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REVIEW

Sorghum: a Star Crop to Combat Abiotic Stresses, Food Insecurity, and Hunger Under a Changing Climate: a Review

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Abstract
Climate change poses considerable challenges to global crop production, manifesting in harsh abiotic stresses like drought, high temperatures, and extreme weather events. These adversities exacerbate food insecurity, hunger, and poverty, particularly impacting vulnerable communities in underdeveloped countries. Amid this pressing scenario, a pivotal shift towards resilient crops capable of withstanding such environmental strains is imperative. Sorghum emerges as a promising climate-smart crop, uniquely equipped to endure adverse climatic conditions, and address nutritional needs. This review critically assesses the landscape of sorghum resilience amidst climate change and outlines its multifaceted role in bolstering food security and alleviating hunger. It goes beyond prior studies by emphasizing specific gaps in understanding sorghum's adaptability to diverse abiotic stresses and its underexplored potential in mitigating food crises. Notably, it delves into novel perspectives, such as the efficacy of biostimulants in enhancing sorghum resilience and the cultivation of sweet sorghum for biofuel production in marginal lands. By elucidating the unmet potentials and highlighting avenues for harnessing sorghum's resilience, this study aims to catalyze informed strategies for combating the deleterious impacts of climate change on global food security and hunger.

Keywords Biostimulants · Drought · Food security · High temperature · Salinity

1 Introduction

Throughout history, sorghum crops have been utilized globally for sustenance and as animal feed. Due to the growing interest in sorghum as a nutritional option for humans, recent literature analyses emphasize its valuable nutrients, active components, potential health benefits, and its gluten-free characteristic (Mohamed et al. 2022; Aguiar et al. 2023). To meet the increasing food requirements of the continuously expanding population, projected to exceed nine billion by 2050, a critical imperative exists to enhance cereal production by approximately 70% (Neupane et al. 2022). The disparity in agricultural productivity remains a subject of concern (Mundia et al. 2019). This difference may be attributed to various factors, including but not limited to adverse weather conditions, suboptimal farming practices, input choices, crop diversification, and the prevalence of crop diseases and insect pests. Food demand is expected to surge by 30 to 50% in the next 30 years (Hadidi et al. 2023).

Sorghum, a staple food in many impoverished countries of South Asia and Africa (Chadalavada et al. 2021),

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is primarily cultivated in Africa, followed by America (FAOSTAT 2023) (Fig. 1). *Sorghum bicolor* L. Moench, a cultivated type, is known for its self-pollination and possession of a C4 photosynthetic pathway, contributing to its high photosynthetic efficiency (Goyal et al. 2020). It exhibits efficient utilization of nitrogen resources and produces substantial biomass (Tu et al. 2023). Sorghum and millets offer diverse variations, making them more nutritionally superior and resilient to challenging ecological conditions compared to maize (Hassan et al. 2021). Given climate change, population growth and urbanization in Asia and Africa, it is crucial for sorghum and millets to play a pivotal role in the global food system. Sorghum exhibits resistance to various abiotic stresses such as drought and salinity (Sharma and Joshi 2022) but has not received substantial research funding (George et al. 2022). As reported by Proietti et al. (2015), sorghum cultivation is primarily concentrated in regions where other food crops encounter performance challenges. This crop demonstrates the ability to thrive in areas where maize and other major cereal crops fail or are less suitable due to constraints imposed by climate and soil conditions (Rao et al. 2016). It can be grown with minimal resources and flourishes in arid and hot environments (Prabhakar et al. 2022). Moreover, it offers higher nutritional value, making it a preferable choice for utilization and exploitation (Khoddami et al. 2021). Aside from its role in human nutrition, it is also being utilized as a feedstock for producing bioethanol (Mubarak Alqahtani 2023).

Meeting the nutritional needs of the rapidly expanding global population amidst the profound impacts of climate change on the global food system represents a significant and intricate challenge. Climate change has far reached consequences, intensifying and increasing the frequency of phenomena such as precipitation, droughts, soil degradation, and sea level rise (Chadalavada et al. 2021). Undoubtedly, these events significantly affect the global agricultural system, resulting in various dimensions of food insecurity, including availability, stability, access, and utilization (Peng and Berry 2019). The Intergovernmental Panel on Climate Change (IPCC 2018) projected that about 122 million individuals could be pushed into extreme poverty due to global warming by 2030. The anticipated population surge will strain the primary production sector, particularly agriculture, as it endeavors to meet the rising food demands of the growing population. The global impact of climate change, alongside the ongoing decline in arable and fertile land, creates a challenging scenario where fulfilling the world's food demand using current agricultural practices becomes increasingly difficult, if not nearly impossible (Kumar et al. 2022).

According to the report of FAO, IFAD, UNICEF, WFP, and WHO (2021), global hunger notably increased in 2020 due to the COVID-19 pandemic. This surge significantly affected around 21%, 9%, and 9.1% of the population in Africa, Asia, and Latin America and the Caribbean, respectively. The report underscores the urgency of implementing robust strategies to accelerate progress, particularly in addressing food accessibility disparities. Failing to do so is likely to hinder the achievement of the goal to eliminate hunger by 2030. Additionally, the report highlights how the COVID-19 pandemic has worsened the already slow progress towards ending hunger, with its future impacts expected to unfold in the coming years. The report suggests that countering the effects of the pandemic on human health requires the implementation of exceptional measures.

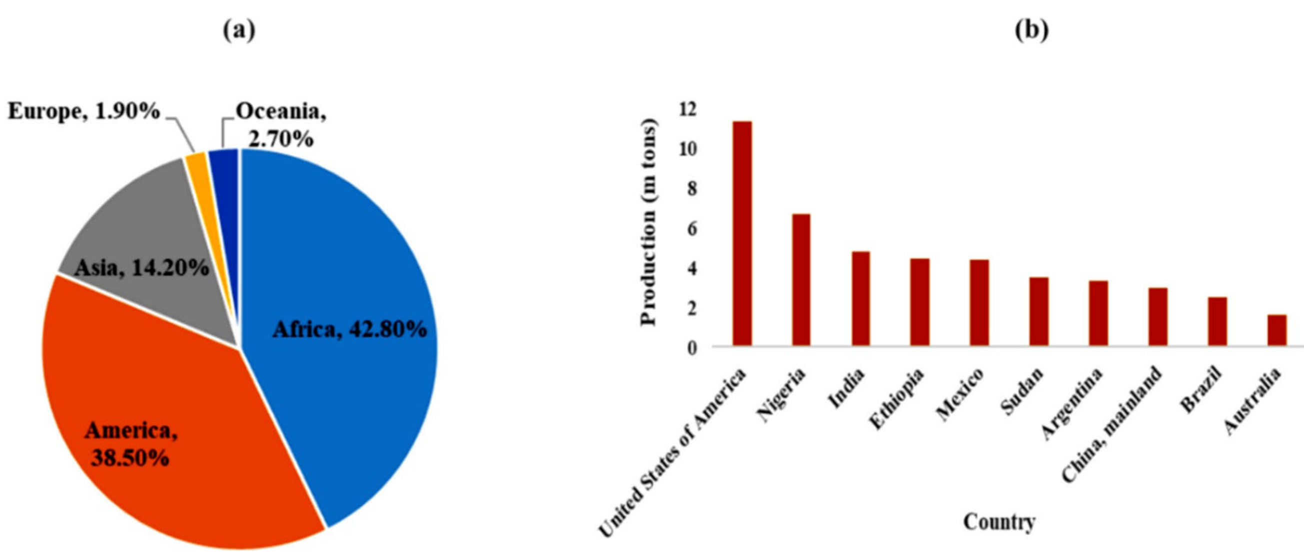


Fig. 1 Production share of sorghum **a** by region and **b** top ten sorghum-producing countries in the world (FAOSTAT 2023)

