

REVIEW PAPER

Sorghum's Potential in Marginal Environments: Importance, Distribution, Diversity, Stress Tolerance, and Bio-enhancement with AMF and Silicon

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ABSTRACT

Climate change and declining soil health continue to impact crop productivity posing threat to food security, health, and financial security of households in arid and semi-arid areas. The purpose of this review was to explore the potential of sorghum as an alternative food and industrial crop in areas prone to drought, depleted soil fertility, salinity, and waterlogging. Moreover, discuss distribution and genetic diversity for its potential utilization in breeding programmes for tolerant cultivars and in expanding production areas. Furthermore, understand sustainable interventions to enhance its tolerance to drought and low soil fertility. Sorghum is a source of macro and micro nutrients, health-beneficial compounds, and is used as food, feed, and in the manufacturing of industrial products. Hence, a potential crop in marginalised regions prone to drought, salinity, waterlogging, and poor soils can help curb hunger, malnutrition, health-related challenges, and poverty. Sorghum has a broad genetic diversity widely cultivated under diverse agro-ecological conditions and rich in nutrients, hence a potential alternative crop where other cereal crops fail. The crop has high use efficiency of soil nutrients, sunlight, and moisture in water-limited conditions. Additionally, the ability to survive under low soil inputs reduces the cost of production, soil acidification, and pollution caused by excessive fertilizer application. Arbuscular Mycorrhizal Fungi and silicon alleviate drought and salinity stress, hence suitable interventions to enhance yields and yield components of sorghum to address food insecurity and ensure the suitability of the environment in ASAL.

HIGHLIGHTS

- ❶ Sorghum is a rich source of macro and micro nutrients, and health-beneficial compounds.
- ❷ The crop has broad genetic diversity, widely adapted to diverse agroecological conditions.
- ❸ Advanced mechanisms and high use efficiency of soil nutrients, sunlight, and moisture enable the sorghum crop to survive under adverse conditions and limited resources.
- ❹ The ability of sorghum to survive under low inputs could reduce the cost of production, soil acidification, and pollution.
- ❺ Use of AMF and silicon is a suitable intervention to enhance yields and yield components of sorghum to sustain food security, health, and environment in arid and semi-arid regions.

Keywords: Climate change, food security, genetic diversity, interventions, nutrition, soil health, sorghum

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Sorghum (*Sorghum bicolor* (L.) Moench) is a cereal crop mainly grown in arid and semi-arid tropical areas experiencing diverse agro-ecological conditions. The crop is ranked fifth most important cereal after wheat, maize, rice, and barley (Ananda *et al.* 2020; Stefoska-Needham and Tapsell, 2020; Takanashi, 2023). Globally, it covers an estimated area of 40.8 million hectares, with a production of 57.9 million metric tons (Andiku *et al.* 2021). According to Africa continent produced 29.6 to 31 million metric tonnes between 2013 and 2023 (FAO, 2023a, FAOSTAT, 2025).

Sorghum crop is well adapted to drought and nutrient-depleted soils, making it important in farming systems where other food crops fail (Derese *et al.* 2018; Hadebe *et al.* 2017). It is among the crops that play a key role in sustainability of global food security for the increasing human population and livestock, as a bioenergy source, and a basis for various industrial products (Habyarimana *et al.* 2020; FAOSTAT, 2023). With its ability to survive under conditions where other crops fail (Andiku *et al.* 2022; Adedugba *et al.* 2023), sorghum has the potential to meet food demand in areas prone to low and erratic rainfall coupled with poor soil fertility (Hadebe *et al.* 2021).

Climate change continues to decrease crop yields, causing food insecurity in marginalized areas where resources are limited (Alhammad *et al.* 2023; Santosh *et al.* 2024). The unpredictable changes pose the greatest threat to seed systems, food security, and poverty alleviation. Moreover, crop yield is affected by negative nutrient imbalances as a result of traditional farming practices that fail or under-replenish soil fertility (Otieno *et al.* 2022; Shao *et al.* 2023). Declining soil fertility in such areas is compounded by the high cost of soil fertility amendments and farmers' risk aversion (Muui *et al.* 2019; Maitra *et al.* 2024). Although crops tolerant to various abiotic stresses have been documented, extreme drought and highly nutrient-depleted soils hamper productivity (Mohapatra *et al.* 2023; Chappa *et al.* 2026). Excessive use of nitrogenous fertilizers causes soil acidification, nitrous oxide emissions, and accumulation of nitrates in water bodies, contributing to climate change and environmental pollution (Tóth and Tóth, 2024).

Limited water availability affects plant metabolism and development, and impairs the yield (Anjum

et al. 2011; Dietz *et al.* 2021; Jia *et al.* 2025). Plants possess acclimation mechanisms enabling them to program their gene expression and developmental activities to optimize growth and development under prevailing environmental conditions (Dietz *et al.* 2021; Heydarzadeh *et al.* 2023; Barutwanayo *et al.* 2025). Duration and time at which water stress occurs determine the crop yield (Dietz *et al.* 2021). Water stress negatively impacts vegetative and generative yields, reduces seed germination and crop establishment (Dietz *et al.* 2021). Period of water stress episodes impacts on plant morphology and on the accumulation of secondary compounds (Ranjan *et al.* 2025; Rezaei-Chiyaneh *et al.* 2023).

Salinity is characterized by the accumulation of soluble salts in the soil and also in irrigation water (Dehnavi *et al.* 2024; Bulle *et al.* 2025; Maitra *et al.* 2026a). Salinity stress, which impairs plant growth and development, is more pronounced in regions experiencing hot and dry conditions. Such areas experience high evaporation rates and limited water for irrigation (Mukhopadhyay *et al.* 2021). Additionally, it can be a result of climate change, excessive water usage, deforestation, industrial activities, and pollution, which influence food security and crop productivity globally (Phour and Sindhu, 2023).

