Viability of Pearl Millet as a Climate Resilient and Nutritious Cereal in the West African Sahel

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Declaration

I declare that this thesis is all my own work [except where specified otherwise] and that I have not obtained a degree in this University, or elsewhere, on the basis of this work.

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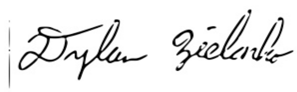

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Abstract

Pearl millet is an important cereal grain grown throughout the West African Sahel (WAS), where it is utilized as a source of nutrition, income and livestock fodder in a region facing severe levels of food insecurity and malnutrition. This review examines the current state of pearl millet in the WAS food system, with emphasis on cultural and nutritional relevance, cropping systems, pearl millet varieties, threats to production, future scenarios for continued production under near term climate challenges, and options for arid agriculture research institutes and extension systems to implement to improve production of pearl millet in the WAS. While pearl millet yields are relatively low compared to other global cereals, this aspect of their production is offset by the crop's ability to survive and produce reliable yields despite unfavorable soil and climate conditions across the arid region. Through increased mechanization, microdosing applications of nitrogen, phosphorus, and potassium (NPK) fertilizers, intensification of cereal-legume intercropping systems and widespread distribution of Striga and pathogen resistant hybrid seeds, pearl millet production systems can produce higher and more reliable yields in WAS. While climate change and poverty threaten the present and future of pearl millet production, it remains a high potential crop for the arid environment and traditional food pathways across the WAS.

Keywords: Sahel, West Africa, Arid Agriculture, Pearl Millet, Climate Change, Food Security

Introduction

Pearl Millet (*Pennisetum glaucum* [L.] R. Br.) is an important cereal grain widely produced on nearly 32 million hectares (ha) in the arid and semi-arid tropical regions of Africa and India (Satyavathi et al., 2021). Based on the number of hectares devoted to production, pearl millet is ranked as the sixth most important cereal crop globally, after rice (*Oryza sativa)*, wheat *(Triticum aestivum*), maize (Zea *mays*), barley (*Hordeum vulgare*) and sorghum (*Sorghum bicolor*) (FAOSTAT, 2022). While pearl millet is grown in more than 30 countries across five continents, India is the world's largest producer of pearl millet with nearly 36% of global output, amounting to over 11 million tonnes in the 2020-2021 financial year (Sanjana Reddy et al., 2021).

Over the past decades, production of millets (an annual warm-weather cereal category which includes multiple small seeded grass species like pearl millet, finger millet and fonio) has increased dramatically in Africa – especially across West Africa – where it is considered to be of major importance in the seventeen countries in the region (Satyavathi et al., 2021). One-third of the world's millet is grown in Africa, with about 70% of African millet being produced in West Africa (Azare et al., 2020).

Table 1: 2021/2022 Market Year Top Pearl Millet Producing Countries in Africa

Country	Production (tonnes)
Niger	2,361,150
Nigeria	2,118,642
Sudan	1,653,466
Mali	1,639,136
Senegal	1,145,301
Ethiopia	1,102,311
Burkina Faso	77,712
Chad	68,453

Source: Modified from Foreign Agricultural Service - United States Department of Agriculture (2022)

Niger, Nigeria, Mali, Senegal, Burkina Faso, and Chad are the largest producers of pearl millet in the WAS (Table 1). Pearl millet is harvested on over 14 million hectares (ha) across the WAS (Table 2), and accounts for 19% of the cultivated area used for cereal grain production (Macauley & Ramadjita, 2015). Pearl millet is an important crop in the arid WAS region, particularly in Senegal, Burkina Faso, Mali, Niger, and northern Nigeria, contributing to both rural food security and livelihood stability by serving as a highly nutritious cereal grain and income generating commodity for small-scale farmers (Garí, 2002). Average yields vary across the region due to a number of factors including climate, production practices, and economic conditions (Bationo et al., 2011). The primary purpose for growing pearl millet grain in the WAS is for human consumption. However, the leaves and stalks (known as stover) also provide value as livestock feeding material, cooking and heating fuel, and building construction materials (Mason et al., 2015; Obilana, 2003).

Table 2: 2020 Pearl Millet Area Harvested and Yield in WAS

Country	Area Harvested (ha)	Yield (hg/ha)
Niger	6,743,482	5203
Mali	2,164,374	8876
Nigeria	2,000,000	10000
Burkina Faso	1,183,792	8084
Chad	1,160,336	5917
Senegal	1,023,065	11190
Mauritania	11,647	2257

Source: Modified from FAOSTAT (2022)

The soils of the semi-arid and arid regions of the WAS are known for their predominantly sandy textures, coupled with both low levels of nutrients and organic matter (Bationo et al., 2011; Mason et al., 2015). Rainfall is scarce and irregular; soil and air temperatures are high; and the length of the growing season varies from year-to-year (Bationo et al., 2011; Mason et al., 2015).

While private sector breeding programs have released over 50 hybrid varieties of pearl millet in India since the 1960s (Singh et al., 2014), private sector breeding companies in the WAS are limited (Pucher, 2018; Sattler & Haussmann, 2020). Pearl millet breeding programs in the WAS are primarily orchestrated by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), which acts upstream of national crop breeding initiatives within National Agricultural Research Systems (NARS), predominantly funded by public financing (Pucher, 2018). Open pollinated varieties (OPV), as opposed to single cross hybrids, are the most common variety of pearl millet in WAS (Pucher, 2018; Sattler & Haussmann, 2020). The production of hybrid seed is a cost intensive process requiring specialized labor and time (Sattler et al., 2019). The availability of improved OPVs is increasing in several regions of the WAS, especially in areas where smallholder farmer seed cooperatives collaborate with national and global breeding projects (Pucher, 2018; Serba et al., 2017), however there are currently only a small number of private seed companies producing and marketing pearl millet seed in the WAS (Table 3) (Pucher, 2018).

