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REVIEW

Impact of climate change and adaptations for cultivation of millets in Central Sahel

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Abstract

Climate change has impacted agricultural production systems, especially in the Sahel region, which is fragile climatically, politically, and economically. This region is of particular concern due to its rising population and strategic importance on the African continent. Our review focused on the impact of climate change on millet production in the Central Sahel and aimed to identify adaptation strategies by the farmers. This review shows that increased temperature has a negative impact on millet yield and growth parameters. Other climatic factors significantly affecting millet production in the Central Sahel include drought, desertification, dry spells, rainfall variability, and wind. Projected data suggests a decline in millet production in northern, central, and western Mali by 21%, 20%, and 18%, respectively, by 2030. Additionally, there is an anticipated 17% decrease in pearl millet production in Sub-Saharan Africa by 2050 under future climate change projections. Nevertheless, farmers in the Central Sahel have devised a variety of indigenous climate change adaptation strategies to sustain millet production. These adaptation strategies encompass Zai, half-moon, stone-line, and intercropping. These adaptation practices have proven effective in mitigating the effects of climate change on millet production in the Sahel region. This review suggests strengthening farmers' adaptive capacity to climate change, promoting regional knowledge, integrating millet as a fundamental crop group for food security in the Central Sahel, adopting zero-tillage or minimum-tillage practices during crop production, diversifying crops, and providing heat- and drought-tolerant crop varieties.

Keywords Climate change · Impact · Millet · Adaptation · Central Sahel

Introduction

In the cereal world, millets are a miscellaneous collection of crops that generally produce small seeds (Garí 2002; Weber and Fuller 2008; Padulosi et al. 2015). Smallholder farmers in Africa and Asia cultivate dozens of millet species that originated from various genera and were domesticated (Sakamoto 1987; Garí 2002; Fuller 2011; Fuller et al. 2021). Despite adverse agroecological conditions, millets thrive, and their nutritional value makes them a particularly valuable crop (Tadele 2016; Suneetha et al. 2019). Millets serve as crucial plant genetic resources for poverty-stricken

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farmers living in parched, nonfertile, and marginal lands (Garí 2002). Africa hosts significant centers of millet origin, diversity, and production (Garí 2002; Dida et al. 2008; Winchell et al. 2018). In West Africa, millets like fonio, black fonio, and guinea millet are considered truly African millets (Garí 2002). Globally recognized millet species, such as pearl millet and finger millet, are extensively cultivated in Africa and elsewhere (Garí 2002; Belton and Taylor 2004; Saxena et al. 2018).

African farmers have inherited a vast genetic diversity of these millets, alongside cultivars adapted to harsh agroecological conditions. Millet finds its way into a wide range of foods and appetizers (Amadou et al. 2011; Abah et al. 2020). Many food products, including bread, beer, cereal, and more, can be made using millet (Taylor et al. 2006; Saleh et al. 2013). Even today, millets remain a staple food globally (Karuppasamy 2015; Chandra et al. 2021), regaining popularity due to its versatility and ease of cultivation (Obilana 2003; Mal et al. 2010; Karuppasamy 2015).

Millet offers various health benefits, including improved digestion, heart protection, and a high concentration of essential nutrients such as potassium, vitamin A, vitamin B, phosphorus, antioxidants, niacin, calcium, iron, and zinc, with finger millet boasting the highest concentration of vitamins and minerals (Obilana 2003; Saleh et al. 2013; Devi et al. 2014; Hassan et al. 2021). When it comes to essential amino acids like methionine and cystine, there is no nutritional difference between millets and most cereals for the human body (Obilana 2003; Anitha et al. 2020; Hassan et al. 2021). The Sahel region cultivates several millet varieties, contributing significantly to global millet production.

The West African Sahel (17° W–230 E/13° N–17° N), commonly referred to as the Sahel, is already recognised as a region characterized by significant interactions between climate variability and crucial socioeconomic sectors, such as agriculture and freshwater resources (Ben Mohamed et al. 2002; Kandji et al. 2006; Desmidt et al. 2021). The Sahel region receives an annual rainfall ranging from approximately 350 to 800 mm along a north–south axis (Ben Mohamed et al. 2002; Biasutti 2019). This Sahel region extends over approximately 5000 km, spanning from Senegal to Kenya (Stephen 2014; Epule et al. 2017). The Central Sahel countries encompass Burkina Faso, Mali, and Niger, and according to the 2017 ND-GAIN Index, these countries rank among the 20% most vulnerable nations to global climate change (Cooper and Price 2019). Out of 181 ranked countries, Burkina Faso, Mali, and Niger are positioned within the top 10% of highly vulnerable nations (Cooper and Price 2019). Agriculture, particularly subsistence farming, as well as transhumant livestock rearing, which are major sources of income and livelihood in the region, face threats from climate change (Kamuanga et al. 2008; Lewis and Buontempo 2016; Giannini et al. 2017; Molina-flores et al. 2020).