Genetic diversity determines how plants respond to various stresses, among other factors (Majeed *et al.* 2023). Understanding the level of tolerance in germplasm enables the selection of genotypes that exhibit higher sustainability and performance under adverse conditions (Amombo *et al.* 2022; Kaur *et al.* 2023). As climate change and low soil fertility continue to decrease yields, hardy crops such as sorghum could reduce food insecurity, malnutrition, increase income, and diversify food products.

MATERIALS AND METHODS

The current article was based on a literature review focusing on the importance of sorghum, its distribution, and genetic diversity in Africa, adaptation to drought, low soil fertility, salinity, and waterlogging. Additionally, a review was done on the use of AMF and silicon to enhance the tolerance to further improve yields and yield components of sorghum as a key to curb hunger, malnutrition, health crisis, poverty, and for a sustainable environment.



RESULTS AND DISCUSSION

Importance of sorghum

Sorghum thrives in regions with varied climatic conditions and soils, hence, an important staple food for millions of people globally, averting food insecurity and poverty (Mbulwe and Ajayi, 2020). The plant has an extensive root system contributing to soil conservation (Tanwar *et al.* 2023). The crop can survive under low agricultural inputs, providing food security to the resource-poor farmers in marginalized zones. As a C₄ crop, it's hardy with high energy and drought resilience ability, making it a suitable crop in climate change situations (Sunoj *et al.* 2020; Lee *et al.* 2021).

The crop has a diverse usage as a staple food, bioenergy source, feed and fodder for livestock, and industrial products (Habyarimana *et al.* 2020) as illustrated in Fig. 1.

The grain is rich in protein, lipids, carbohydrates, dietary fiber, crude fiber, minerals, and vitamins as shown in Table 1 (Olawole *et al.* 2019; Espitia-Hernández *et al.* 2022; Tanwar *et al.* 2023). The carbohydrates are digested slowly, permitting a steady and prolonged source of energy to the consumer compared to other cereal crops. The protein composition is deficient in gliadin and glutenin, making it nutritious option for individuals grappling with celiac disease or gluten intolerance

(Salazar-Lopez' *et al.* 2018). The high fiber aids in digestion, reducing constipation, regulating blood sugar levels, and lowering cholesterol, aiding in weight management.

In Table 1, some parameters lack values. Kindly add them as follows 1. Non-starch polysaccharides (g/100 g) with a value of 6.0–15.0, β -kafirins (%) with a value of 8–13 and Unsaturated fatty acids (%) with a value of 83–88.

Table 1: Nutritional composition of sorghum grain

Components	Range
Protein (%)	4.40–21.10
Water-soluble protein (%)	0.30–0.90
Lysine (%)	1.06–3.64
Starch (%)	55.60–75.20
Amylose (%)	21.20–30.20
Soluble sugar (%)	0.70–4.20
Reducing sugar (%)	0.05–0.53
Crude fiber (%)	1.00–3.40
Fat (%)	2.10–7.60
Ash (%)	1.30–3.30
Calcium (mg/100 g)	11.00–586.00
Phosphorus (mg/100 g)	167.00–751.00
Iron (mg/100 g)	0.90–20.00
Thiamine (mg/100 g)	0.24–0.54
Niacin (mg/100 g)	2.90–6.40
Riboflavin (mg/100 g)	0.10–0.20
Tannin (%)	0.1–7.22