Table 3: Seed Companies in WAS Region

Company Name	Country of Business Origin	Commercially Available Seed Types
AGRIPLUS	Mali	Field Crops and Vegetables
AINOMA	Niger	Field Crops and Vegetables
Da-Allgreen Seeds	Nigeria	Field Crops and Vegetables
Faso Kaba	Mali	Field Crops and Vegetables
Maslaha Seeds	Nigeria	Field Crops Only
NAFASO	Burkina Faso	Field Crops Only
Premier Seed	Nigeria	Field Crops Only
SEDAB	Senegal	Field Crops Only
Soprosa	Mali	Field Crops and Vegetables
Tropicasem	Senegal	Field Crops and Vegetables
Value Seed	Nigiera	Field Crops and Vegetables

Source: Modified from Diallo (2018)

The purpose of this study is to provide a review of research, development, and innovation on pearl millet in the WAS. Topics covered include pearl millet cropping systems, varieties, cultural and nutritional relevance of the crop, millet's potential as a substitute for wheat amid the current global food crisis, threats to millet production, and the viability of millet as a climate change resilient cereal grain. Concluding remarks include some options for pearl millet research and arid agriculture innovation to improve pearl millet production systems across the WAS.

Food Security in the West African Sahel

At the 1996 World Food Summit, the Food and Agriculture Organization of the United Nations (FAO) defined food security as "a situation when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for a healthy and active life" (FAO, 1996). Food and nutrition insecurity remains a major challenge across the WAS and its population of 135 million people (Amole et al., 2022). In a region targeted report, The Food Security and Nutrition Working Group (FSNWG) (currently co-chaired by the Intergovernmental Authority on Development – Climate Prediction and Applications Centre [ICPAC] and the FAO) stated that after three years of continuous declines, most nations which encompass the WAS are enduring the worst food and nutrition crisis in a decade (Table 4) (FSNWG, 2022). The FSNWG's analysis of the WAS shows high rates of hunger and malnutrition, with 30 million people experiencing acute food and nutrition insecurity (FSNWG, 2022). These 30 million people are currently in areas designated by the Integrated Food Security Phase Classification (IPC) as phase 3-4 (Phase 3: Crisis, Phase 4:Emergency) (FSNWG, 2022). These phases include acute malnutrition and the selling of essential assets in order to purchase food and non-food essentials (FSNWG, 2022). Included in this figure are over 1.5 million people currently classified in the Emergency phase (IPC level 4) (FSNWG, 2022).

Table 4: Food Insecurity Indicators in West African Sahel Countries

Country	Average Moderate or Severe Food Insecurity 2018-20 (% of population)	Average Severe Food Insecurity 2018-20 (% of population)	Global Hunger Index Rank, 2021 (Out of 116 countries)
Burkina Faso	47.9	15.4	91
Chad	Not reported	Not reported	113
Mali	Not reported	Not reported	92
Mauritania	41.2	6.6	85
Niger	56.4	16.6	Not reported
Nigeria	53.5	17.3	103
Senegal	44.0	10.0	66

Source: Modified from FAOSTAT (2022) & von Grebmer et al. (2021)

The FSNWG (2022) has indicated that, if no measures are taken to quickly address the level of food and nutrition insecurity in the WAS, the number of those living with acute food and nutrition insecurity will rise to nearly 41 million during the 2022 “lean season”, the period between harvests that lasts from June to August. The number of people classified in the Emergency phase (IPC level 4) is estimated to exceed 2.5 million during the 2022 lean season (FSNWG, 2022). This rise in acute hunger represents a nearly 140% increase compared to the five-year average, and an increase of 42% when compared to the 2021 Lean Season (FSNWG, 2022).

The current state of malnutrition in West Africa is of concern. In 2022, over 12 million cases of global acute malnutrition (GAM) (also known as wasting) are projected for children under five (FSNWG, 2022). Within these figures, severe acute malnutrition accounts for over 3 million cases (FSNWG, 2022). Burkina Faso, Mali, Niger, Mauritania, Senegal and Chad are the countries most severely affected (FSNWG, 2022). Estimates indicate 6.3 million cases of GAM, coupled with 1.4 million SAM cases across the WAS (FSNWG, 2022). In 2022, the SAM cases reached a record high level for the fifth-year consecutive year, with figures representing a 27% increase compared to 2021, and a 62% increase when compared to 2018 levels (FSNWG, 2022).

The 2022 State of Food Security and Nutrition in the World reported that globally 31.9% of women were experiencing moderate or severe food insecurity compared to 27.6% of men in 2021 (FAO, 2022). This gap of more than 4% represents an increase compared to 3% in 2020 and 1.7% in 2019 (FAO, 2022). This report highlighted that the food security gender gap is continuing to widen due to compounding crisis like conflicts, climate variability and extremes, and economic slowdowns and disruptions stemming from the ongoing COVID-19 pandemic (FAO, 2022). A saddening reality in the WAS is that during times of food crises, those most vulnerable to human rights violations and malnutrition are women and children (FSNWG, 2022). In the context of the food and nutrition security challenges facing WAS, pearl millet is a cereal that can be an important source of nutrition in the WAS.