Climate change is currently exerting its influence on the Sahel region, as documented by various studies (Ben Mohamed et al. 2002; Van Duivenbooden et al. 2002; Lewis and Buontempo 2016; Serdeczny et al. 2017; Epule et al. 2017; Ahmed 2020). Temperatures in the Sahel have experienced an increase ranging from 0.2 to 2.0 °C over the past three decades (Intergovernmental Panel on Climate Change 2007; Epule et al. 2017; Sheen et al. 2017; Biasutti 2019; Zhang et al. 2021). This temperature shift, along with shifting rainfall patterns, has led to adverse effects such as reduced crop production, increased tree mortality, declining species richness, and density (Gonzalez et al. 2012; Epule et al. 2017).

Food systems in the Sahel are under immense strain, with climate change contributing to food insecurity for approximately 50% of the 60 million inhabitants in the Sahel (Epule et al. 2017). It is evident that these climatic changes pose a significant threat to agriculture in developing countries, particularly in the Sahel region, which raises a legitimate concern regarding their potential negative impact on poverty and sustainable development (Van Duivenbooden et al. 2002; Ben Mohamed et al. 2002; Ouedraogo et al. 2006; Mendelsohn 2008, 2014; Legg and Huang 2010; Epule et al. 2017; Tanure et al. 2020; Abubakar et al. 2021a, b; Malhi et al. 2021).

Furthermore, there is a growing concern that climate change will impede the development of Sahelian agriculture (Food and Agriculture Organization 2009; Lalou et al. 2019; Ahmed 2020; Mbow et al. 2021). In the Sahel, food security and rural livelihoods have suffered from the increasingly unpredictable and irregular weather systems (FAO 2009). Recent floods in Burkina Faso and persistent droughts in Ethiopia have devastated farms and homes throughout the Sahel, providing explicit examples of the impacts of climate change (FAO 2009; González et al. 2011; Philip et al. 2018; Tazen et al. 2019; Dos Santos et al. 2019; Hirvonen et al. 2020). Frequent droughts and floods exacerbate water scarcity, food insecurity, and famine, elevating the region's vulnerability to climate change (Mendelsohn 2008; Msowoya et al. 2016).

The consequences of climate change in the Sahel are reflected in rising food prices and declining calorie availability, contributing to malnutrition (Msowoya et al. 2016). Agricultural production has also been severely impacted by these climatic changes (Heinrigs 2010; Serdeczny et al. 2017). Despite long-standing predictions of substantial impacts, there have been few studies measuring climate impacts in the Sahel (Mendelsohn 2008). Nevertheless, agriculture continues to persevere in the Sahel, with farmers employing various adaptation mechanisms to cope with the effects of climate change (Schultz and Adler 2017; Epule et al. 2017; Ahmed 2020; Monerie et al. 2021).

This review is primarily centered on the effects of climate change on millet production in the Central Sahel, with the aim of identifying the adaptation strategies implemented by farmers. This review serves as a guide for policymakers in the Central Sahel by shedding light on the impact of climate change on millet. It also contributes to our understanding of the geographical aspects of the Central Sahel while addressing an identified gap in the existing literature. Further research is required to enhance climate projections and evaluate the efficacy of diverse agricultural adaptation measures within the Central Sahel. It's important to note that this review does not encompass post-harvest impacts and adaptations. Instead, our focus lies on four indigenous adaptation strategies: Zai, half-moon, intercropping, and stone-line.

Millets cultivated in Sahel region

Millets play a crucial role as staples and ethnobotanical crops in the Sahel region, as evidenced by studies conducted by Obilana and Manyasa (2002), Power et al. (2019), Ponnaiah et al. (2019), and Champion et al. (2021). Taylor (2015) has documented the vernacular names of millets in the Sahel, including "'gero' (Nigeria, Hausa), 'hegni' (Niger, Djerma), 'sanyo' (Mali), and 'dukhon' (Sudan, Arabic)". Millets are not only thermophilic, thriving in high-temperature environments, but they are also xerophilic, capable of reproduction with minimal water, as pointed out by Saxena et al. (2018).

In the Sahel and Sub-Saharan Africa, nine millet species serve as major sources of energy and protein for approximately 130 million people, as indicated by Garí (2002) and Obilana (2003). However, only four of these species are cultivated significantly in the Sahel region, namely pearl millet (*Pennisetum glaucum*, constituting 76% of the total production area), finger millet (*Eleusine coracana*, 19%), fonio (*Digitaria exilis*, 4%), and black fonio (*Digitoria iburua*, 0.8%) (Obilana 2003; Ramashia et al. 2019). Prosso and foxtail millet varieties are exceptions, as they are not grown in Africa (Obilana 2003; Habiyaremye et al. 2017; Saxena et al. 2018).