The integration of the alternative crops into the global food system is pivotal for adequately addressing the nutritional needs of individuals affected by malnutrition, while also considering their capacity to thrive amidst climate change challenges (Feyisa 2022). Presently, sorghum emerges as a prime contender due to its resilience to adverse climatic conditions and its ability to flourish in marginal lands (Chadalavada et al. 2021). These advantageous traits enable its cultivation without encroaching upon the space allocated for other primary cereal crops. Moreover, sorghum exhibits significant promise in fulfilling global nutritional needs. The primary objective of this review is to assess the current global status of food security and hunger, emphasizing the exploration of sorghum's potential in alleviating the issues associated with food insecurity and hunger in the context of climate change.

1.1 Justification of the Review

Several studies have indicated that small grains outperform maize concerning drought-resistance and yield in semi-arid regions (Svodziwa 2020). The existing unfavorable macroeconomic conditions, along with consecutive years of drought, have led to severe food security concerns that are increasingly worrisome (Wudil et al. 2022). Moreover, the COVID-19 pandemic further exacerbates this situation. The current circumstances offer an ideal opportunity to introduce new technologies and underutilized crops to tackle the urgent problem of food insecurity and hunger, considering the significant influence of climate change. Sorghum, in this context, emerges as a wise choice and holds the potential to substantially contribute to sustaining food and nutrition in regions grappling with persistent challenges posed by climate change.

2 Abiotic Stresses and Agriculture

The alterations of climatic patterns stand as a significant and persistent global concern affecting both the present and future state of the world. Climate change, a multifaceted issue primarily characterized by atmospheric CO_2 concentrations exceeding 400 ppm, has the potential to induce various effects. These effects include heightened air temperatures, abrupt fluctuations in annual, seasonal, and daily temperatures, shifts in precipitation patterns, increased frost occurrences, and prolonged drought periods (Patterson et al. 2013). The phenomenon of climate change is expected to significantly impact different aspects of agriculture, such as crop production, soil characteristics, water utilization, and livestock. (Datta et al. 2022). Global food demand is being driven to its maximum due to a continually growing population. Improving crop productivity per unit of land area represents the most viable approach to achieving sustainable food security. However, the full potential productivity of numerous crops on a global scale remains unachievable due to various adverse conditions and inadequate management practices (Saharan et al. 2022).

The primary factors significantly affecting crop yield include weather-related challenges, such as elevated temperatures, elevated carbon dioxide levels, and excessive precipitation. Climate change can substantially impact crop production, altering the timing of planting and harvesting, as well as environmental conditions for plant growth (Nkwi et al. 2023). The effects of climate change on crop production involve changes in temperature and precipitation patterns, increased frequency, and intensity of extreme weather events like droughts, floods, and storms, proliferation of pests and diseases, alteration in soil moisture and temperature, and shifts in water availability (Fig. 2). These changes have the potential to cause food security and financial setbacks for agricultural producers. Additionally, climate change influences the interaction between plants and pathogens, affecting various aspects such as plant life, the development of host resistance, disease severity, the emergence of new pathogen types, and the pathogenicity of the pathogens (Raza and Bebber 2022).

Climate change is projected to significantly impact global cereal crop production by 2100. Specifically, substantial reductions in yields are anticipated for crucial cereal crops like maize, wheat, and rice. The projected decrease in production for wheat is almost 72%, and 45% for maize and rice (Adhikari et al. 2015). To counteract the adverse effects of climate change on crop production, implementing adaptation strategies and mitigation measures is crucial (Wijerathna-Yapa and Pathirana 2022). Healthy soils act as a natural reservoir of essential plant nutrients and play a pivotal role in achieving improved agricultural productivity (Gerke 2022). Fluctuations in environmental conditions due to climate change, such as increased erosion, compaction, reduced soil health, and lowered productivity, have significant implications for soil (Lal et al. 2011). Consequently, this can affect food security, biodiversity, and the overall ecological health of the planet. Increased CO_2 levels have been linked to soil acidification, altering soil pH levels and subsequently diminishing fertility, negatively impacting plant growth (Lal et al. 2011).

Increasing temperatures have the potential to accelerate decomposition and the cycling rates of nutrients, potentially causing changes in both the levels and structure of soil nutrients. Elevated temperatures may significantly impact diversity and spatial arrangement of soil microorganisms, which play a crucial role in maintaining soil health (Barreiro et al. 2020). Changes in precipitation patterns, such as increases instances of intense rainfall or prolonged arid periods, can contribute to soil

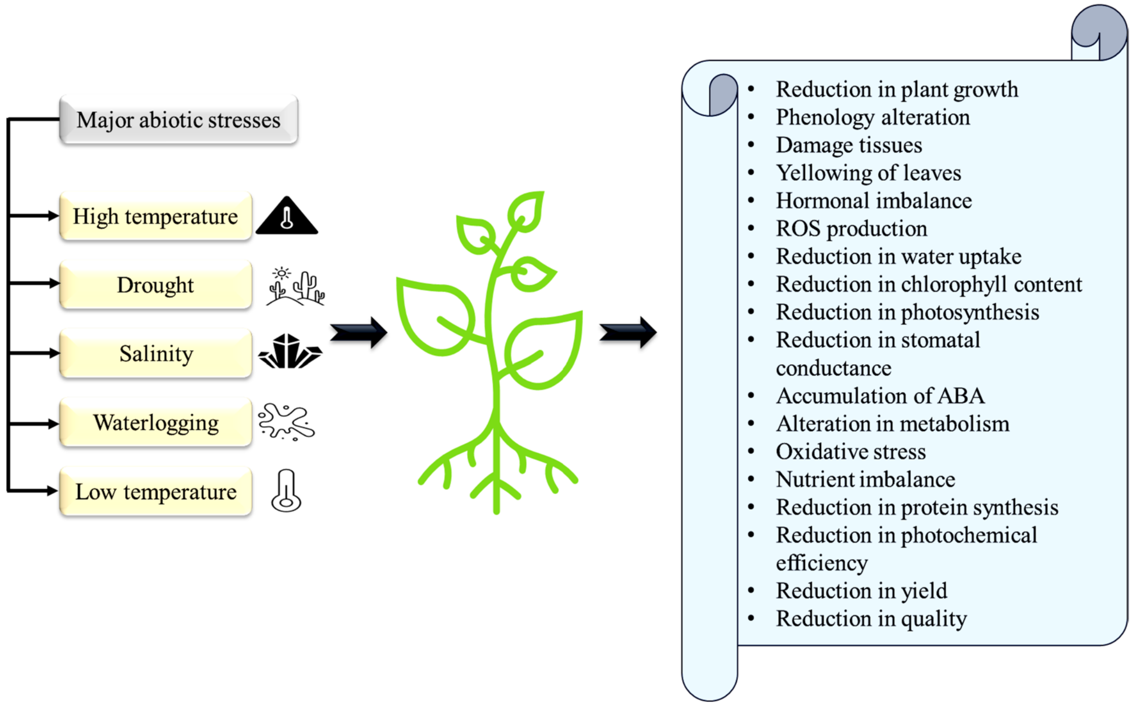


Fig. 2 Major abiotic stresses and their effects on crops. ROS, reactive oxygen species; ABA, abscisic acid

erosion, heightened runoff, and reduced water infiltration into the soil. This has the potential to degrade soil quality and subsequently deteriorate its ability to retain water and essential nutrients. Alterations in precipitation patterns may also lead to changes in the distribution and diversity of soil microorganisms, thereby significantly affecting the overall health and productivity of the soil (Pareek 2017).