Nutritional Relevance of Pearl Millet in the WAS

A diversified diet, rich in foods with adequate levels of macronutrients (carbohydrates, fibers, fats, and proteins) and micronutrients (vitamins and minerals), is a vital component of achieving a healthy life. Pearl millet grain is nutritionally equivalent or superior to most common, global cereals. The consumed grain is rich in protein, iron, zinc, magnesium, calcium, phosphorus, copper, manganese, riboflavin, and folic acid (Table 5) (Obilana, 2003; Satyavathi et al., 2021; Shukla et al., 2015). Pearl millet serves as a near equal source of energy (347 Kcal/100g) when compared to other commonly consumed cereals in the region: wheat (321 Kcal/100g), rice (356 Kcal/100g) maize (125 Kcal/100g) and sorghum (349 Kcal/100g) (Malik, 2015). Pearl millet offers a nutritional content which matches or exceeds many of the other common cereals in relation to fiber, calcium, and iron content per 100g of grain (Satyavathi et al., 2021; Serba et al., 2017). It offers between 3-122% more fiber than rice, wheat, and sorghum. Its calcium content (27.4mg per 100g of grain) nearly matches that of sorghum (27.6mg per 100g of grain), is comparable to wheat (39.4 6mg per 100g of grain) and far exceeds rice (7.5mg per 100g of grain). Pearl millets impressive iron content (6.4mg per 100g of grain) exceeds that of rice, wheat, and sorghum (.6mg, 3.9mg, 3.9mg per 100g of grain respectively). As a nutrient dense cereal grain, pearl millet is likely to continue to serve as a vital crop for bolstering food security and combating malnutrition in the harsh climate of the WAS region.

Table 5 - Nutritional Comparison of Pearl Millet Versus Other Cereals (per 100g of grain)

Nutritional Content	Crop			
	Pearl Millet	Sorghum	Rice	Wheat
Carbohydrates (g)	61.8	67.7	78.2	64.7
Protein (g)	10.9	9.9	7.9	10.6
Fat (g)	5.43	1.73	0.52	1.47
Energy (Kcal)	347	334	356	321
Dietary Fiber (g)	11.5	10.2	2.8	11.2
Calcium (mg)	27.4	27.6	7.5	39.4
Phosphorus (mg)	289	274	96	315
Magnesium (mg)	124	133	19	125
Zinc (mg)	2.7	1.9	1.2	2.8
Iron (mg)	6.4	3.9	0.6	3.9
Thiamine (mg)	0.25	0.35	0.05	0.46
Riboflavin (mg)	0.20	0.14	0.05	0.15
Niacin (mg)	0.9	2.1	1.7	2.7
Folic Acid (μg)	36.1	39.4	9.3	30.1

Source: Modified from Satyavathi et al. (2021)

Cultural Relevance of Pearl Millet in the West African Sahel

Pearl millet is typically used to make several different dishes across the WAS. Thick porridges known as "Tuwo" in the Hausa language or "Tộ in French (also spelled toh) are common foods prepared across all WAS countries (Satyavathi et al., 2021). The porridge is prepared by cooking whole pearl millet grains or a decorticated grain flour with water, and is often paired with a sauce (Hama-Ba et al., 2019). This sauce is generally made from vegetables or available leafy greens (Hama-Ba et al., 2019). Pancakes and gruels are also common traditional dishes featured across most nations of the WAS. Gruel preparation entails fermenting a paste obtained by soaking whole millet grains followed by milling and wet sieving (Hama-Ba et al., 2019). Pancakes are prepared using whole or decorticated grains which are converted to a fermented millet paste and then fried (Hama-Ba et al., 2019).

A steam-cooked "couscous" like pearl millet dish is more common in the French speaking countries of the WAS (Satyavathi et al., 2021). Another popular dish in the francophone countries of the WAS is a thin porridge known as "Bouillie" (Satyavathi et al., 2021). A thin-bodied porridge known as "Fourra" and a fried caked called "Masa" are very popular pearl millet-based dishes in Nigeria and Niger (Satyavathi et al., 2021). Popular Senegalese stews, porridges, and pudding are derived from millet flours, known as "Soungouf" and "Araw" (Satyavathi et al., 2021).

Pearl millet grains are also used in the brewing of both alcoholic or nonalcoholic beverages throughout Africa, as well as in China, India and Pakistan (Satyavathi et al., 2021). Traditional African beers brewed with grains like pearl millet and sorghum differ from the globally-known European lager style beers (Taylor, 2003). African beers like "Pito" are generally lower in alcohol (2.5-3% alcohol by volume) than European lagers (Agu, 1995; Taylor, 2003). Pito is the name given to a widely produced and consumed beer across the WAS brewed with sorghum or millet. Pearl, proso and finger millets are used to produce the fermented beverage. According to Taylor (2003), Pito possess a viscous-like texture, and its taste is sour due to the presence of lactic acid during fermentation (Fadahunsi et al., 2013; Taylor, 2003). Pito often has a pinkish, brown appearance due to the presence of anthocyanidin pigments in the millet grain and also cloudy because of yeast buildup and grain residuals in the brew (Agu, 1995). Pito also differs from other global lager style beers because it does not contain hops as a bittering agent, and the brew is often consumed while still actively fermenting (Taylor, 2003).