Pearl millet takes precedence as the most vital millet species in the Central Sahel, contributing significantly to cultivated areas, production, and food security (Ben Mohamed et al. 2002). Remarkably, the Sahel region accounts for nearly 37% of the global millet cultivation area, yielding an impressive 79% of the total millet production in Africa (Ben Mohamed et al. 2002). Nevertheless, millet production is unevenly distributed among Sahelian countries, with Nigeria (54%), Niger (20%), Mali (9%), Burkina Faso (8%), Senegal (5%), and Sudan (4.8%) emerging as the prominent producers, although their relative importance may vary from year to year (Ben Mohamed et al. 2002; Obilana 2003).

Millets are consumed as a staple food (78%) as well as in beverages and for other purposes (20%) (Arendt and Zannini 2013). These hardy crops thrive in sandy soils and are typically intercropped with other crops like sorghum, cowpea, guinea corn, and sesame, among others, as discussed in several studies (Diangar et al. 2004; Zegada-Lizarazu et al. 2006; Omae et al. 2014; Bitew et al. 2019; Sogoba et al. 2020). Figure 1 depicts the location of the Sahel region and the countries (Niger, Mali, and Burkina Faso) that form the Central Sahel.

Impact of climate change on millet production in Sahel region

Butt et al. (2005) estimated that without the adaptation of tolerant varieties, pearl millet grain yield would decrease by 6–12% in Mali under various climate change scenarios (Hadley Center Coupled Model and Coupled General Circulation Model). Similarly, it is projected that by 2030–2050, millet production will decrease by 21%, 20%, and 18% in northern, central, and western Mali, respectively (Butt et al. 2005; Kirtman et al. 2013). Furthermore, this decline is expected to reach 40% due to elevated temperatures (Sultan et al. 2013; United Nations High Commissioner for Refugees 2021). Due to climate change, climate models predict a 17% reduction in the yield of pearl millet in Sub-Saharan Africa by 2050 (Burney et al. 2010; Sultan et al. 2013; Adhikari et al. 2015).

Toure et al. (2018) assessed the impact of climate change on millet yields in Mali using the Decision Support System for Agrotechnology Transfer (DSSAT) model. The authors found that under climate change scenarios (described as Cold-dry, Hot-dry, Cold-wet), millet grain yields were lower compared to historical weather data. All the millet varieties performed worst under the "Hot-Wet" scenario, indicating increased vulnerability to climate change. Climate change variability and future projections suggest a substantial decrease in millet yields in the Central Sahel and West Africa (Defrance et al. 2020). The yield exhibited a tendency to decline while production continued to increase. This phenomenon signifies that more land is being cultivated (Ben Mohamed et al. 2002). This represents the agricultural paradox of the Sahel, a region experiencing chronic food insecurity as a result of climate change and agricultural practices.

Impact of temperature on millet production

By the mid-twenty-first century, it is expected that temperatures in Africa will rise by 2 °C and could exceed 4 °C by the end of this century due to the effects of climate change (Niang et al. 2014; Djanaguiraman et al. 2018). The high air and soil temperatures have the tendency to pose challenges for millet establishment at the beginning of the growing season. During the sowing period, maximum air temperatures may surpass 40 °C, with soil temperatures frequently reaching above 50 °C (Ben Mohamed et al. 2002). The rising temperature significantly impacts millet growth parameters, such as height, leaf area, and dry matter production, all of which decrease as temperatures rise. Germination also experiences a sharp decline with increasing temperature, as highlighted by Dhanuja et al. (2019).

Similarly, Gupta et al. (2015) observed that a maximum daytime temperature exceeding 42 °C, coupled with an increase in the vapor pressure deficit during flowering, sequentially reduces seed set in pearl millet. Rising temperatures adversely affect millet yields, with reductions of up to 41% observed at temperatures exceeding 60 °C, as reported by Sultan et al. (2013).

Besides that, the future potential climate change impacts on millet yields differ markedly from those observed in recent times. When temperatures rise above + 2 °C, it appears that the likelihood of millet yield reduction increases in the Central Sahel and the rest of West Africa (Sultan et al. 2013). It is estimated that millet and sorghum yield in the Sahel region will drop by 15–25% by 2080 when temperatures increase by more than 2 °C (USAID 2017).

Impact of rainfall variability on millet production

In the Central Sahel, the months of May/June and September/October mark the only rainy seasons throughout the year (Abubakar et al. 2021a, b; Ahmed et al. 2021). Rainfall in this region exhibits significant variability, both spatially and temporally, and tends to decrease over time. Rainfall, a dominant climatic factor in the Central Sahel, demonstrates diverse characteristics and impacts various climatic variables, including evaporation, temperature, solar radiation, wind, and humidity, to varying degrees (Ben Mohamed et al. 2002).

