its high nutritional value. In this sense, there was a successful example of the millet project implemented by China-Burkina Faso Agricultural Cooperation, which aims to help Burkina Faso to establish a sustainable millet seed supply system by conducting field trials at farmer level, and construction of a millet seed research center[89]. The yield of millet attained $\geqslant$ 3 t·ha^{-1} after two years compared to the national yield of only 0.7 t·ha^{-1}. This project is expected to continue in future to strengthen such collaboration.

Researcher role: Researchers need to be more participatory in order to identify and take into account the genuine needs of farmers. Particularly, appropriate technologies and knowledge for the right sites and to right target farmers need to be considered. For example, seed breeding should include farmers to reflect their preferences in breeding objectives, as this serves to improve the acceptability of bred cultivars in challenging environments. In Burkina Faso the wide adoption of millet variety MISARARI I by farmers is due to their participation[90]. In addition to breeding programs, pearl millet processing techniques are a potential stimulus in its production.

Extension worker role: The adoption of technologies depends largely on the capability and the availability of extension workers. Based on a survey of sorghum and pearl millet production in Burkina Faso the low adoption of improved cultivars is due to the low level of education of farmers; the less educated households are less receptive to new technologies[37]. Hence, the attitude of the Burkina Faso farmers needs to be encouraged through prompt extension services coupled with education campaigns and farm trials on pearl millet benefits and efficient production systems. The other role of extension workers is to organize the millet sector by motivating the actors to create dynamic cooperatives that will serve as a platform for exchanges on the problems of the sector. This could facilitate the implementation of mechanisms such as the sustainable input supply system, advocacy with research (e.g., training and development on new cultivars responding to market needs), and other companies such as telecommunications, fertilizer and agricultural equipment production firms.

8 CONCLUSIONS AND RECOMMENDATIONS

Pearl millet is a future crop for the semiarid regions of West Africa. The low yield of pearl millet production in West Africa is due to multiple constraints such as the low use of fertilizers in marginal soils, low use of improved cultivars, unsuitable cropping systems and the prevalence of drought, which lead to disease invasion and pest attacks. Growing millet with legumes in intercropping systems or with microdosing techniques increases soil fertility and fertilizer use efficiency. Also, the practices of tied ridges or infiltration pits in millet production promote water conservation and water use efficiency. Thus, an integrated system (intercropping and microdosing) in tied ridges or infiltration pit practices and the implementation of innovative approaches such as the Science and Technology Backyards are necessary to attain maximum millet yields in West Africa. The following aspects should be taken into account to promote millet production in the future.

- Reducing the gap between development actors and smallholders in rural area will serve as a platform for permanent exchanges on the problems in the millet sector in real time between stakeholders (government, researchers and non-governmental organizations), fertilizer and seed companies and smallholders). Also, policies from government for assisting smallholders and the effective involvement of these farmers in the breeding processes will contribute to the increase in pearl millet production.

- Improving smallholder access to innovative agricultural technologies: the training of leader farmers would serve as a conduit to their peers in the extension of technology and in advocacy. This participatory approach will enable the development of technologies based on the needs identified by farmers. In the case of millet production, many practices such as the new millet cultivars adapted to climatic hazards and resistance to diseases and pests, integrated soil-crop system management and fertilizer use efficiency (intercropping and microdosing in tied ridges or infiltration pits) will improve.

• Facilitating strong farmer organization establishment to influence agricultural policies (group ordering of inputs and organizing sale of produce) for the benefit of smallholders. Future on-farm trials coupled with the use of improved cultivars may be needed to provide a holistic approach. These field trials conducted by leader farmers in their own fields, researchers and students assist in the dissemination of technology by empowering smallholders. Also, the implementation of STB will facilitate government and non-government organizations and seed and fertilizer companies to include their expertise for sustainable millet production.

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Compliance with ethics guidelines

Philippe Yameogo, Saturnin Zigani, Xiaoqiang Jiao, Hongyan Zhang, and Junling Zhang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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