Heat and drought are recognized as significant abiotic stresses impacting crop yield and productivity (dos Santos et al. 2022) and have been observed to decrease farm income and agricultural benefits. In the African region, the cowpea crop, holding significant agricultural value, faces adverse effects from drought stress, leading to a marked decline in yields ranging from 34 to 68% (Farooq et al. 2017). Drought stress induces various physiological changes such as reduced photosynthetic activity, fluctuations in cell wall elasticity, and stomatal closure. The nutritional status of crops is influenced by drought, affecting ion concentration in plant tissues. Reduced moisture levels decrease soil nutrients diffusion to root surfaces (Younis et al. 2018), impacting nutrient composition, management, and biosynthetic capacity, ultimately impeding or halting plant growth. Certain abiotic stresses trigger an overproduction of reactive oxygen species (ROS), which possess toxic properties and damage biomolecules like carbohydrates, lipids, nucleic acids, and proteins, negatively affecting plant growth (Zlatev and Lidon 2012). Inadequate water supply and elevated temperatures can also detrimentally affect the transpiration and stomatal conductance of plant leaves (Król 2013). Currently, 91% of the global agricultural sector faces various stresses, with these stresses accounting for about 50% of the overall decline in agricultural production (Younis et al. 2020).

Heat stress is strongly associated with temperature fluctuations. Increases in air and soil temperatures surpassing tolerance thresholds can adversely affect crop growth and development (Zhao et al. 2017). The rise in global temperatures is a significant climatic concern, potentially impacting plant production and crop growth worldwide (Bibi and Rahman 2023). Heat stress has been found to result in reductions in seed germination, photosynthetic activity, and crop yields (Lamichaney et al. 2021; Ullah et al. 2021; Zahra et al. 2023). Elevated temperatures have the potential to hinder pollen grain swelling, leading to reduced pollen vitality and anthers' potential indehiscence (Ullah et al. 2021). Elevated levels of stress have the potential to become unmanageable, leading to plant mortality (Fig. 3). Achieving freedom from stress is an unattainable goal. Thus, it is observed that plants demonstrate metabolic reactions and produce distinct molecules as a means of adapting to challenging environmental conditions (Rupnarayan 2017) Currently, only 10% of crop production originates from agricultural lands in non-stressed regions. The remaining 90% is currently facing one or more

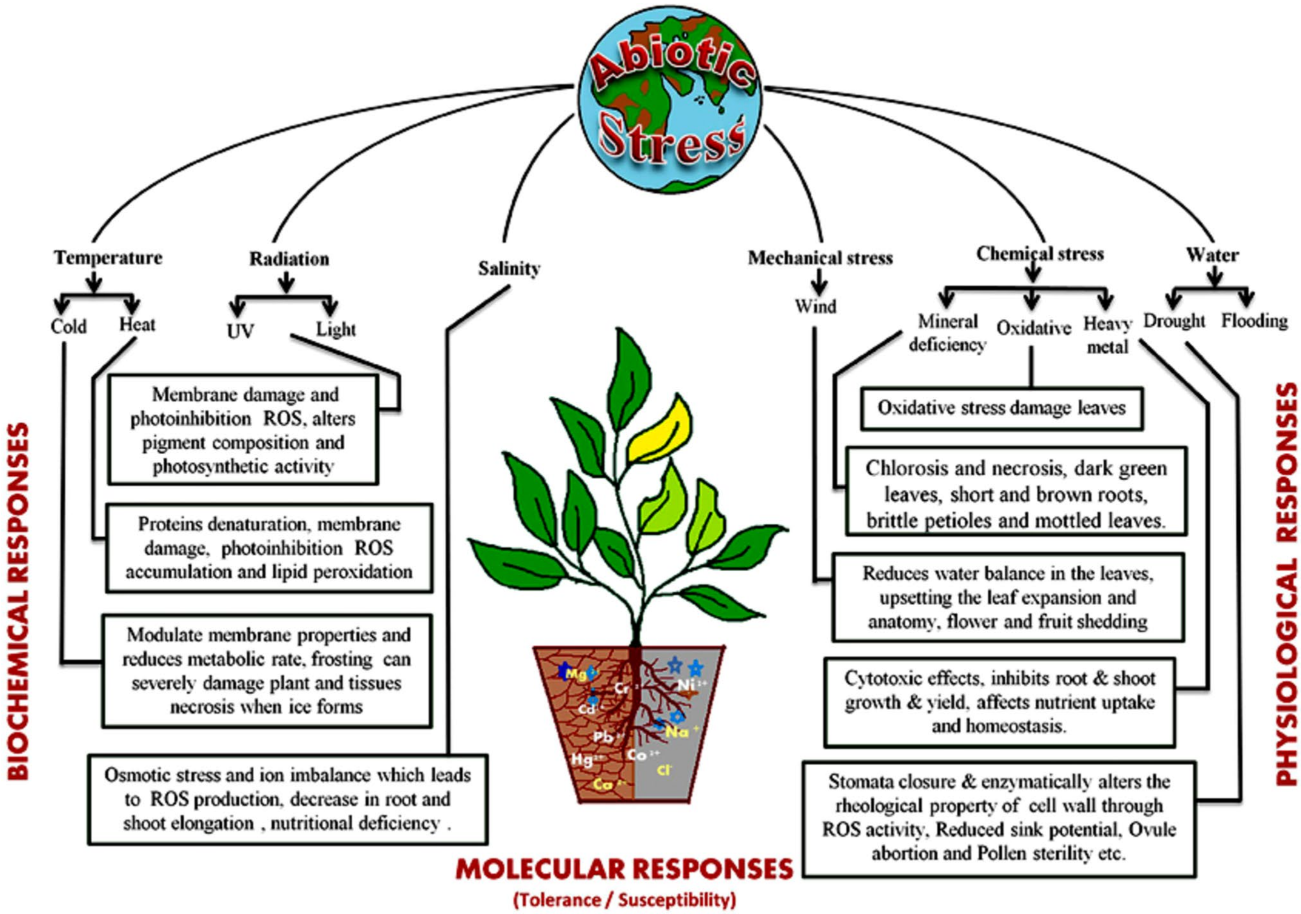


Fig. 3 Different abiotic stresses and their physiological and biochemical effects on plants (Tripathi et al. 2015). UV, ultraviolet; ROS, reactive oxygen species