The variability in rainfall has had a detrimental effect on millet yields, leading to reductions of up to 41% for a − 20% rainfall deficit (Sultan et al. 2013. Sultan et al. (2013) note that "the Sudanese region (southern Senegal, Mali, Burkina Faso, northern Togo, and Benin) seems to be more susceptible to yield reductions than the Sahelian region (Niger, Mali, northern Senegal, and Burkina Faso)".

In the year 2100, it is anticipated that Chad and Niger may be unable to sustain rainfed crops, while Mali could experience a 30% decline in cereal harvests due to the effects of climate change (USAID 2017). Similarly, Defrance et al. (2020) predict a decrease in rainfall across the Western Sahel based on the IPCC scenario RCP8.5 (Representative Concentration Pathway). Under all scenarios considered for the region, agricultural production in the Central Sahel is expected to fall below 50 kg per capita by 2050. This prediction encompasses a range of wet-season precipitation changes from − 20% to + 40%. Additionally, due to uncertainties in agronomic models, there exists ambiguity in impact studies concerning millet and other agronomic yield projections, in addition to climate models (Defrance et al. 2020).

Impact of drought on millet production

Drought is a complex climatic phenomenon characterized by natural reductions in precipitation, which have a negative impact on millet and other crop productions (Ahmed et al. 2021). The Central Sahel region is generally marked by three types of drought: meteorological drought, agricultural drought, and hydrological drought (Stanke et al. 2021; Ahmed et al. 2021; Abubakar et al. 2021a, b). When drought affects well-being, livelihoods, and life, it is classified as a socioeconomic drought (Bryan et al. 2020).

Historically, the Central Sahel has experienced droughts and famines in various years, including 1883, 1903/1905, 1913/1915, 1923/1924, 1942/1944, 1954/1956, 1972/1973, 1982/1983, and more recently in 2004/2005 and 2011/2012 (USAID 2006; Federal Ministry of Environment 2021a; Ahmed et al. 2021). Additionally, in the Sahel, there have been three major droughts known to have occurred in 1883/1885, 1913/1915, and 1942/1944, which follow a regional 30-year cycle (FME 2018; Ahmed et al. 2021). The Sahel and Sudan climatic belts are typically affected by these 30-year drought cycles (FME 2018). Conversely, droughts on a 10-year cycle tend to be more localized, even in areas near the same latitude (FME 2006, 2018).

The increase in the number of drought days and their severity lead to a reduction in millet yield (Boubacar 2012; Diakhaté et al. 2016). Similarly, Winkel et al. (1997) reported that drought has a severe impact on millet, resulting in lower biomass production and significantly reduced grain yield. Interestingly, there is no noticeable effect of rising temperatures on grain size. Tiller flowering is either delayed or completely inhibited within 30–45 days of the onset of drought (De Rouw and Winkel 1998). It has been demonstrated that pearl millet is negatively affected by drought in terms of growth, yield, membrane integrity, pigment content, osmotic adjustment, water relations, and photosynthetic activity (Ajithkumar and Panneerselvam 2014).

Impact of desertification on millet production

Desertification, defined as the degradation of land in arid, semi-arid, and dry sub-humid areas caused by various factors, including climate variability and human activities (Feng et al. 2015; Hu et al. 2020), exerts a significant impact on millet production in the Central Sahel (Ikazaki 2015). This phenomenon entails a decline in soil fertility, soil degradation, and a substantial reduction in potential land productivity, thereby disrupting millet production. As land shifts from being arable to arid, it often becomes unsuitable for millet cultivation (Ikazaki 2015; Moussa et al. 2016; Tanaka et al. 2016). Desertification results in soil compaction, the loss of soil structure, nutrient depletion, and increased soil salinity, rendering the soil unsuitable for millet cultivation (Lal 2015). The alarming rate of desert encroachment is causing the destruction of arable land, prompting migration to more productive areas and exacerbating the pressure on available fertile land (Rasmussen et al. 2001; Holthuijzen and Maximillian 2011; Moussa et al. 2016; Azare et al. 2020). Consequently, vast expanses of arable land in the Central Sahel and the entire Sahel region are disappearing (Ahmed et al. 2021).