Many consumers across the WAS consider alcoholic beverages produced with cereal grains like pearl millet to be actual food due to their taste, nutritional value and hunger satiating qualities (Fadahunsi et al., 2013). Per liter, alcoholic beverages such as pito are nutrient dense with notable levels of manganese, magnesium, phosphorus, calcium, and protein (an impressive 5.9g per liter) (Fadahunsi et al., 2013). As is the case when comparing grain nutritional content, the nutritional content of alcoholic beverages made with pearl millet exceeds other global cereal grains like barley and maize.

The WAS is home to 135 million people, herding around 173 million head of ruminant livestock (Amole et al., 2022). The main feed resources for these millions of ruminants are pastures and crop residues (Amole et al., 2022). In the WAS, crop residues mainly include cereals such as millet and sorghum as well as legumes, such as cowpea and groundnut haulms (Umutoni, Bado, Whitbread, & Ayantunde, 2021). The remaining stems, sheaths and leaves of field crops following grain harvest are known as stovers. During the dry season (November to late May) stover from millet and sorghum production are a primary feed source for ruminant livestock (Amole et al., 2022; Teferedegne, 2000; Umutoni, Bado, Whitbread, Ayantunde, et al., 2021). Drawing from an FAO regional study of member countries of the West African Economic and Monetary Union (also known by its French acronym, UEMOA), Abdoulaye and Ly (2014) found that pearl millet ranks first in terms of residue biomass, accounting for about half of the cereal residues (40m tonnes), followed by sorghum. WAS countries (Niger, Burkina Faso, Mali and Senegal) have the largest share (90%) of crop residues, especially millet and sorghum residues, in the UEMOA region (Abdoulaye & Ly, 2014).

Pearl Millet's Potential as a Substitute for Wheat

Since its beginning in February 2022, the war in Ukraine has created and exacerbated humanitarian crises and contributed to a global increase in food insecurity (Ben Hassen & El Bilali, 2022). Due to the region's high dependency on cereal imports (Table 6) from countries like Ukraine and Russian, coupled with existing problems stemming from Covid-19 pandemic supply chain impacts, many nations within the WAS will be particularly affected. With disruptions in wheat, maize and sunflower imports to the African continent, the current era may present an opportunity to examine if pearl millet can serve as a substitute for imports like wheat.

Table 6: Average Cereals Imports Dependency Ratio in West African Sahel Countries, 2017-19

Country	Percent (%)
Mauritania	-
Chad	4
Mali	4.8
Niger	6.6
Burkina Faso	9.2
Nigeria	16.5
Senegal	42.7

Source: Modified from FAOSTAT (2022)

Pearl millet is used in a variety of different forms across the WAS and globally: unleavened bread, pancakes, biscuits, porridges, gruel, beverages (both alcoholic and non- alcoholic) (Jumoke & Famakinwa, 2022). With a reputation as a poor man's bread, pearl millet flour can be used to substitute 10-20% of wheat flour in numerous breads, pretzels, crackers, tortillas, as well as dried and creamed cereal grain products (Dahlberg et al., 2003; Jumoke & Famakinwa, 2022).

Despite pearl millet's nutritional superiority to many cereal flours, the low shelf-life of pearl millet flour presents a problem in its ability to serve as substitute for wheat (Ali et al., 2022; Kumar et al., 2022). While in storage, pearl millet flour quickly browns and turns rancid due to the crop's high concentrations of C-glycosyl flavone (C-GF's). Additionally, higher C-GF's content was associated with a darker color and off odor of the flour. The enzyme activity following milling of pearl millet grains make the flour unsuitable for human consumption after only 10 days of storage (Ali et al., 2022; Kumar et al., 2022). The short shelf life of pearl millet flour is the primary limitation to consumer adoption and hinders its ability to serve as a more widely used substitute for wheat or rice flour. Ali et al. (2022) has stressed the need for further research to help develop new varieties of pearl millet which can provide flour with extended shelf life, while also retaining its nutritional benefits.

Crop Varieties of Pearl Millet

A 2008 report from the FAO entitled *West African Catalogue of Plant Species and Varieties* outlined 72 pearl millet varieties across 17 West African countries. This report catalogued the pearl millet varieties' genetic nature, days to maturity, height, panicle length, seed kernel weight and yield potential (Mason et al., 2015).

While most pearl millet varieties are short–day photoperiod sensitive, varieties of pearl millet can range from short oasis type species which mature two months after sowing, to varieties which mature after five months, are highly-photoperiod-sensitive and grow up to 4.5 meters tall (Mason et al., 2015). Like most plants, pearl millet can display high levels of heterosis (when F1 progeny exhibit superior or improved traits relative to parental genotypes) and adaptation to abiotic stresses that will intensify and become more frequent as a result of climate change (Jat et al., 2012). Some varieties of pearl millet in the WAS can survive soil surface temperatures of up to 55°C, adapt to frequent drought and heat stress, and reach the grain filling stage despite unfavorable water deficient conditions (Bidinger & Hash, 2004; Winkel et al., 1997).