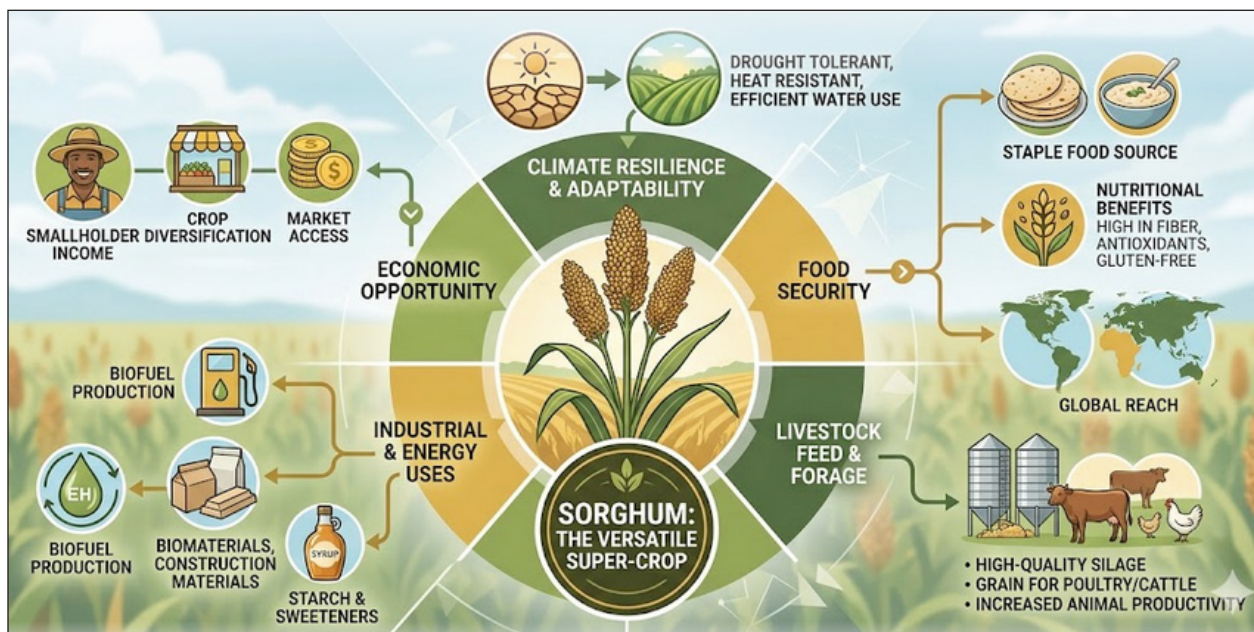


Fig. 1: The importance of sorghum

Phytic Acid (mg/100 g)	875.00–2211.90
Energy value (kcal/100 g)	296.1–356.0
Non-starch polysaccharides (g/100 g)	6.0–15.0
Insoluble fibers (%)	75.0–90.0
Soluble fibers (%)	10.0–25.0
α -kafirins (%)	66–84
β -kafirins (%)	8–13
γ -kafirins (%)	9–21
Reduced lipid (g/100 g)	1.24–3.07
Unsaturated fatty acids (%)	83–88
Linoleic acid (%)	45.6–51.1
Oleic acid (%)	32.2–42.0
Palmitic acid (%)	12.4–16.0
Linolenic acid (%)	1.4–2.8

Source: Hossain *et al.* (2022).

The grain contains essential diverse mineral nutrients relatively high compared to other cereals (Table 2), hence can be supplemented for use in areas where other cereal crops are limited (Abah *et al.* 2020; Andiku *et al.* 2021). These mineral nutrients are crucial in reducing micronutrient deficiency, and health disorders (Andiku *et al.* 2021; USAID, 2021; Tanwar *et al.* 2023). Since sorghum is a major staple food providing macro and micro nutrients (Sarshad *et al.* 2021), it can play a key role in curbing malnutrition.

Distribution and genetic diversity of sorghum in Africa

According to Venkateswaran *et al.* (2018), sorghum was domesticated and diversified in Africa, and continues to play an important food security role in the continent. Sorghum is believed to have originated from the Northeast quadrant of Africa and slowly dispersed to other parts of Africa, eventually spreading to Asia and the rest of the

world (Zidenga, 2004). The large production of sorghum in Africa is not only owed to the fact that it originated from Africa, but also due to its ability to tolerate drought condition. According to Wortmann *et al.* (2009), sorghum is widely prominent in eastern and southern African regions (Fig. 2).

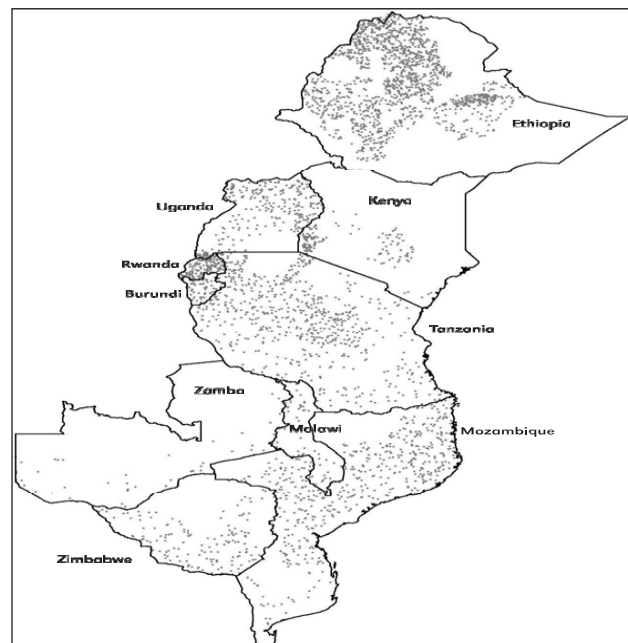


Fig. 2: Distribution map of grain sorghum production in selected countries (Wortmann *et al.* 2009) *(1 dot = 1000 ha/year)

Sorghum is among the self-pollinating diploid with $2n=2x=20$ chromosomes cereal crop in the family of Poaceae comprising an estimated genomic size of 730 megabytes (Paterson *et al.* 2009). Sorghum comprises five primary races, namely bicolor, guinea, caudatum, durra, and kafir, and intermediate races, which encompass a mixture of basic races (Mangshin *et al.* 2021). Studies have indicated diversity in adaptability of the basic races and intermediate races forming clusters

Table 2: Comparison of nutrient composition of sorghum grain with other cereals

Cereal type	Protein (g)	Fat (g)	Crude fibre (g)	Carbohydrate (g)	Energy (kcal)	Calcium (mg)	Iron (mg)
Rice (brown)	7.9	2.7	1.0	76.0	363	33	1.8
Wheat	11.6	2.0	2.0	71.0	348	30	3.5
Maize	9.2	4.6	2.8	73.0	358	26	2.7
Sorghum	10.4	3.1	2.0	70.7	329	25	5.4
Pearl Millet	11.8	4.8	2.3	67.0	363	42	11.0
Finger Millet	7.7	1.5	3.6	72.6	336	35	3.9

Source: Abah *et al.* 2020.



of what is predominantly cultivated in certain regions within Africa. In Africa, the crop has a wide genetic diversity comprising landraces, cultivated, semi-wild, and wild genotypes. High levels of genetic diversity have been reported in Ethiopia, Eritrea, Sudan, Kenya, Uganda, Burundi, and Rwanda, pointing to the possibility of an area of domestication (Mangshin *et al.* 2021).