Impact of dry-spell on millet production

The term "dry spell" refers to an extended period of unusually low rainfall and abnormally dry weather conditions, lasting longer than typical but not as severe as a full-fledged drought (Barron et al. 2003; Sawa and Ibrahim 2011; Fall et al. 2021). Dry spells manifest as consecutive days without any precipitation (Breinl et al. 2020). Specifically, a dry spell is officially recognized when there is an absence of rain for three or more days within the wet season (van Duivenbooden et al. 2002; Fox and Rockström 2003; Traore et al. 2017; Bako et al. 2020). In addition to limiting soil moisture for millet cultivation, dry spells pose a significant threat to nutrient uptake, thereby having a detrimental impact on millet yields (Paudyal et al. 2016; Breinl et al. 2020). In many instances, the occurrence of dry spells not only reduced millet yields in the region but also led to complete crop loss during the prolonged periods of occurrence, effectively resulting in drought conditions. Dry spells adversely affect key millet growth stages, including panicle initiation, flowering, and grain filling (Traore et al. 2017). Historically, the Central Sahel droughts of 1972/73 and 1984 were primarily attributed to the cumulative impact of prolonged dry spells, and the severity of these dry spell effects on millet yields closely correlates with soil water storage capacity (Barron et al. 2003).

Impact of wind on millet production

Another climatic factor influencing millet growth and yield is wind (Ben Mohamed et al. 2002). There is significant soil loss as a result of strong winds and dry soils (Issaka and Ashraf 2017; Yang et al. 2020). The wind has a powerful effect on bare soils by removing vast quantities of soil and transporting it away, then depositing it onto young millet seedlings (Sterk et al. 1995). It is imperative to resow millet several times per year due to the weight of this deposition combined with the high soil temperatures. By removing the clays and organic matter from the soil, wind erosion renders the surface soil less productive (Gemma Shepherd et al. 2016). In addition to destroying soil structure and biological activity, the removal of clay and organic matter diminishes native soil productivity and damages millet production and the health of the soil resource (Ikazaki 2015; Gemma Shepherd et al. 2016). Millet can also be damaged by wind erosion due to the abrasive action of saltant particles on seedlings. Nigerien farmers are not particularly concerned with soil particle loss; however, they are more concerned about the loss of nutrients from low-fertility soils due to wind erosion (Ikazaki et al. 2012; Abdourhamane Touré et al. 2019). Wind erosion is common and frequent in the Central Sahel, causing millet seedlings to collapse (Abdourhamane Touré et al. 2019). Ikazaki et al. (2012) and Abdourhamane Touré et al. (2019) have provided valuable insights into soil and nutrient losses resulting from wind erosion.

Moreover, there are other non-climatic factors that contribute to the decline in millet production in the Central Sahel. These factors include bio-physical factors, socio-economic factors, and political factors. Table 1 presents non-climatic factors that influence yield in the Sahel region.

Adaptions in Sahel region

Climate change adaptation involves changing ecological, social, or economic systems in response to actual or anticipated changes in climatic conditions (Stein et al. 2013; IPCC 2018; Mugambiwa 2018). Adaptation involves modifying processes, practices, and structures in order to minimise or capitalise on potential damages (Smit and Wandel 2006; Nelson et al. 2021; Ayers et al. 2006). In the Sahel region, several measures for improving millet yields are available, including seed priming (Coulibaly et al. 2019), dry planting, application of fertiliser and/or manure, contour ridge tillage (Traore et al. 2017), mono-cropping of early maturing varieties, incorporating inorganic fertiliser in very poor soils, low density planting, etc. (De Rouw 2004). Elaborating on these yield improvement measures are beyond the scope of this review. Herein we focus on four indigenous agricultural climate change adaptation strategies in the Central Sahel (Zai, half-moon, stone-line, and intercropping). Indigenous adaptation technologies gleaned through generations of monitoring and observation are proving to be effective in climate change adaptation (Petzold et al. 2020).

The term "Zai adaptation techniques" describes a planting pit with dimensions of 20–30 cm in width, 10–20 cm in depth, and spaced 60–80 cm apart (Danquah et al. 2019; Muchai et al. 2020), resulting in approximately 10,000 pits per hectare (Kathuli and Itabari 2015; Danso-Abbeam et al. 2019). On the bottom of the pit, farmers usually place