Traditional varieties (landraces) of pearl millet in the WAS are tall, with typically low but stable yields (Mason et al., 2015). While studying the crop's water saving characteristic under marginal rainfall condition in Niger and Senegal, Payne et al. (1990) and Dancette (1983) found that pearl millet's yield is related to water use efficiency (WUE) of the crop variety. Breeding programs have developed pearl millet varieties which feature several desirable traits: shorter maturation times, higher grain yields and a canopy which allows for increased light penetration leading to higher yields of intercropped food producing plants (Mason et al., 2015). These hybrid varieties with a suite of improved traits often still underperform in yield production, due to water and nutrient stress coupled with poor farming techniques such as low planting population and low use of NPK fertilizer (Maman et al., 2000; Payne, 1997). Therefore, factors such as location, cropping system, disease and pest resistance and intended use of the pearl millet yield must be considered for a farmer to choose the best varieties for their fields.

Pearl Millet Cropping Systems

Pearl millet is produced both as a sole monocrop or intercropped with other common nutritional staple crops of the WAS region: ground nut (*Arachis hypogaea), s*orghum (*Sorghum bicolor*), maize (*Zea mays*) or cowpea (*Vigna unguiculata*) (Reddy et al., 1992). WAS intercropped systems are location specific and the system's production practices vary greatly due to soil quality, climate conditions, agronomic input availability, and crop variety accessibility at the site of production (Mason et al., 2015).

One regional example is the intercropping systems across Niger that utilize hill planting (planting cereal grain seeds in clusters in raised soil mounds). Late maturing, tall varieties of pearl millet are planted after the early, minimal rains (first 10-20 mm of precipitation) of the growing season (Reddy et al., 1990). Intercropping with less resource competitive crops like early maturing cowpea cultivars helps to minimize the risk of yield loss (Ntare, 1990). Cowpeas are often planted following the sowing of pearl millet, generally two to six weeks after the planting of pearl millet (Ntare & Bationo, 1992; Reddy, 1988). It is recommended that spacing between pearl millet rows be 1.5m with two rows of cowpea planted between them (Reddy, 1988). This intercropping of cowpea should be planted when it is time for the first weeding of the pearl millet rows (Mason et al., 2015). In this particular system of intercropping, WAS farmers prioritize the full development of pearl millet for both grain yields and stover (Mason et al., 2015). Cowpea is utilized for grain and stover as well, but is considered of secondary importance to pearl millet production. Pearl millet will mature before cowpea, leaving the plant to utilize the remaining soil moisture or a late season rainfall to help produce an adequate yield (Fussell et al., 1987).

Pearl millet is also grown in agroforestry systems with the leguminous trees *Faidherbia albida*, *Vitellaria paradoxa and Parkia biglobosa* (Mason et al., 2015; Reij & Smaling, 2008). These tree species have long served as an important component of Sahelian agriculture in the cropping systems of Senegal, Mali, Burkina Faso, Niger, Chad, Sudan, and Ethiopia, and in parts of northern Ghana, northern Nigeria, and northern Cameroon (Boffa, 1999; Kho et al., 2001; Mokogolodi et al., 2011). Yields of pearl millet are substantially higher in a production system intercropped with *F. albida,* with increases of 36-169% in studies conducted by Mokgolodi et al. (2011), Reij et al. (2009), and Kho et al. (2001). These increased yields are attributed to higher levels of nutrients in the soil, increased availability of water, more growth suitable microclimates and improved soil physical properties (Kho et al., 2001; Mokgolodi et al., 2011; Vandenbeldt & Williams, 1992).

The tree's unique reverse phenology is beneficial to pearl millet production because the growth cycle is a different time than other cereal grain crops with its leaf growth occurring in the dry season and the foliage drops during the months of millet growing season, reducing shade and allows the crops below the canopy to grow (Mason et al., 2015; Mokgolodi et al., 2011;

Vandenbeldt & Williams, 1992). Vandenbeldt and Williams (1992) demonstrated greater pearl millet growth especially during early stages of crop establishment due to decreased soil temperature as result of shading from the pearl millet/ *F. albida* intercropped production system. The *F. albida* leaves entering soils serve as a supply of organic fertilizer during the pearl millet growth season, and a dense strand of 50 large trees per ha offered the equivalent of almost 50 tonnes ha^{-1} of manure (Mokgolodi et al., 2011). The nutrient provided by the fallen leaves increases pearl millet productivity and reduces the need for extended fallow periods on the region's poor-quality soils (Garrity et al., 2010; Kho et al., 2001; Mokgolodi et al., 2011; Reij et al., 2009). The Kho et al. (2001) experiment found that levels of soil nitrogen and phosphorus were estimated to be 200% and 30% higher, respectively, under the *F. Albida canopy*, compared to open fields used for pearl millet production.

Bush fallowing is a subsistence agriculture method, where a field is cultivated for several years and then left uncultivated for years to allow the piece of land to regain its fertility (Ramakrishnan, 1984). Soils across the WAS are very sandy and infertile, making bush fallow a common practice to help improve levels of soil organic matter and nutrient content (Mason et al., 2015; Reddy et al., 1990). Under these bush fallow systems, fields will traditionally be used for crop production for 3-5 years then spend 7-15 years in an uncultivated state to replenish soil nutrients (Mason et al., 2015). Bush fallow is only used by 2% of pearl millet producers in millet producing countries like Niger, Burkina Faso, and Nigeria (Schlecht & Buerkert, 2004). Due to population increases, accelerated soil degradation, and expanding economic development, the bush fallow method is decreasingly able to adequately improve levels of crop nutrients (Mason et al., 2015).