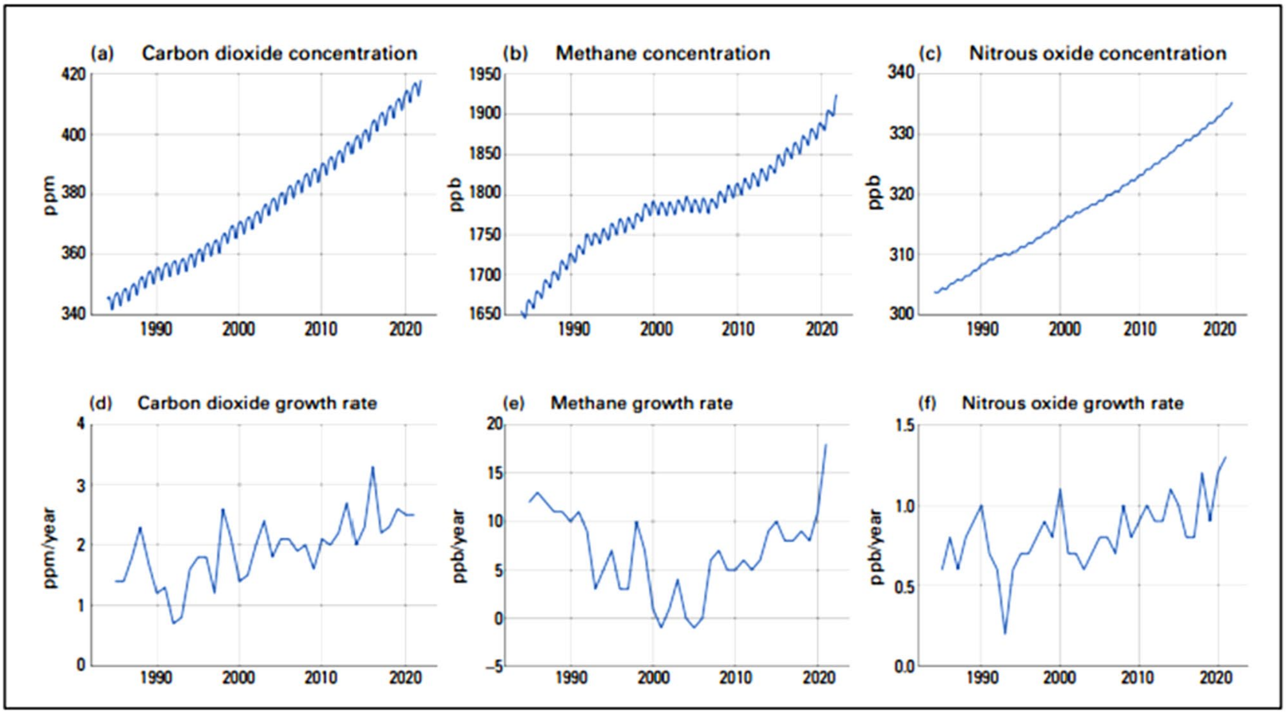
environmental stressors (Younis et al. 2020). Plants continuously adapt to abiotic stress through biochemical, physiological, molecular, and phenotypic mechanisms. However, there is an ongoing need for further efforts aimed at enhancing stress tolerance through genetic enhancement of plant defenses, advancement of resource conservation technologies, and implementation of alternative strategies.

3 Role of Sorghum in Changing Climate

Climate change poses a significant threat to global food security due to its profound impact on agricultural productivity. Recent global average values for the mole fraction of CO_2 were recorded at 413.2 ± 0.2 ppm (Bennedsen et al. 2019). Similarly, Jiang et al. (2019) reported that the mean surface mole fraction values for N_2O and CH_4 were 333.2± 0.1 and 1889± 2 ppb, respectively. These findings indicate that as of 2020, these concentrations reached their highest levels (Jiang et al. 2019). Moreover, the values exhibit an increase of 149%, 123%, and 262% in comparison to the pre-industrial values, which specifically refer to the period prior to 1750 (WMO 2021). Long-lived greenhouse gases surged by 47% from 1990 to 2020, with notably, CO_2 accounting for nearly 80% of this increase (Butler 2020), contributing to the escalating global temperatures (Fig. 4). Climate change has significantly impacted crops in arid and semi-arid regions, leading to widespread food insecurity and malnutrition for millions in these areas (Chadalavada et al. 2021). Sorghum and certain millet varieties have been identified as potential catalysts for a sustainable agricultural transformation, referred to as the "harbingers of ever green revolution," owing to their versatility, adaptability, and drought resistance (Chaturvedi et al. 2022).These climate-smart crops have shown the ability to yield substantial biomass, emphasizing the need to integrate small grains such as millets, sorghum, and rapoko into the conventional food chain to bolster food security in the face of climate change (Phiri et al. 2019).

Underutilized crops like sorghum and amaranth could serve as viable alternatives for food production due to their untapped potential in mitigating climate change effects (Ichsan et al.

(a)



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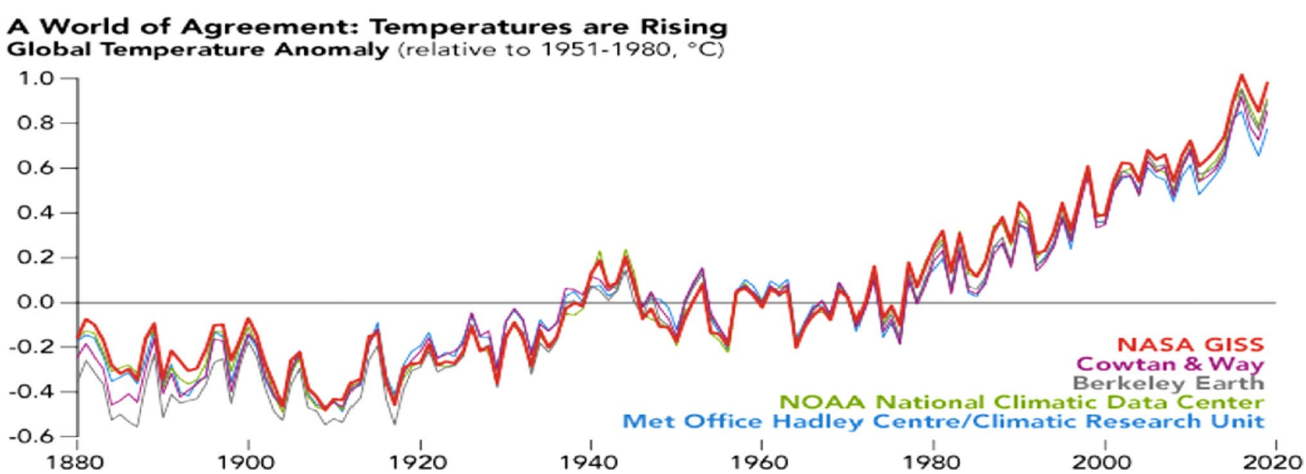

Fig. 4 **a** Increase in various greenhouse gases from 1984 to 2021 (WMO 2022). **b** Annual global surface temperature (1880–2020). Obtained from: https://earthobservatory.nasa.gov/world-of-change/global-temperatures, accessed on 15 July 2023

2021). Sorghum, in particular, demonstrates a higher carbon dioxide absorption rate 50–55 tons per hectare annually, surpassing other cereal crops (3–10 tons per hectare) as well as forests (16 tons per hectare) (Popescu et al. 2018). Additionally, its greater capacity for oxygen release positions sorghum as an environmentally sustainable crop (Popescu et al. 2018). With global food security becoming increasingly precarious due to rising population and climate change impacts (Lesk et al. 2016), urgency mounts to accelerate plant breeding methods and discover new traits to enhance yield and adaptability to abiotic stresses. This imperative is driven by the projected decline in crop productivity resulting from both climate change and rapid population growth, essential to ensuring future food availability and security (Abdelrahman et al. 2017).