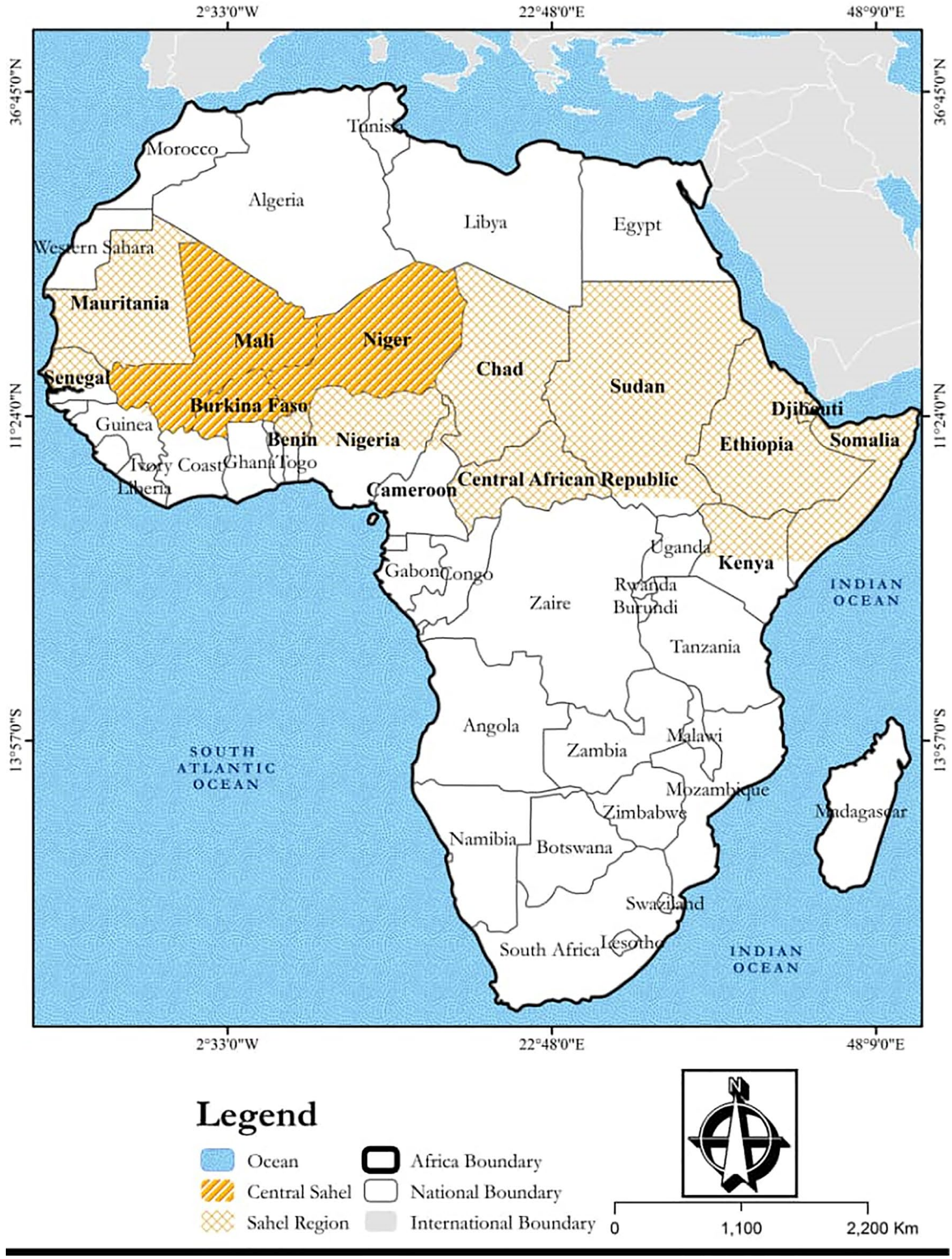

Fig. 1 The location of Sahel region and the Central Sahel countries. *Source*: Modified from Epule et al. (2017)

approximately two handfuls of organic material (either animal dung or crop waste). Seeds are planted in these pits as soon as the rains begin. Zai combines water and nutrient management into one technique that farmers can manage themselves, requires few external inputs, and is financially accessible (Jouquet et al. 2018; Danso-Abbeam et al. 2019). The Zai pits also collect and concentrate water at the plant base (Fatondji et al. 2009; Danjuma and Mohammed 2015).

Table 1 Non-climatic factors that contribute to low millet yields in Sahel

Types	Descriptors	Specifications
Bio-physical factors	Soils	Physical vulnerability to wind and water erosion; occasional thin surface crust; cultivation of marginal soils; low water-holding capacity; and low soil fertility
	Carrying capacity pests and diseases	Exceeded in terms of limiting access to rangelands
Socio-economic	Population	The population is growing rapidly (3.5% per year, doubling every 30 years); people are moving into marginal areas; and the educational level is low
	Extension and outreach	Extension services that are either non-existent or of poor quality; a reduction in agricultural research activities
	Inputs	An organic manure fertilizer, biocide, pesticides, and low-level chemical fertilisers
	Credit	National agricultural credit has vanished
	Market	Only for onion, and cowpea in Niger; the rest is for internal/domestic consumption
	Land tenure and fragmentation	Excessive exploitation as a result of non-ownership, inheritance, family and communal disputes over land
Political instability	Conflict	Insurgency, religious extremism and banditry (Niger, Mali and Burkina Faso) prevents farmers from land cultivation
Breeding	Cultivar types	Developing crop varieties to increase yield or resist pests and diseases
Poor Farming Practices	Inadequate crop rotation, improper planting techniques, and monoculture	Can lead to nutrient depletion, soil exhaustion, and reduced yields
Lack of Access to Inputs	Limited access to quality seeds, fertilizers, and pesticides	Reduces crop yields due to inadequate resources for optimal cultivation
Infrastructure Deficiency	Lack of transportation, storage facilities, and market access	Hampers the efficient movement of crops to markets and reduces profits for farmers
Cultural Practices	Traditional farming methods and beliefs	May resist the adoption of modern, more productive agricultural practices