Morphological, biochemical, and molecular markers have been used to study the genetic diversity of crop species worldwide (Enyew *et al.* 2022). The diversity of sorghum germplasm has been possible through the application of morphological markers globally, where differences are noted by days to flowering, height of plants, panicle size, color of the grain, size and shape of the grain, and grain yield (Akatwijuka *et al.* 2019; Andiku *et al.* 2022; Apunyo *et al.* 2022). However, these traits are highly influenced by prevailing environmental conditions coupled with low polymorphism and heritability (Chakrabarty *et al.* 2022; Mufumbo *et al.* 2023). As a result, genetic markers have been employed alongside the morphological markers to study single-nucleotide polymorphisms (SNPs) in trait mapping and diversity of sorghum (Faye *et al.* 2021; Sagar *et al.* 2022; Enyew *et al.* 2022; Gimode *et al.* 2024).

Studies on genome-wide association in sorghum have revealed genomic regions linked to diverse traits across African countries (Girma *et al.* 2019; Habyarimana *et al.* 2020; Enyew *et al.* 2022; Maina *et al.* 2022). High phenotypic diversity in sorghum germplasm in Uganda has been reported (Kasule *et al.* 2024). High phenotypic diversity coupled with moderate heritability of traits is an indication of a rich gene pool that can be exploited for crop improvement in the wake of climate change (Akatwijuka *et al.* 2019; Andiku *et al.* 2022; Apunyo *et al.* 2022; Kasule *et al.* 2024).

Diverse morphotypes of sorghum have been reported in various sorghum growing regions of Africa as indistinct races of *S. bicolor* forming a crop – wild – weed complex. A high genetic diversity of sorghum genotypes exists in different sorghum growing regions of Kenya (Muui *et al.* 2016; Mudaki *et al.* 2023). The unique genetic diversity could be exploited as a source of novel genes for developing varieties with high resistance to pests and diseases, tolerance to low moisture and soil fertility, among

others (Muui *et al.* 2016). In Uganda, sorghum indicated a wide diversity of adaptability to diverse environmental conditions (Chakrabarty *et al.* 2022). Wild relatives and genotypes of sorghum rich in genes conferring resistance to ergot and green bug (Wu *et al.* 2024), and tolerance to water stress (Borrell *et al.* 2000) have been reported in Ethiopia. The genotypes exhibited a potential source of genes that confer resistance to biotic and abiotic stresses and an ability to adapt to changing environmental conditions (Mengistu *et al.* 2020; Enyew *et al.* 2022).

Farmers in Nigeria and West Africa grow landraces that are adapted and survive harsh environmental conditions. Such landraces, together with wild and semi-wild relatives, are a rich source of genetic variation (Yahaya *et al.* 2023), which could be useful in crop improvement. In African cropping systems, sorghum landraces are highly valued for their resilience to biotic and abiotic stresses (Afolayan *et al.* 2019). As reported by Yahaya *et al.* (2023), the landraces were highly heterogeneous, revealing sufficient genetic variability.

Several reports have indicated the presence of significant genetic variation among sorghum genetic resources from East Africa for agronomic and quality traits (Akatwijuka *et al.* 2019; Kataka *et al.* 2018). High level of genetic variations for grain yield, nutritional quality, quantitative agronomic traits, grain Fe and Zn concentrations have been documented (Andiku *et al.* 2022). Furthermore, the study revealed the presence of the stay green trait, which is important for post-flowering drought tolerance (Andiku *et al.* 2022) and resistance to mold in sorghum (Das *et al.* 2020).

Sufficient genetic variation for the quantitative traits in sorghum accessions sampled from Uganda, Ethiopia, India, and southern Africa exists (Akatwijuka *et al.* 2019; Desmae *et al.* 2016). The high degree of genetic variation is attributed to the differences in their genetic constitution and the long selection history of the materials in various geographical locations in East Africa, including Kenya, Sudan, Tanzania, and Uganda (Andiku *et al.* 2022).

A wide diversity of sorghum landraces is cultivated under equally diverse agro-climatic conditions and practices by subsistence farmers in the eastern province of Kenya (Labeyrie *et al.* 2016). The

sorghum landraces continue to be maintained by cultural preferences and traditional practices by the farmers. As climate change continues to threaten food security as a result of crop failure, the genetic diversity of hardy crops could salvage the situation, especially in arid and semi-arid regions (Mudaki *et al.* 2023; Sharma *et al.* 2026). Locally adapted genotypes of sorghum to marginalized environments are a rich source of major genes conferring tolerance to varied biotic and abiotic stresses (Muui *et al.* 2019; Mudaki *et al.* 2023). Additionally, the locally available sorghum genotypes are high-yielding, early maturity among other traits preferred by smallholder farmers as reported in Kenya (Muui *et al.* 2019).

However, the sorghum crop has been neglected due to the perception as food for the poor (Kane-Potaka *et al.* 2021). These species of crops, seemingly regarded as having lower potential, are actually an untapped natural resource that, when properly harnessed, can result in a decreased rate of degradation of the environment. Their cultivation may lead to sustainable production systems, provide diversity in diet and supply deficient micronutrients, provide extra income for farmers, and prevent loss of genetic diversity.

Adaptation of the sorghum crop to drought

Drought (water stress) is the major setback in crop production, mainly in Sub-Saharan Africa, accounting for about 10–15% crop yield loss (Mohamed *et al.* 2023). Drought is caused by insufficient water in the soil due to irregular rain distribution, low precipitation, and prolonged dry periods (Wu and Zou, 2017; Ochieng' *et al.* 2023). Water stress lowers the soil water potential, hampering normal crop growth and its productivity (Wu and Zou, 2017; Begum *et al.* 2019). Though studies have indicated drought reduces grain yield to some extent in sorghum, the plant has different mechanisms to cope with the stress. The plants respond through the production of signaling hormones (salicylic acid, jasmonic acid, ethylene), and activation of physiological reactions to reduce water loss, surface area, and mechanisms. Moreover, plants are able to reduce cell turgor pressure, increase production of secondary metabolites and various phytochemicals (glycine betaine, choline, proline) (Kheiry *et al.* 2017; Carlson *et al.* 2020).