Threats to Pearl Millet Production

Average pearl millet yields in the WAS remain low at 450-650 kg ha^{-1} (Fuller et al., 2019; Sattler & Haussmann, 2020) and there are multiple of threats that constrain production.

Climate Threats

The WAS is predicted to see shifts in temperature, rainfall, storm intensity and frequency, and sea level rises throughout the 21st century. Currently, rates of annual precipitation across the WAS are scarce (300-500 mm/year), but also vary from year to year, causing drought and occasionally flooding (Haussmann et al., 2012; Vadez et al., 2012). These patterns of low and erratic rates of precipitation are predicted to worsen as climate change will threaten the smallholder farmers across the region whose agriculture systems are almost exclusively rainfed (Cooper et al., 2008; Jarvis et al., 2011). Maximum temperatures across the WAS exceed 42°C (Yadav et al., 2015) and soils across the region are weathered, depleted of nutrients (especially phosphorus) and have low pH levels (Bationo et al., 1992; Gemenet et al., 2014).

While pearl millet can produce reliable yields in arid regions with low and unpredictable rainfall, drought still poses a threat to production in the WAS. This drought stress results in low and unreliable yields (Chitalu, 2014; Wilson, 2007). Post flowering drought stress is one of the most impactful abiotic factors and has been shown to reduce grain yields by 70% (Chitalu, 2014; Yadav, 2010). Total crop failure can result from excessive rainfall during the flowering stage (Chitalu, 2014; Newman et al., 2010). Terminal or end-of-the season drought generally occurs at the post flowering stage of crop development. The post flowering stage is highly sensitive to prolonged moisture deficit conditions, with yield losses of 40-49% following periods of terminal drought (Fussell et al., 1991). The combination of widespread nutrient deficient soils, climate stress and low adoption of adequate agricultural inputs contributes to poor yields (Jukanti et al., 2016).

Biotic Threats

A range of biotic sources threaten pearl millet production in the WAS. These include the parasitic weed Striga and downy mildew caused by the bacteria *Sclerospora graminicola.*

The parasitic weed Striga (*Striga hermonthica)* poses the most significant threat to pearl millet production in the WAS (Mason et al., 2015). Low soil fertility, drought, and sequential seasonal plantings of pearl millet and other regional cereals increases the prevalence of Striga infestation (Andrews & Bramel-Cox, 1993). These conditions are common throughout the WAS. Striga seed build-up and subsequent spread can be stymied during long fallow period where it is unable to leech host cereal grain plants (Mason et al., 2015).

Downy mildew (*Sclerospora graminicola)* remains the most damaging pearl millet disease. When conducting field trials on yield loss in Niger, Gwary et al. (2009) found downy mildew caused grain yield losses of up to 33.8%. While downy mildew is the most damaging and prevalent disease, other diseases of concern are rust (*Puccinia substriata*), smut (*Moesziomyces penicillariae*), ergot (*Claviceps fusiformis*) and leaf spot (*Pyricularia grisea*) (Mason et al., 2015).

Pest Threats

The biotic threats to pearl millet production includes a slew of pests. Insect pests threatening pearl millet production throughout the WAS include the pearl millet leaf miner (*Heliocheilus albipunctella* de Joannis), stem borer (*Coniesta ignesfusalis*), armyworms (*Spodoptera exempta*), and several different species of grasshoppers (Mason et al., 2015). Pearl millet does however possess a high capacity to withstand insect stress (Mason et al., 2015). This natural tolerance is important in a region where agrichemicals like insecticides are expensive and remain financially unavailable for most smallholder farmers (Buntin et al., 2007). Widespread poverty among the WAS's smallholder farmers, together with safety concerns are largely responsible for the limited adoption of insecticides in pearl millet production (Abate et al., 2000).

Along with the abiotic and biotic stresses, yield increasing inputs such as fertilizers and insecticides are often far too expensive for smallholder farmers across the WAS (Sattler & Haussmann, 2020). Inaccessibility and lack of training on proper use, impede adoptions of these useful agronomic tools (Sattler & Haussmann, 2020).

Future Prospects for Pearl Millet in the West African Sahel

There are a number of promising strategies for intensifying pearl millet production in the WAS. Implementation of these methods presents an opportunity for food security improvement in the face of a rising regional population and climate change challenges.

Inputs

Testing of pearl millet's response to nitrogen, phosphorus, and potassium (NPK) fertilizer application as well as the crop's response to diammonium phosphate (DAP) shows great promise for boosting pearl millet yields through increasing rates of fertilizer application (Nourou et al., 2020). Currently fertilizer use is low in Sub-Sahran African (SSA) and does not surpass a rate of 6–7 kg ha^{-1} of NPK compared to fertilizer use in developing countries where the average is nearly 100 kg ha^{-1} (Reij & Smaling, 2008). Over a three-year period, Bielders and Gérard (2015) found that microdose fertilizer application of DAP (2 g $hill^{-1}$), NPK (6g $hill^{-1}$), or DAP (2g $hill^{-1}$) with urea (1g $hill^{-1}$) applied at the tillering stage contributed to increased grain yields of 43, 46 and 69 kg ha^{-1} respectively. The application of NPK fertilizer increased pearl millet by 54.9% compared to the unfertilized control plot. Similarly, Aune et al. (2019) found that a microdose fertilizer rate of 0.4 g NPK $hill^{-1}$ (4 kg NPK ha^{-1}) in the more arid central Mali and a microdosing rate of 0.8 g NPK $hill^{-1}$ (20 kg NPK ha^{-1}) in the southern region of the country brought about a 26% increase in pearl millet grain yields. This strongly suggests pearl millet producers should apply fertilizer to optimize pearl millet grain and stover yield (Maman et al., 2000).