4 Sorghum Performance Under Abiotic Stresses

4.1 Drought

Drought is widely acknowledged as one of the most devastating natural disasters, significantly impacting global crop productivity (Prasad et al. 2021; Abd El Mageed et al. 2023). Projections further indicate an expected escalation in both the frequency and severity of drought events in the upcoming years (IPCC 2013). Wilhite (2000) asserts that drought accounts for roughly 20% of the overall damage caused by natural hazards worldwide. In addition to its detrimental effects on agricultural production, drought yields enduring economic and social consequences. These encompass migration (Gray and Mueller 2012), poverty, civil unrest and conflicts (Von Uexkull 2014), famine, gender disparities (Fisher and Carr 2015), adverse health effects (Ebi and Bowen 2016), and reduced hydro-energy generation (Shadman et al. 2016). It is widely acknowledged as a significant contributor to food insecurity. Prolonged periods of low precipitation and aridity in regions with limited rainfall pose a considerable challenge to agricultural practitioners, intensifying the state of food insecurity (Ayanlade et al. 2018). This challenge is exacerbated by ongoing alterations in global climate patterns (Sakadzo and Kugedera 2020). Projections suggest that nearly two billion individuals will face the consequences of water scarcity by 2025 (Nellemann et al. 2009). When compounded by the effects of global warming, this issue is anticipated to present significant challenges in urban regions (IPCC 2014a).

Sorghum is esteemed as a more fitting option in semi-arid regions due to its adaptability and eco-compatibility, demonstrated by its potential for drought resistance (Dube et al. 2018). Considering the dwindling water resources and the increasing global population, it becomes evident that small grains like sorghum will increasingly become a preferred choice for human consumption in the future (Chazovachii 2012). Sorghum displays a higher capacity to endure water scarcity compared to many other cereal crops, and it can thrive in various soil conditions (Mohamed et al. 2022). This crop has been utilized due to its heightened ability to withstand water stress as a second harvest in areas characterized by arid climates, where cultivating another annual crop presents challenges (de Almeida et al. 2019). The plant is renowned for its exceptional agronomic traits, including its capability to flourish in diverse environmental conditions such as arid climates, high altitudes, extreme temperatures, infertile soils, as well as alkaline and saline soil compositions (Xiong et al. 2019). These attributes of sorghum can be ascribed to its extensive root system characterized by a high ratio of roots to leaves and its leaves possessing waxy surface that enables them to curl in response to external stimuli (Rooney and Waniska 2000). In situations of severe drought, where maize crops might fail, it has been observed that small grain crops like sorghum and millet can still yield a certain amount for subsistence purposes.

Drought tolerance characteristics can be classified as constitutive, representing inherent qualities or adaptive, denoting traits expressed in response to stress (Kamal and Ahmad 2022). Sorghum's ability to endure drought conditions can be credited to various morpho-physiological factors (Fig. 5). These factors encompass stay green traits, a deep rooting system, enhanced water utilization efficiency, C4 photosynthesis, the capacity for homeostasis, and a high epicuticular wax coating (Yigit et al. 2016; Tiwari et al. 2021). The term "stay-green" describes a plant's capability to endure water scarcity after flowering, thus preventing premature leaf senescence during the grain filling stage, especially under severe moisture stress (Hossain et al. 2022). This trait significantly enhances crop productivity and ensures consistent crop yields in limited moisture conditions.

It is believed that epicuticular wax (EW) possesses advantageous characteristics contributing to stress tolerance including resistance to salinity, drought, and disease (Ahmad et al. 2020). Wax secretion and deposition are influenced by a

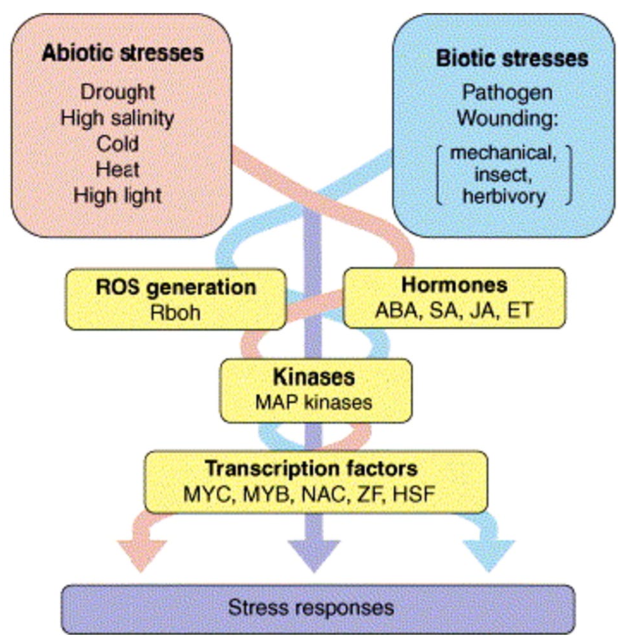

Fig. 5 Plants signal defenses against a variety of biotic and abiotic stressors. ROS, reactive oxygen species; ABA, abscisic acid; SA, salysilic acid; JA, jasmonic acid; ET, ethylene; MAP, *m*itogen-activated protein kinases*;* MYC, master regulator of cell cycle; MYB, Myb proto-oncogene protein*;* HSF, heat shock transcription factor

multitude of factors, including species, organ type, developmental stage, and prevailing environmental conditions. Despite significant variations in its content and structure, the hydrophobic nature of EW remains predominant (Dalal et al. 2012). Sorghum stands out among cereal crops due to its remarkable capacity for producing a substantial quantity of EW on both its abaxial leaf blade and sheath, particularly in the initial stages of reproduction. Sorghum wax demonstrates the most significant accumulation of free fatty acids, ranging from a carbon chain length of 16 to 33 (Jenks et al. 2000).

Burow et al. (2009) identified an acylCoA oxidase gene, that functions in lipid and wax synthesis along with seven other potential transcripts within the BLOOM-CUTICLE (BLMC) region of sorghum. The substantial EW layer aids in reducing non-stomatal water loss in plants and enhances sorghum's water use efficiency by regulating nocturnal water loss (Burow et al. 2008). The ability of plants to endure and tolerate drought conditions is closely linked to two primary traits, namely osmotic adjustment (OA) and antioxidant capacity (Fig. 6). OA involves the accumulation of osmolytes like amino acids (e.g., proline), sugars (e.g., sucrose and fructans), polyols (e.g., mannitol and pinitol), quaternary amines (e.g., glycine betaine), ions (e.g., potassium), and organic acids as response to water deficits and is a heritable characteristic (Ahmad and Kamal 2021). In sorghum, the regulation of OA is governed by two main genes, namely OA1 and OA2, alongside other genes that exerts relatively minor effects (Basnayake et al. 1995).