Adopted and modified from Ben Mohamed et al. (2002)

The success of the Zai adaptation technique became evident during the droughts of the 1970s and 1980s that ravaged the entire Sahel region (Danjuma and Mohammed 2015; Danso-Abbeam et al. 2019). Research conducted in northern Burkina Faso revealed that the utilization of Zai led to an increase in millet crop yields by more than 100% (Ouedraogo et al. 2010). Additionally, Zai was found to enhance cereal yields by 428–1200 kg/ha in Togou, Leeba, and Yanteng, Burkina Faso (Barbier et al. 2009; Sawadogo 2011; Nyamekye et al. 2018). Numerous other studies also confirm the effectiveness of Zai in improving yields (Kaboré and Reij 2011; Nyamekye et al. 2018; Ebi et al. 2011; Danjuma and Mohammed 2015; Moussa et al. 2016; Mutua-Mutuku et al. 2017; Muchai et al. 2021; Oduor et al. 2021). In the late 1950s, the half-moon adaptation technique was introduced to complement and strengthen the effectiveness of Zai adaptation techniques.

The half-moon adaptation technique was introduced in 1958 to the Sudan-Sahel region of Yatenga by Burkina Faso's environmental services (Nyamekye et al. 2018). The half-moon technique modifies the Zai strategy: a basin is dug on gentle slopes, and the excavated soil forms an arched dyke that follows the contour lines (Organization for Economic Cooperation and Development 2009). The half-moons are arranged in stepped contour lines to collect runoff water that seeps into the soil (OECD 2009; Nyamekye et al. 2018). The gap between adjacent half-moons along the same contour line and between two sequential lines is 4 square meters. The average density per hectare is 315 half-moons (Zougmoré et al. 2014; Nyamekye et al. 2018). Half-moons are well suited for semi-arid and arid regions due to their ability to collect runoff water (Nyamekye et al. 2018). Half-moons have a larger surface area than Zai, allowing them to hold more water (Nyamekye et al. 2018). Half-moons enhance moisture depths by 20–40 cm and optimise soil water reserves (OECD 2009). They boost farm output when a mineral or organic supplement is added (Zougmoré et al. 2014). In addition, growing shrubs on the beds helps improve crop yields on farms and appropriately preserves the half-moons (Onyango 2015). The half-moon effectively collects runoff water, but it requires more organic matter to improve soil fertility (Nyamekye et al. 2018). Millet yields obtained using half-moons range from 1400 to 2000 kg/ha (Sawadogo 2011; Nyamekye et al. 2018). Compared to other adaptation techniques, the half-moon technique was found to be the most effective response to deteriorating growing conditions in the Sahel (Kagamèbga et al. 2011). Although the effectiveness of half-moon differs from that of contour stone bounds in terms of runoff collection and reducing erosion.

Water runoff causes cropland erosion, which can be minimised with contour stone bunds (Gebrernichael et al. 2005; Wakolbinger et al. 2015). Contour stone bunds (25–50 cm wide and approximately 25 cm high) are constructed from a mix of small and large stones embedded 5–15 cm in the ground (Critchley and Bielders 2007). They are built in a series behind each other along the natural contour of the land, usually 20–50 m apart depending on the slope of the terrain. The bund slows runoff by acting as a barrier, reducing erosion, and increasing water infiltration into the ground (Gebrernichael et al. 2005; Critchley and Bielders 2007). Overall, stone-lined landscapes increase or maintain soil water retention, enhance water harvesting capabilities, boost organic matter content, improve soil fertility, promote natural tree regeneration, reduce slope length, enhance soil structure, increase ground cover, and prevent evaporation (Nyssen et al. 2007; Critchley and Bielders 2007; Ponce-Rodrguez et al. 2019; Traoré et al. 2020). In addition, stone-line increases soil water, yield, revenue, and resilience (Traoré et al. 2020). This directly or indirectly improves millet yields. Stone-lines enhance millet yield by over 50%, which on average equals 450 kg/ha to 1500 kg/ha, or UDS 98–294/ha (Nyamekye et al. 2018; Traoré et al. 2020).