Sorghum, a C_4 photosynthetic plant, has a high efficiency use of nutrients, sunlight, and water in drought conditions compared to other cereal crops (Kolozsvári *et al.* 2022). Additionally, sorghum has a deep root system enabling it to tolerate drought and thrive under water-limited conditions (Bollam *et al.* 2021). The water use efficiency enables the sorghum crop to produce even under moisture-deprived farming lands (Hadebe *et al.* 2020). Plant WUE is the yield output per unit of evapotranspiration, which is influenced by various plant characteristics such as morpho-physiological traits, genotype, plant population, soil water holding capacity, and agronomic practices (Mabhaudhi *et al.* 2016; Hadebe *et al.* 2017). Thus, the plant can utilize any available moisture from the soil, enabling it to survive under water-limited conditions.

Water stress negatively impacts soil nutrient absorption potential, mobilization of nutrients, and their transportation within the plant tissues (Sarshad *et al.* 2021). Depleted soil moisture decreases plant size, yield, biomass, and crop quality, attributed to its effect on nutrition and physiological processes (Syengo *et al.* 2019; Kaaria *et al.* 2021). Uptake of nutrients from the soil by plants is associated with the amount of water available in the growth media and the rate at which the nutrients diffuse to the root surface (Doğan and Akinci, 2011; Kaaria *et al.* 2021). According to Kaaria *et al.* (2021), sorghum genotypes tested were able to take up phosphorus and nitrogen under reduced soil moisture levels.

The structure of the root system (root length, surface area, root angle, root length density, and weight) provides drought tolerance by regulating the amount of soil area a plant can explore for water (Bucksch *et al.* 2014; Muluken *et al.* 2024). The role of root system architecture has been documented to increase grain yield under drought conditions in sorghum. Studies on root system architecture of sorghum genotypes, wheat, and rice have pointed to enhanced performance under drought conditions (Habtamu *et al.* 2021). Sorghum particularly develops long, narrow roots able to penetrate deep soil zones to access moisture. The dense and prolific roots system that provides a large surface area for water absorption, reduced leaf area, lowering the amount of water loss through transpiration, presence of motor cells along the midrib that helps in leave rolling during moisture stress thus reducing



water loss through the leaves, and its ability to maintain stomata opening at low levels of leaf water potential through osmotic adjustment (Younis *et al.* 2000; Kaaria *et al.* 2023).

To avert water stress, sorghum tends to adjust water use efficiency, transpiration rate, mobilization of photosynthetics, and biochemical alterations (Zhang *et al.* 2019a; Gumo *et al.* 2025). Sorghum plants have the ability to reduce water loss through transpiration and absorb more water from the soil even at low levels (Badigannavar *et al.* 2018). Most sorghum genotypes flower and mature early before the onset of the dry seasons (Zhang *et al.* 2019a). The plant's ability to remobilize assimilates and increase high photosynthetic rate enables the crop to attain high yields under water stress conditions compared to other crops (Badigannavar *et al.* 2018). Moreover, the plants adjust osmotic activities within the roots, produce more proline and enzymes resistant to dessication, and exhibit high stomatal conductance (Badigannavar *et al.* 2018; Temesgen *et al.* 2022). Studies have shown that sorghum has photosynthetic recovery after rehydration, sustaining grain production (Chaves *et al.* 2009). Lower stomatal conductance and reduced transpiration rate during the vegetative phase conserve water that can be utilized during the grain filling stage in water-limited environments (Lopez *et al.* 2017).

Sustaining normal chlorophyll content under water stress conditions enables sorghum plants to tolerate the stress and sustain their productivity (Chen *et al.* 2016). The chlorophyll content influences the plant's ability to absorb sunlight for photosynthesis (Chen *et al.* 2016; Temesgen *et al.* 2022). Plants developing under drought environments exhibit reduced chlorophyll content. Stay green has been reported in sorghum genotypes, delaying leaf senescence and resulting in an increase in grain yield. This trait is attributed to high leaf nitrogen, cytokinins, and chlorophyll contents at the flowering stage during water stress conditions (Borrell *et al.* 2000; Temesgen *et al.* 2022). Furthermore, stay-green plants tend to retain more green leaf area, reduce tillering and formation of smaller upper leaves, enlarging the leaves on the lower part (Kassahun *et al.* 2010). This reduced size of the upper canopy reduces plant water demand during the pre-flowering phase, conserving the water for grain

filling to increase biomass and grain yield (Borrell *et al.* 2014a). Furthermore, high water content available at post-flowering stages enables the plant to sustain photosynthetic activities for a longer period (George-Jaeggli *et al.* 2017).

Tolerance of the sorghum crop to low soil fertility

Sorghum is a C_4 photosynthetic plant, and its efficient use of nutrients makes it adaptable to diverse soil conditions (Paterson *et al.* 2008). Though tolerant to low soil fertility, sorghum still depends mainly on nitrogen (N) fertilizer to achieve higher grain yields. Nitrogen is essential as a constituent of biomolecules, nucleotides, amino acids, proteins, and hormones required for plant growth and development (Bollam *et al.* 2021). As a constituent of plant cells, including nucleic acid and amino acids, N is required in large amounts for enhanced crop productivity (Gweyi-Onyango, 2018).