Glycine-betaine (GB) is a well acknowledged osmoprotectant that contributes to enhancing abiotic stress tolerance (Kamal and Ahmad 2022). Wood et al. (1996) demonstrated the upregulation of two genes, namely BADH1 and BADH15, responsible for encoding betaine aldehyde dehydrogenase in sorghum plants experiencing limited water availability. This upregulation positively associated with the deposition of GB. Proline, an osmolyte accumulating in response to abiotic stresses. P5CS (EC 2.7.2.11), is an enzyme commonly known as D1-pyrroline-5-carboxylate synthetase. It plays a pivotal role in regulating proline biosynthesis. Two closely related P5CS genes, SbP5CS1 and SbP5CS2, were isolated from sweet sorghum. These genes are located on chromosomes 3 and 9, respectively. Under conditions of limited water availability, the expression of these genes increased (Su et al. 2011). In a recent study, 80 genes responded differentially to drought stress in genotypes that exhibit resistance to drought. Among these, about 70% exhibited upregulation while 70 genes were novel with presently unknown functions. Among these genes are several uncharacterized proteins associated with drought tolerance during the seedling stage (Abdel-Ghany et al. 2020). It is crucial to implement robust policies and governmental assistance to promote sorghum cultivation due to its superior performance in challenging environmental conditions compared to maize (Nciizah et al. 2021). Various drought tolerant sorghum genotypes are given in Table 1.

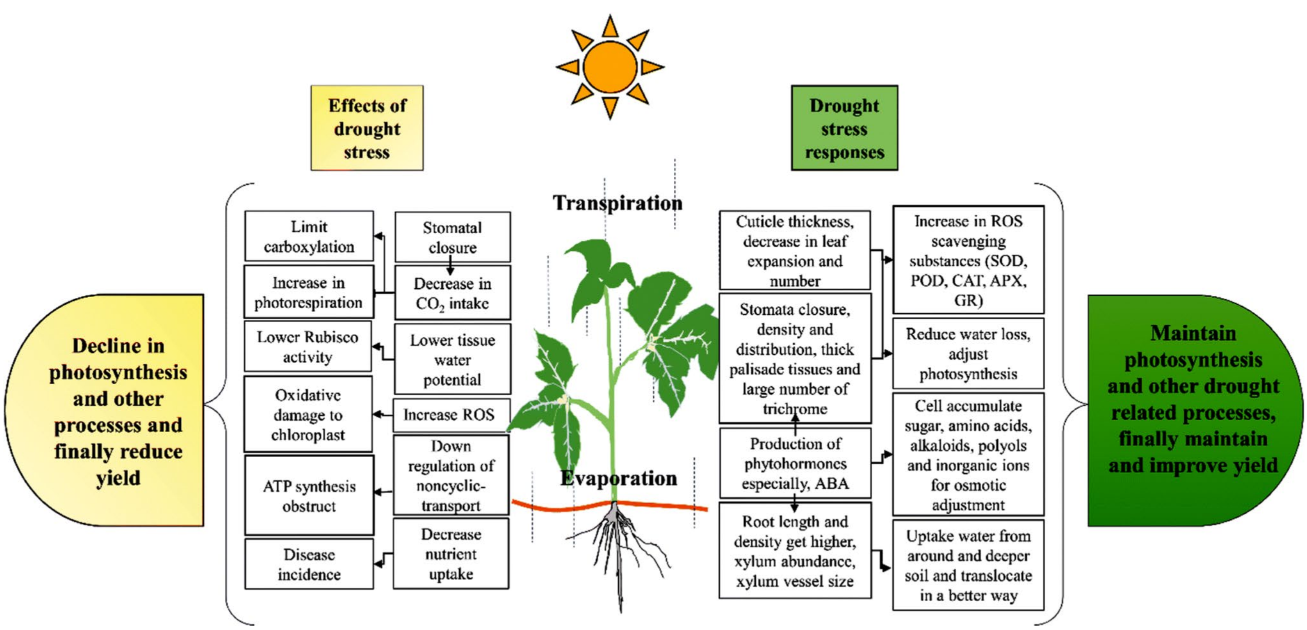

Fig. 6 Process of plant drought-tolerance *ATP,* adenosine triphosphate ROS, reactive oxygen species; SOD, superoxide dismutase; POD, peroxidase; CAT, catalase; APX, ascorbate peroxidase; GR, glutathione reductase; ABA, abscisic acid

Table 1 A list of some drought-tolerant sorghum genotypes

Genotype	Year of release	Country	References
Seredo	1970	Kenya	Timu et al. (2014); Maluk (2018)
Serena	1975	Kenya	Timu et al. (2014); Maluk (2018)
Gadam	1982	Kenya/South Sudan	Mwadalu and Mwangi (2013); Timu et al. (2014)
Tengemeo	1986	Tanzania	Wambugu and Kamanga (2014)
Macia/phofu	1999	Tanzania/Kenya/Namibia	Saadan et al. (2000)
Yarwasha	2003	ARC Sudan	Osman (2007); Smale et al. (2018)
Gadam El Hamam	2004	South Sudan/Sudan/Kenya	CIAT et al. (2011)
PAHAT, SAMURAI 1 and SAMURAI 2	2006	Indonesia	Sihono (2010); Human et al. (2011)
ArfaGadamak8	2009	ARC Sudan	Osman (2007); Smale et al. (2018)
RSC02-3seL(bulk) to RSC149-3sel(bulk)	2012	USDA-ARS	Klein et al. (2013)
IESV 92043 DL	2017	KALRO, Kenya/Somalia/Zimbabwe	Maluk (2018)
SAMSORG 47	2018	Nigeria	GLDC (2018); ICRISAT (2019)
SAMSORG 48	2018	Nigeria	GLDC (2018); ICRISAT (2019)
SAMSORG 49	2018	Nigeria	GLDC (2018); ICRISAT (2019)

4.2 High temperature

High temperatures and drought are recognized as the two primary abiotic stresses that adversely affect crop growth, development, and yield (Abdelrahman et al. 2020; Mohamed et al. 2019). Crop production faces significant constraints due to high temperatures, specifically when they surpass the optimal range (Fig. 7). Such elevated temperatures detrimentally impact the regular physiological growth and development of crops (Prasad et al. 2021). Projections indicate a global air temperature increase of approximately 3.7–4.8 °C by the end of this current century (IPCC 2014b). This increase is primarily linked to the escalation of greenhouse gases, with particular concern surrounding CO_2 (Frank et al. 2015). Furthermore, the upward trend in average atmospheric temperature, coupled with frequent occurrences of high temperatures, poses a significant threat to the global food system, thereby adversely affecting both global and local food security (IPCC 2014a). In contrast to other cereals,