Pearl millet seeds can be protected with the treatment of Apron Star, a crop protection chemical cocktail consisting of metalaxyl fungicide plus furathiocarb insecticide (Scheuring et al., 2002; Thakur et al., 2011). The use of Apron Star as a seed treatment increased pearl millet yields by 30-45% when applied to a landrace in Mali (Scheuring et al., 2002). Hess et al. (2003) noted that the use of Apron Star is shown to be effective only during the first 35 days of plant growth. With the damaging infestation of downy mildew occurring during the seeding stage of plant development, application during this first 35 days of growth is most effective and is shown to reduce over 80% of yield loss in crops suffering from downy mildew infestations (Hess et al., 2003).

Production

Pearl millet production across the West African Sahel is dominated by manual sowing and weeding and features low use of mineral and organic fertilizer. Nourou et al. (2020) conducted an experiment to intensify pearl millet production in Niger using a crop production package consisting of seed priming, fertilizer microdosing (0.3 g NPK $hill^{-1)}$, seed treatment with a combined fungicide/insecticide, and sowing and weeding using a combined planter/weeder (multicultivator). The multicultivator machine used was the Malian super-eco (produced by Agric. Construction Cissé et Frerès, Koutiala, Mali) (Nourou et al., 2020). Mechanized operations cut the average sowing and weed time to 20.3 hours ha^{-1} a significant labor hour reduction from the 70.2 hours ha^{-1} in manual operations. In the mechanized operation, the time to plant maturity was reduced by 11 days compared pearl millet growing in the traditional farming practice. There was an increase in average grain yield as well with the mechanized operation producing 1470 kg ha^{-1} compared to the 946 kg ha^{-1} in traditional operations (Nourou et al., 2020). Additionally, there was an increase in the pearl millet stover yields as well; the mechanized operation produced 3005 kg ha^{-1} compared to 2460 kg ha^{-1} produced in the traditional operation (Nourou et al., 2020). The improved package increased the gross margin of pearl millet sales by 80.2% compared to the traditional production method (Nourou et al., 2020). The mechanized operation's increase in pearl millet grain and stover yields was a direct result of more precise sowing, faster crop maturation, effective fertilizer microdosing and superior weed management. Pearl millet producers should increase plant population and apply fertilizer to optimize pearl millet grain and stover yield (Maman et al., 2000).

Seed priming is an on-farm pre-sowing treatment that uses controlled hydration to initiate the germination process before they seeds are planted. This early germination process can better enable seeds to survive under adverse climate conditions such as extreme draught or heat (Nourou et al., 2020). Aune et al. (2012) observed a 40% increase in pearl millet grain yields when seeds were primed prior to planting in the low rainfall regions of Mali; when seed priming was combined with the application of 0.3 g NPK fertilizer $hill^{-1}$, increased millet yields by 106%. With its low cost, seed priming is a promising practice for resource-poor farmers in the WAS.

Intercropping Systems

Crop rotation (Bagayoko et al., 2000), intercropping (Buntin et al., 2007), and agroforestry (Kho et al. (2001) increase biodiversity and can curb yield loss from pests and pathogens ultimately producing higher yields. Location, annual rainfall, and distribution of rainfall across the growing season all influence the ideal number of rows and spacing of a pearl millet intercropped system (Odo & Bibinu, 1998). According to Mason et al. (2015), recommendations for pearl millet intercropping systems are predominately focused on Niger, and are outdated with most sources approaching 20 years old. Studies should be updated to incorporate new crop varieties and production practices into recommendation for continued and expanded intercropping systems for broad use across the WAS.

When microdosed with mineral fertilizers and combined with organic fertilizers like mulch derived from pearl millet crop residue, cereal-legume intercropping systems can be used to improve soil fertility and boost grain yields across the WAS. In a study conducted over 25 years in Niger, Bado et al. (2022) examined the long-term effects of utilizing organic and mineral fertilizers use in cowpea/pearl millet intercropped systems. The common millet/cowpea intercrop system without phosphorus fertilizer (TrM/C) was compared with four other cropping systems each receiving a microdose of P fertilizer: millet as a monoculture (MM), millet/cowpea intercrop (M/C), millet-cowpea rotation (M-C), and M/C and rotation with cowpea (M/C-C) (Bado et al., 2022). Nitrogen fertilizer along with the residues of pearl millet were applied individually or in a combined application in all five cereal-legume cropping systems (Bado et al., 2022). All four intercropped systems with phosphorus fertilizer (MM, M/C, M-C and M/C-C) increased grain year over year compared to the traditional system (TrM/C) (0.02-0.43 t/ha) (Bado et al., 2022).

The most significant yield increase was seen in the M/C-C and M-C intercropped systems which produced 4 and 4.2 times more grain yield than that of the TrM/C system, respectively (Bado et al., 2022). The MM, M/C, M-C and M/C-C intercropped systems increased soil phosphate levels by 3.4-4 times. Notably, the highest millet yields were achieved in years with lower levels of rainfall, exemplifying the role of nutrients in the pearl millet/cowpea intercrop systems (Bado et al., 2022).