Studies have shown that about 50–70% of applied nitrogen fertilizer is lost to the environment through volatilization, leaching, groundwater runoff, and nitrous oxide emissions from N fertilizer residues. Besides, high application of N fertilizers not only demands increased investment by the farmers but also results in soil acidification (Bollam *et al.* 2021). Studies have indicated that excessive application of nitrogenous fertilizer highly contributes to soil acidification and greenhouse gas emissions, escalating climate change (Sairam *et al.* 2025; Maitra *et al.* 2026b). To lower the cost of production through reduced N fertilizer application and achieve environmentally friendly cropping systems, the adoption of crop genotypes such as sorghum with high nitrogen use efficiency (NUE) and better yield is critical for sustainable production (Bollam *et al.* 2021).

Genotype and nitrogen source influence the response of crops to nitrogen. Most studies have shown that variations in nitrogen use efficiency under high nitrogen availability are highly attributed to the capacity of the genotypes to uptake Nitrogen. In sorghum, the NUE in genotypes tolerant to low nitrogen levels is determined by their high mobilization and utilization efficiency (Bollam *et al.* 2021). The ability for NUE in sorghum is controlled by genes associated with N uptake, assimilation, and mobilization (Diatloff *et al.* 2017).

Sorghum production is mainly done in semi-arid lands characterised by low soil fertility among other constraining factors (Shamme *et al.* 2016; Workat *et al.* 2020). Such soils have low organic carbon and nitrogen since there is inadequate organic material, and nitrogen is lost through leaching, denitrification, and volatilization (Queiroz *et al.* 2018; Kathuli *et al.* 2023). In semi-arid areas, nitrogen, a macro element required for growth, development, and high yields in crops, is very limiting, hence requiring frequent replenishment for increased productivity (Queiroz *et al.* 2018; Egeru *et al.* 2019; Priyadarshani *et al.* 2026; Workat *et al.* 2020). Nitrogen application in excess, however, results in environmental pollution and acidification of soils. Studies have shown that sorghum genotypes with the ability to grow in low-fertility soils and maintain high yields have high nitrogen efficiency (Dobermann, 2007). Sorghum genotypes documented to exhibit high nitrogen use efficiency attain increased yields based on crop production system (Maranville *et al.* 2002).

Nitrogen use efficiency, which is the ability of a plant to utilize nitrogen available within the root zone, indicates the grain yield per unit amount of fertilizer nitrogen from the soil and applied fertilizer (Shamme *et al.* 2016). Root characteristics determine uptake of nutrients by plants (Wang *et al.* 2016). According to Mohamed *et al.* (2023), root systems of plants play a key role in ensuring crop yield under nutrient-deficient soils, among other adverse environmental conditions. Root length and root hair density have been reported to influence Phosphorus (P) uptake in barley under low soil fertility (Brown *et al.* 2012). Studies have shown that higher root number and more root hair density in sorghum resulted in enhanced nutrient acquisition under low soil fertility (Mohamed *et al.* 2023). As reported by this study, sorghum genotypes that developed long roots enhanced P uptake under low soil nutrient availability coupled with low moisture levels.

Salinity tolerance in the sorghum crop

Salinity poses a significant threat to food security, particularly in arid and semi-arid regions due to high temperature and low precipitation (Mukhopadhyay *et al.* 2021). Salinity causes osmotic stress, ion toxicity, mineral deficiencies, physiological disorders, and biochemical impairments in plants (Balasubramaniam *et al.* 2023; Dehnavi *et al.* 2024).

Saline conditions exacerbate the generation of reactive oxygen species (ROS) in plant tissues, which cause loss of membrane integrity of cells (Hasanuzzaman *et al.* 2020). According to Naorem *et al.* (2023), salinity also damages soil structure, reduces root development, nutrient uptake, and activities of beneficial microorganisms.

Under saline conditions, the sorghum crop has exhibited moderate tolerance through gene expression, where the plant activates its adaptive biochemical and physiological responses (Mansour *et al.* 2021). The crop has exhibited the ability for the seed to germinate, and the plants grow and develop with minimal interference under saline conditions. Due to its C₄ metabolism, sorghum can sustain photosynthetic activity and dry matter accumulation not only under high temperature and low moisture, but also in soil saline conditions (Reddy, 2019).

Sorghum can limit the mobility of excessive sodium ions to the shoots, reducing their effects on plant activities. The plant has the ability to exclude sodium and regulate its transportation from the root system to the leaves by unloading it from the xylem into the roots (Almodares *et al.* 2014; Shakeri and Emam, 2017; Yang *et al.* 2018). Indeed, the plant has the ability to localize sodium ions in cell vacuoles as osmolytes for osmosis adjustment, compensating for the potential drop in the environmental conditions. According to Rajabi *et al.* (2024) and Mansour *et al.* (2021), salt-tolerant sorghum genotypes effectively regulate osmotic activities, have strong antioxidant enzyme activity, and maintain a potassium ion to sodium ion ratio. These mechanisms enhance and maintain high and stable photosynthesis efficiency, stomatal function, and membrane integrity, which ensure increased yields. Sorghum is also able to maintain cellular osmotic pressure, protect the metabolism from reactive oxygen species, and assemble photosystems under saline conditions by accumulating proline, sugars, an increase in chlorophylls and carotenoids, and enhanced antioxidant enzymatic activity (Hussain *et al.* 2019; Yilmaz *et al.* 2020).