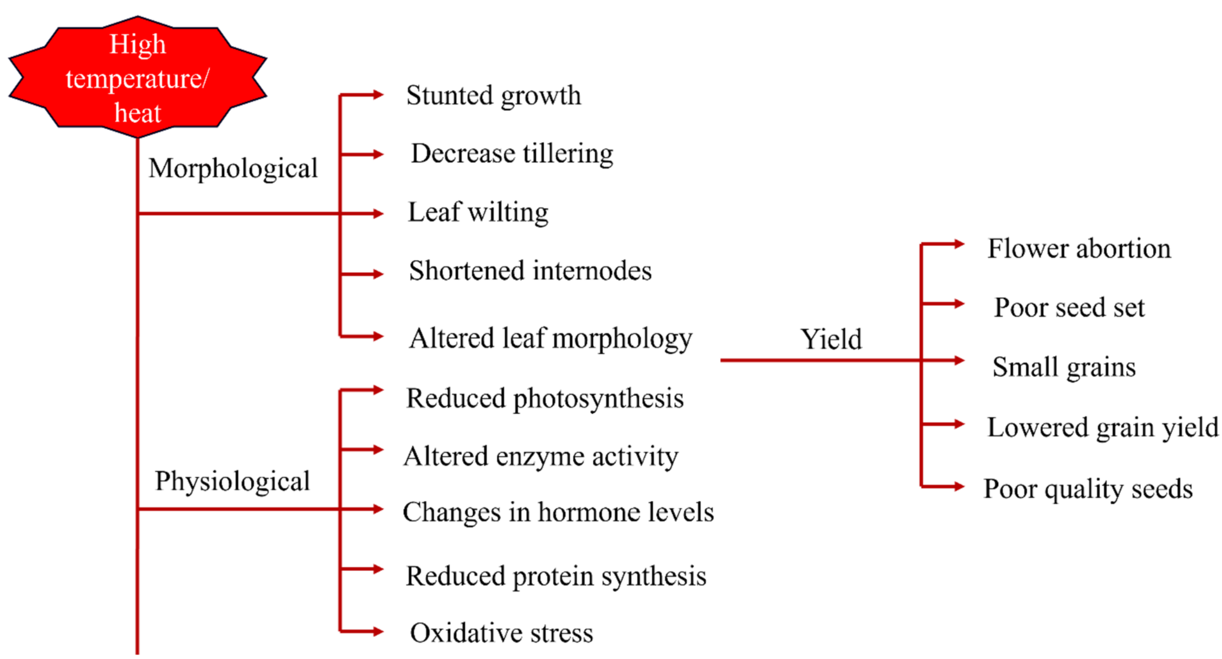

Fig. 7 Some adverse effects of high temperatures on morphological, physiological, and yield attributes of sorghum

sorghum shows a greater capacity to withstand elevated temperatures and demonstrates resilience in environments surpassing 38 °C (Ichsan et al. 2021). Sorghum is commonly cultivated in semi-arid regions characterized by excessively hot or dry conditions, which presents limitations for successful maize cultivation (Ichsan et al. 2021). Growing sorghum in regions with elevated temperatures may be a prudent choice due to its heat tolerance, potentially enabling a harvestable yield in situations where other crops could face complete yield loss (Akinseye et al. 2020).

Sorghum genotypes demonstrating accelerated seed filling rates and prolonged duration within the physiological maturity period, while experiencing heat stress, hold the potential to produce higher yield. Additional characteristics linked to heat stress tolerance in sorghum, such as early morning flowering and canopy temperature depression, have also been reported (Prasad et al. 2019). The presence of early morning flowering allows plants to avoid or escape high temperatures that typically arise later in the morning (Prasad et al. 2021). The ability of plants to alleviate high temperatures within their canopies is a trait that shows promise in preventing elevated temperatures in plant tissues (Prasad et al. 2021). In their study, Mutava et al. (2011) successfully identified various sorghum genotypes exhibiting cooler canopies (escaping heat) and higher canopy temperatures (tolerating heat), resulting in increased grain yield. Multiple crop characteristics contribute to this observed tolerance including pollen traits and the pollination process. Tack et al. (2017) asserts that the pollination process in sorghum plays a pivotal role in enhancing sorghum's heat stress tolerance.

Self-pollination in sorghum reduces the distance pollen grains travel, thereby limiting their exposure to elevated temperatures. Sorghum's abundant pollen production from panicles enhances the likelihood of pollen survival compared to other crops. According to Khalifa and Eltahir (2023), the early-morning dispersion of pollens aids sorghum in minimizing exposure to daytime heat. Various traits associated with this crop's capacity to endure high temperatures include variations in transpiration rate throughout the day, adjustment in seed filling rates and duration, and mechanisms that lower canopy temperature. Despite sorghum's commendable attributes for heat stress tolerance, it is important to acknowledge that excessively high temperatures can negatively impact crop development (Tack et al. 2017). The incidence of heat stress holds the potential to significantly reduce sorghum yield (Prasad et al. 2015). Consequently, the anticipated climate change induced heat stress might adversely affect sorghum productivity in regions where temperatures already exceed or approach the optimal range particularly in arid and subarid regions. On the contrary, there is evidence suggesting that climate change could push regions with sub-optimal temperatures towards the optimal temperature range, aiding in the growth and development of crops (Choi and Eltahir 2023).

4.3 Waterlogging

Waterlogging stands as a prominent abiotic stress factor, posing a significant threat to agricultural endeavors. Over recent decades, there has been a global upsurge in waterlogging incidents within agricultural areas (Kaur et al. 2020). This surge is chiefly attributed to the heightened frequency and unpredictability of rainfall events, themselves outcome of climate change (Hirabayashi et al. 2013). It has been observed that in the USA, crop production losses due to flooding have ranked second in frequency, following only drought, in recent years (Li et al. 2019). The anticipated escalation of these incidents is forecasted as a direct result of the global climate change phenomenon, imposing constraints on crop production across different regions worldwide (Ploschuk et al. 2020).

Sorghum, known for its robust tolerance towards adverse environmental conditions, is commonly cultivated in regions with low elevation and inadequate drainage (Huang 2018), making it susceptible to waterlogging-induced stress. Sorghum can withstand temporary waterlogging (Matsuura et al. 2016) better than other crops like maize (Von Haden et al. 2021). Nevertheless, there are notable differences in waterlogging susceptibility among different sorghum cultivars (Müller et al. 2020). For instance, sorghum cultivars with extensive root growth may not be well-suited for cultivation in regions prone to flooding (Promkhambut et al. 2011). Waterlogging affects sorghum roots extension (Matsuura et al. 2005), root functionality (Zhang et al. 2019), and impeding nutrients and water uptake due to decrease oxygen availability (Ahmed et al. 2013). The alteration in leaf water content can reduce photosynthesis capacity (Zhang et al. 2019), ultimately affecting overall crop productivity.

The impact of waterlogging on plants is influenced by various factors such as genotype, environmental circumstances, developmental stage, and the duration of the waterlogging. The waterlogging tolerance mechanism in sorghum encompasses several key aspects, notably an increased rate of seedling emergence (Von Haden et al. 2021). Additionally, sorghum exhibits a higher tolerance of seed germination to anoxia, the absence of oxygen, which contributes to its ability to withstand waterlogging (Alam et al. 2017). Furthermore, sorghum shows a greater tendency for tillering, producing additional shoots from the base of the plant as a response to waterlogging stress (Alam et al. 2017). Another adaptation of sorghum to waterlogging involves the development of adventitious and nodal roots (Matsuura et al. 2005). It has been observed that sorghum copes with waterlogging stress by adjusting leaf chlorophyll levels and modifying fluorescence parameters (Zhang et al. 2019). It has been proposed that the impact of waterlogging on sorghum yield depends primarily on the development stage during excessive moisture stress rather than solely on its duration. Nevertheless, the longer the waterlogging persists, the more severe the detrimental effects on sorghum become.

4.4 Salinity

The excessive salt content in sorghum farming is becoming a global concern across various regions (Dawood et al. 2022). According to Wang et al. (2014), the expression of the SbHKT1, 4 gene family, which encodes high-affinity potassium transporters, is significantly increased in salt-tolerant sorghum varieties when they are exposed to sodium ions (Na^+). This leads to an enhanced Na^+/K^+ ratio and promotes optimal plant growth. Dalal et al. (2012) assert that salinity restricts plant growth due to nutritional constraints, ion toxicity, and osmotic stress. Although sorghum is commonly considered to have moderate tolerance, it is more vulnerable to certain factors compared to maize. Notably, sweet sorghum exhibits a significant level of salt tolerance (Sui et al. 2015).