During the growing season, intercropping involves planting two or more crop species in a single field at the same time (Mousavi and Eskandari 2011; Maitra 2019). These involved several intercropping patterns, such as mixed intercropping, row intercropping, strip intercropping, and relay intercropping (Mousavi and Eskandari 2011; Bybee-Finley and Ryan 2018; Maitra 2019). Row-intercropping (a combination of two or more crops planted in regular rows or two or more crops grown simultaneously) is the most widely accepted form of intercropping in the Sahel, particularly the Central Sahel. This involved intercropping millet with cowpea, millet with sesame, millet with Guinea corn, etc., or both depending on farmer preferences. Intercropping enhances millet production, greater use of environmental resources, reduction of pests, diseases, and weed damage, stability and uniformity of yield, improved soil fertility, and increased soil nitrogen fixation where legumes are present (Mousavi and Eskandari 2011; Omae et al. 2014; Bybee-Finley and Ryan 2018; Maitra 2019; Maitra et al. 2021). The success of intercropping depends significantly on choosing the right combination of crops, considering the local crop environment and the availability of suitable varieties (Maitra 2019). Various studies have confirmed that intercropping millet with legumes or other cereals in the Central Sahel region yields positive results (Maitra et al. 2001; Sarr et al. 2008; Aune et al. 2012; Omae et al. 2014; Sanou et al. 2016; Bogie et al. 2019; Saharan et al. 2018; Sogoba et al. 2020).

Future prospects

There are several future bottlenecks to increased production of millet, including climate change, unpopularity of available improved varieties, inappropriate focus of a crop research programme, erratic producer pricing policies, processing technology, pests and diseases (e.g., striga), agronomic problems, and environmental stresses (Rouamba et al. 2021; Bado et al. 2021). There are huge challenges in the development of millet genetic resources to improve varieties in Africa, especially in the Sahel region (Kanlindogbe et al. 2020; Sharma et al. 2021). Governments and policymakers have given pearl millet relatively little attention as a poor man's crop in terms of supporting upstream science (Srivastava et al. 2020). A lack of funding for pearl millet genomics research has always been an issue, especially in the Sahel region and other developing countries (Serba et al. 2019). High crossbreeding rates, heterozygous nature, and inbreeding depression all cause problems for the crop, causing bottlenecks in breeding programmes (Srivastava et al. 2020). Drought-tolerant millet varieties can be developed with the advancement and effective integration of genomic tools (Srivastava et al. 2022). The least disturbing maturity period (70–75 days) is obtained by adding new germplasm collections to drought-resistant crossing programmes (Srivastava et al. 2022). Improved sustainability in millet through economically sound processes that minimise negative environmental impacts while conserving natural resources and maintaining or improving soil fertility is important. Among smallholder farmers in developing countries, millet could improve their food and nutritional security in the future (Gairhe et al. 2021). There is also a need to monitor grain minerals in future cultivars, improving multiple nutrients (Govindaraj et al. 2022). For rain-fed marginal lands to be promoted as a source of income, this crop (millet) will need increasingly high priority and policy support (Gairhe et al. 2021). There is potential in the application of geographic information systems (GIS), from land-use planning and suitability assessment to climate suitability assessment to millet-soil-yield monitoring, soil fertility management, post-harvest operations, etc. (Buckner et al. 2016). Millets are drought-resistant and need little input; they are the "marvel grain" of the future. Millets are environmentally friendly and sustainable for the farmer who grows them because of their high tolerance to severe conditions. They also give everyone access to affordable, high-nutrition options. However, there is a need for further research on the relationship between millet and climate change in the Sahel in order to better plan our future actions and adapt to unavoidable climate changes.

Conclusion

Climate change poses significant threats to millet production and food security, especially in the densely populated Sahel region, which grapples with food insecurity and malnutrition. However, millet cultivation has shown resilience in the face of climate change. To secure a sustainable millet sector and address these challenges, it is crucial to incentivize Sahel farmers to embrace indigenous adaptation techniques. Indigenous strategies can enhance millet yields while conserving land and promoting habitat regeneration, aligning with climate goals. This approach, though less economically disruptive, is pivotal for long-term economic resilience in Sahel countries. This review advocates for cultivating drought-resistant, early-maturing millet varieties and preserving millet genetic diversity through seed banks, fairs, and farmer networks, with a focus on West African millets. Active participation in millet research, indigenous adaptation technologies, and understanding the link between farmer genetic resources and climate adaptation are encouraged. Farmers should adopt proven crop mixtures to ensure production stability during climate fluctuations and build grain and seed reserves as insurance. Policy reforms, agricultural insurance enhancements, and strategic grain reserves are essential. Transitioning to sustainable millet production will not only benefit the Sahel's environment and health but also sets an example for Africa and beyond. Stakeholders, including farmers, policymakers and consumers must prioritize the future over short-term interests to bring about this transformative change promptly.

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Declarations

Conflict of interest The authors declare that they do not have any conflict of interest.

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