Mechanisms in sorghum for tolerance to waterlogging

Over the years, waterlogging episodes resulting from heavy downpours have become more frequent

on agricultural land due to climate change (Khalifa and Eltahir, 2023). As climate change intensifies, the episodes will be more limiting crop production in many parts of the world (Ploschuk *et al.* 2018). Sorghum is relatively more tolerant to waterlogging than other crops, such as maize (von Haden *et al.* 2021). Hence, a suitable crop for most regions prone to flooding, especially in lowlands and farms with poor drainage.

Waterlogging limits root extension, development, and their functions in plants (Zhang *et al.* 2019b). Excessive water also interferes with oxygen supply and uptake of nutrients and water by the plants. Sorghum's ability to tolerate waterlogging is due to the potential of high seedling emergence rates (von Haden *et al.* 2021), high tillering ability (Alam *et al.* 2017), and development of adventitious and nodal roots under such conditions. Moreover, sorghum plants are able to reduce chlorophyll in leaves and alter fluorescence (Zhang *et al.* 2019b), reducing the negative effect of waterlogging.

Potential amendments to enhance the yield and yield components of sorghum

Despite the ability of the sorghum crop to thrive under water and soil nutrient-deficient conditions, there is still a need to use technologies that can boost production further to eradicate poverty and hunger. Such soil and water management technologies include the use of bio-fertilizers such as Arbuscular Mycorrhizal Fungi (AMF) and application of

silicon (Fig. 3) (Ngugi *et al.* 2022; Mohamed *et al.* 2023). Studies have shown that AMF alleviates the negative effects of water stress on plants (Li *et al.* 2019). Similarly, an increase in tolerance to drought and salinity stress of the sorghum crop provided with silicon nutrition has been reported. Although sorghum is considered a drought-tolerant crop, water deficiency still affects its nutrient mobilization and uptake, with negative impacts on yield (Ajeigbe *et al.* 2018; Abreha *et al.* 2022). Therefore, sustainable interventions are necessary to enhance the productivity of sorghum to address food insecurity and ensure the sustainability of the environment in arid and semi-arid areas (Birhanu and Negussie, 2024).

Silicon (Si) has been reported to alleviate plant growth and productivity under abiotic and biotic stresses (Moradtalab *et al.* 2019; Kaaria *et al.* 2023). The element is absorbed by plants in the form of monosilicic acid, later polymerized to form phytoliths upon translocation to the shoots (Garg and Bhandari, 2016). Silicon reduces transpiration rate (Kim *et al.* 2016), increases stiffness and strength of cell walls (Garg and Singh, 2018), and provides defence mechanisms to insect pests and pathogens (Cuong *et al.* 2017; Garg and Singh, 2018). Many studies have reported the ability of silicon in the mitigation of abiotic and biotic stresses in various crops such as sorghum, soybean, and chickpea (Moradtalab *et al.* 2019; Kaaria *et al.* 2023).

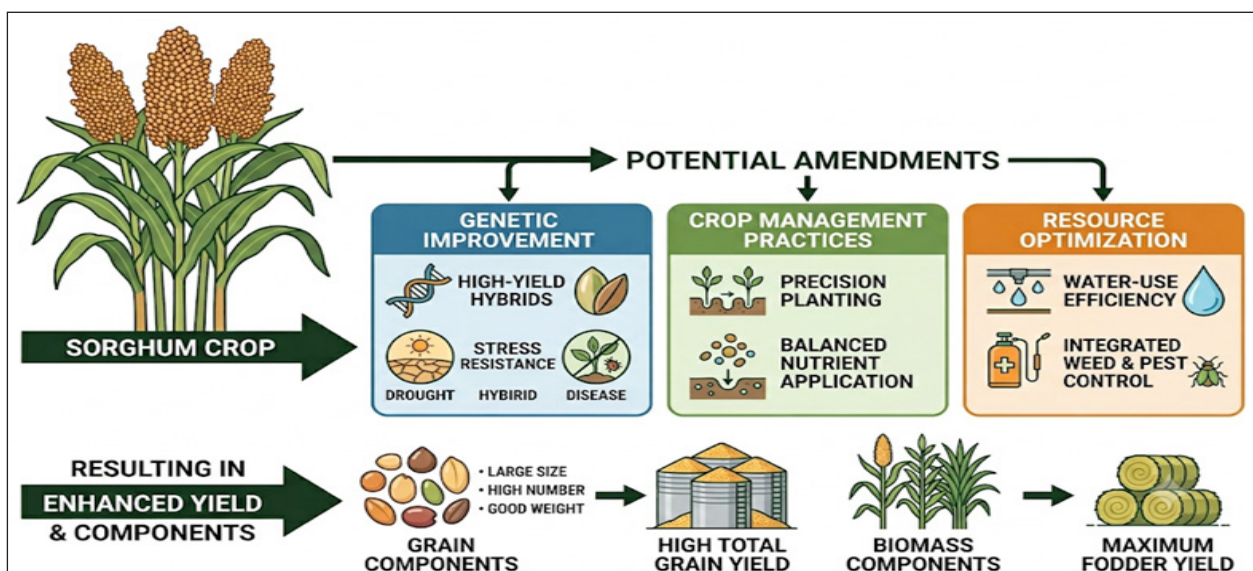


Fig. 3: Integrated approaches to upgrading sorghum productivity: From input amendments to optimized yield outcomes

As climate change negatively impacts crop production, the use of silicon could increasingly enhance the yields and yield components of sorghum (Kaaria *et al.* 2023). Findings of a study by Kaaria *et al.* (2023) showed that silicon application increased root biomass accumulation in sorghum. The results were in line with other reports showing that silicon enhances crop production by improving plant growth and yields through mitigation of water stress and nutrient imbalances (Khenizy and Ibrahim, 2015). Furthermore, silicon treatments recorded increased root length resulting in improved cell turgor, cell wall metabolism, and cell enlargement, thus enhancing water and nutrient uptake (Ramy and Atef, 2019; Raza *et al.* 2025; Kaaria *et al.* 2023). Kaaria *et al.* (2023) reported that supplementation of soils with silicon ameliorates the effects of water stress in sorghum. According to the findings of this study, plants supplied with silicon attained high grain and stover yields under depleted soil moisture. Other related studies showed that silicon alleviates water stress in soybean by increasing chlorophyll content and photosynthesis in plants. Also, silicon enabled maintenance of water status in chick pea under low soil moisture and improves physiohormonal attributes in soybean (Zhang *et al.* 2017).