The introduction of the wasp species *Habrobracon hebstor* has proven to be an effective biological control for decreasing pearl millet leaf miner population across test sites in Mali, Burkina Faso and Niger (Payne et al., 2011). In 2015 and 2016, a large-scale release of the parasitoid in five regions of Niger was conducted. Two years later, farmers reported an average of 76% mortality rate in leaf miner larvae and a 50% increase in millet yield due to the parasitoid release (Amadou et al., 2017). With pesticide control widely inaccessible in the WAS, training and support for smallholder farmers in rearing and releasing *Habrobracon hebetor* can greatly improve their resiliance to leaf miner (Payne et al., 2011).

Varieties

Improved varieties can help pearl millet withstand biotic (and abiotic) threats. For example, since 2006, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), along with partnering national and academic agricultural research institutes across the WAS, have worked to develop a diverse and accessible Striga-resistant pearl millet gene pool. The primary cultivated genepool of pearl millet can be subject to recurrent selection to target crops with Striga resistance, high panicle yield and to a lesser extent, resistance to another pearl millet pathogen, downy mildew (Kountche et al., 2013). In Striga-infested fields during the 2011 rainy season at Sadoré (Niger) and Cinzana (Mali), Kountche et al. (2013) conducted a species selection cycle among parental landraces and experimental varieties derived from previous selection cycles. This process of recurrent selection led to a decrease of Striga infestation (up to 51% in some plots). Such Striga resistant cultivars and landraces will improve Striga control in pearl millet production across the WAS. The use of resistant varieties is also an effective method of downy mildew control (Hess et al., 2003; Thakur et al., 2011).

Improved pearl millet cultivars also show promise in increasing the crop's value as livestock fodder through benefits such as pest and pathogen resistance, weight gain performance, and lower greenhouse gas emissions (Umutoni, Bado, Whitbread, & Ayantunde, 2021). Several species of pearl millet (MISARI-1 & ICMV 167001) possess a high fodder biomass, producing a stover that is high in fiber and crude protein, while others display higher digestibility and average daily weight gain for livestock (ICMV 167005 & ICMV 167002) (Zampaligré et al., 2022). Adoption of these dual-purpose cultivars offers an opportunity to increase fodder quality, productivity and availability for livestock which has the potential to enrich the livelihoods of small holder farmers across the entire WAS (Zampaligré et al., 2022). As new varieties are developed, it is critical that producers in the WAS are able to access cultivars of pearl millet with desirable traits such as higher nutritional value or drought, pest, and pathogen resistance.

Conclusion

While climate change and poverty threaten the present and future of pearl millet production, the crop has the potential to continue producing a source of nutritious grain in conditions of the arid environment, while also corresponding to the traditional food pathways across the WAS. It serves as a nutrient dense crop offering a reliable source of grain in a region facing food insecurity emergencies and increasing levels of widespread hunger. The stover left from the harvest of pearl millet provides an excellent feed for millions of ruminants which bolster the income and livelihoods of the WAS's smallholder farmers. Through increased mechanization, microdosing applications of NPK fertilizer, and widespread distribution of Striga and pathogen resistant hybrids, pearl millet production can improve and continue producing higher and more reliable yields in the warming and increasingly water stressed region.

The unfortunate reality is yield improving inputs and agriculture machinery are financially out of reach for millions of impoverished smallholder farmers across the WAS. There is opportunity for continued intercropping of pearl millet with cowpeas and supporting the scaling of agroforestry systems with the leguminous tree species *Faidherbia albida* as a promising cropping system which improves nutrient content in the region's poor soil, while also producing more crops for human consumption and biomass to be used as livestock fodder. Nourishing the regions livestock herds with the remaining stover brings nutrient rich manure to those farmers who cannot afford synthetic fertilizers.

International agricultural research organizations such as ICRISAT play an important role in the collection, conservation and sharing of germplasm of dryland crops and their wild relatives. As custodian of the world's largest pearl millet genebank, ICRISAT continues to work collaboratively with WAS NARS and smallholder farmers in their pearl millet research and innovation efforts. To build more resilient systems of pearl millet production, there are opportunities for increased efforts in relation to:

- Participatory approaches with smallholders and rural communities to improve and co-create knowledge of how smallholder farmers approach drought preparation and household food insecurity.
- Promoting the scaling of leguminous tree– intercrop–livestock farming systems which can provide multiple benefits such as increased yields of pearl millet straw residues and stover, while also improving the nutrient content and fertility of the soils in WAS.
- Improving smallholder farmers access to capital needed to help them effectively purchase and microdose NPK fertilizers.
- Improving smallholder farmers access to mechanized equipment and farm tools which can boost yields and reduce hours of farm labor.
- Sustainable utilization of pearl millet germplasm through evaluation of germplasm collections, creation of novel genotypes through crossing and breeding programs and multi-locational variety testing that is farmer participatory.
- Policy and institutional research on pearl millet commodity markets and seed systems across the WAS.

- Ensuring regional seed companies can more effectively retail and deliver improved pearl millet seeds to smallholder farmers.
- Addressing the acute food insecurity problem in the WAS by creating crisis mitigation programs, such as grain, fodder and seed banks and emergency food reserves across the WAS.

In this looming era of climate change, which threatens production of cereal crops and imperils the livelihoods and food security of millions, pearl millet has major potential to serve as a redeemer for smallholder farmers and financially insecure households across the West African Sahel.

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