According to Liu *et al.* (2015), drought tolerance in silicon-treated sorghum could also be partly attributed to the ability of the element to regulate aquaporin genes. Silicon has been reported to help in retaining water in plant tissues by reducing transpiration rate and partially blocking transpiration bypass flow (Gunes *et al.* 2008). These improve the water economy of the crop, maintain an efficient absorption of nutrient elements, thus improving yields (Kaaria *et al.* 2023). Kaaria *et al.* (2023) reported that silicon amendments in sorghum improved uptake of phosphorus from soils with low moisture levels and enhanced its translocation to the biomass above the ground. Nitrogen uptake and NUE increase with silicon amendments as reported in sorghum and wheat (Alsaeedi *et al.* 2019).

Uptake and accumulation of potassium (K) in sorghum plant tissue increased with amendments of silicon (Kaaria *et al.* 2023). Similar results were reported in maize, cucumber, sugarcane, and barley, where K uptake was enhanced by silicon nutrition under water stress conditions (Dong *et*

al. 2018; Alsaeedi *et al.* 2019). This is attributed to the increased activity of H⁺P- ATPase by silicon promoting cellular uptake of K through activation of K⁺ channels and carriers across plasma membranes (Kaaria *et al.* 2023). Studies by Kaaria *et al.* (2023) reported that silicon nutrition increased calcium (Ca) uptake in sorghum. Similar results were reported by Elrys and Merwad (2017) and Merwad (2018). Similarly, amendment with silicon resulted in increased Magnesium (Mg) uptake in sorghum (Kaaria *et al.* 2023). Studies have shown silicon nutrition improves uptake and translocation of Mg in most plants (Greger *et al.* 2018; Alsaeedi *et al.* 2019).

Sorghum is highly colonised by different species of Arbuscular mycorrhizal fungi (AMF), enhancing their biomass accumulation. Studies have shown partitioning and allocation of more resources to sorghum grain due to AMF colonisation, resulting in increased yields (Watts-Williams *et al.* 2021). AMF-inoculated sorghum plants showed high accumulation of P, Zn, and Fe in grain, which also resulted in greater grain yield and harvest indices (Watts-Williams, Emmett *et al.* 2019; Watts-Williams *et al.* 2021).

Studies have shown AMF improve the availability of nutrients such as phosphorus that are less mobile in soils (Mirriam *et al.* 2023; Qi *et al.* 2022; Tibbett *et al.* 2022). Other studies have shown enhanced N uptake with an increase in AMF colonisation (Shen *et al.* 2023; Wu *et al.* 2024; Xue *et al.* 2024). Arbuscular mycorrhizal fungi have an extended thin hyphal network able to penetrate small soil pores, enabling them access to residual water and nutrients such as nitrogen that remains in dry soils (Diagne *et al.* 2020; Abdalla *et al.* 2023; Hammer *et al.* 2024). Thus its potential to increase nutrient transportation in dry soils experiencing disrupted connectivity of water films (Xue *et al.* 2017; Bauke *et al.* 2022). AMF colonization of roots in sorghum has been reported to improve uptake of nitrogen and phosphorus.

The symbiotic relationship of AMF and plants aids in nutrient uptake and enhanced resistance to pathogens within the root system and in resistance to water stress (Birhanu and Negussie, 2024; Mirriam *et al.* 2023). Studies have shown improvement in plant growth, grain weight, and grain yield of sorghum under AMF colonization under water stress conditions (Alizadeh *et al.*



2011). Additionally, sorghum plants colonized by AMF reduced transpiration rate, had enhanced photosynthesis, and increased root development in water stress conditions (Chandra *et al.* 2022).

CONCLUSION

Sorghum is widely cultivated under diverse agroecological conditions, experiencing drought, soil salinity, nutrient-depleted soils, and waterlogging. A broad genetic diversity exists for use in the development of diverse cultivars to extend the production area, thus increasing yields. The untapped gene pool can lead to sustainable production systems and prevent loss of genetic diversity. The crop is rich in nutrients, health-beneficial compounds, and is used as food, feed, and the manufacture of industrial products. These attributes make it a potential crop to curb food insecurity, malnutrition, health challenges, and poverty in areas where other crops tend to fail due to unfavourable ecological conditions. Sorghum has various mechanisms to cope with water stress, salinity, excessive water, and low soil nutrients. The high use efficiency of nutrients (nitrogen and phosphorus), sunlight, and moisture in water-limited conditions enables it to produce under adverse conditions where other crops fail. The NUE enables the crop to survive under low soil inputs, lowering the cost of production, reducing soil acidification, and environmental pollution from inorganic fertilizers. Arbuscular Mycorrhizal Fungi and silicon enhance tolerance to abiotic and biotic stresses, hence suitable interventions to improve yields and yield components of sorghum in addressing food insecurity and ensuring the suitability of the environment in ASAL.

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