The process of seed germination plays a crucial role in determining the progression of plant populations in saline environments. Certain sweet sorghum genotypes, capable of enduring high salt levels, exhibit a notable ability to sustain a high germination rate even under salt stress (Molotoks et al. 2020). Additionally, Yang et al. (2020) have observed that plants employ various strategies to withstand and adapt to salt stress to ensure their survival. In summary, sweet sorghum efficiently expels sodium ions (Na^+) from its system, leading to a relatively low concentration of Na^+ in its aboveground components. Furthermore, the cultivation of salt-tolerant sweet sorghum has been found effective in maintaining a high sugar content in its aboveground components through mechanisms like defense against photosynthate aggregation, enhancing sucrose biosynthesis, and inhibiting degradation processes. It has been observed that the strategy employed by plants to tolerate salt during the germination and seedling stages varies, indicating the need for further exploration in this field (Hossain et al. 2022).

Salt is a significant environmental stressor, negatively impacting both crop productivity and quality. Soil salinity poses a significant concern in regions characterized by both irrigated and arid conditions. The introduction of irrigation worsens salt content in soil due to factors like poor water quality, inadequate drainage, and the influx of seawater in coastal areas. Arid and semi-arid regions face significant evaporation rates, leading to increased salt accumulation. This process, known as ion leaching, contributes to water scarcity around plant root zones (Shabani et al. 2015). While sorghum shows some level of salt tolerance, there are variations among different cultivars. Plants exhibit resistance to salinity through three distinct mechanisms, as outlined by Kamal and Ahmad (2022). These mechanisms include the exclusion of Na^+ from the cytoplasm, which can occur either due to limited absorption or through active ion pumping. Additionally, plants are capable of sequestering Na^+ within vacuole and may prefer accumulating Na^+ in leaf tissues. Nevertheless, only a limited range of genotypes can effectively store Na^+ within leaf cell vacuoles, influencing the nutritional value of plants (Kamal and Ahmad 2022).

According to Patanè et al. (2013), sorghum plants that were subjected to elevated salt concentrations exhibited reduced rates of germination and prolonged germination durations. Sui et al. (2015) observed a decline in the net photosynthetic rate, PSII photochemical efficiency, stomatal conductance, and intercellular CO_2 concentration in salt-sensitive sweet sorghum species. The presence of detrimental ions, namely sodium (Na^+) and chloride (Cl^-) hinders ion absorption, leading to a deceleration in this physiological mechanism. According to Hasegawa et al. (2000), salt-tolerant varieties effectively distinguish between K^+ and Na^+, displaying lower Na^+ to K^+ ratios in their tissues, rendering them more resilient to salt stress. In comparison to salt sensitive genotypes, the salt-tolerant sorghum genotypes showed reduced accumulation of Na^+ ions in both root and shoot tissues, resulting in a lower Na^+ to K^+ ratio (Bavei et al. 2011a). Additionally, the salt-tolerant genotype exhibited higher accumulation of Ca^{2+} in both leaf and root tissues compared to the sensitive genotypes, namely Kimia and Payam. This increased Ca^{2+} buildup facilitates enhanced growth and reduced absorption of sodium (Bavei et al. 2011b).

The genetic complexity of sorghum poses a significant challenge in improving its salt tolerance, despite its comparative advantage over wheat and maize in this regard (Kamal and Ahmad 2022). Salt stress affects the concentration of chlorophyll in plants and their photosynthetic efficiency through both direct and indirect mechanisms. Directly, it impacts enzyme activity and expression pertaining to chlorophyll synthesis and photosynthesis, causing immediate impacts. Indirectly, it operates through distinct regulatory pathways such as the activation of antioxidant enzyme systems. Salinity notably affects various photosynthesis-related parameters in sorghum. Specifically, under saline conditions, the maximum quantum yield of photosystem II (PSII; Fv/Fm), the photochemical quenching coefficient (qP), and the electron transport rate (ETR) significantly decreased while the non-photochemical quenching (qN) increased (Netondo et al. 2004). Kumar Swami et al. (2011) observed that the abundance of the ATP synthase, a-subunit protein in sorghum leaves, increased following a 96-h exposure to a concentration of 200 mM NaCl. This finding suggests that salt stress influences the photosynthetic machinery in sorghum leaves.

4.5 Heavy Metals

The accumulation of heavy metals (HMs) in agricultural soils stems from various factors including sewage sludge application, phosphatic fertilizers use, industrial wastes disposal, and inappropriate agricultural irrigation practices (El-Mahdy et al. 2021). The accumulation of HMs in plants has been observed to increase the production of ROS. These ROS molecules hinder various biochemical and physiological processes, leading to nucleic acids denaturation and enzymes inactivation. Ultimately, this oxidative stress induced by HMs accumulation can cause cell death (Abu-Shahba et al. 2022). Like other plant species, sorghum has the capacity to accumulate significant quantities of HMs, exhibiting characteristics of a hyperaccumulator (Kamal and Ahmad 2022). Due to its metal-tolerant nature and substantial biomass production, this crop holds potential for use in phytoremediation (Mishra et al. 2021). Nevertheless, elevated HMs concentration has been reported to decrease various plant traits, including plant height, density of root hairs, biomass of shoots, number of leaves, levels of chlorophyll, carotenoids, and carbohydrate content. The morpho-physiological parameters of sorghum were negatively affected by the simultaneous exposure to arsenic, nickel, cadmium, lead, and copper. This led to reduced total plant biomass, leaf water potential, alteration of chloroplast structure, and peroxidation in chloroplast membranes, which can be attributed to the generation of ROS (Gill et al. 2012; Pandian et al. 2020).

Sorghum exhibits a tightly regulated coordination of antioxidant enzymes in response to exposure to HMs toxicity. Moreover, it has been suggested that increased levels of superoxide dismutase (SOD) and catalase (CAT) could potentially be associated with the generation of additional ROS or the overexpression of genes encoding SOD, alongside an augmented presence of hydrogen peroxide (H2O2) (Kamal and Ahmad 2022). The stability of reduced glutathione (GSH) levels is maintained through the augmentation of GSH and glutathione reductase (GR) activity. In plants treated with HMs, enhanced GR activity leads to increased availability of NADP+. NADP+ acts as an electron acceptor from the electron transport chain, facilitating proper functioning of biochemical reactions at the cellular level (Jawad Hassan et al. 2020). It is worth noting that Soudek et al. (2014) observed tissue-specific alterations in antioxidant levels. Specifically, they found increased activity of peroxidase (POX) and glutathione S-transferase (GST) in the shoots of sorghum plants under zinc and cadmium stress, while no such increase was observed in the roots.

The accumulation of suitable soluble solutes such as proline and proteins, alongside an increased in the malondialdehyde (MDA) content, can facilitate osmoregulation as a part of the adaptive response, enabling plants to withstand stress (Ahmad et al. 2020; Parida and Das 2005). Emamverdian et al. (2015) revealed that even under heightened stress, sorghum showed an increase in the protein content, indicating its ability to tolerate a specific threshold of heavy metal stress. Changes observed in protein composition under abiotic stress conditions could potentially serve as valuable biomarkers to understand the fundamental mechanisms underlying plant stress responses. A total of 33 differentially expressed protein spots were analyzed using MALDITOF/TOF MS in cadmium exposed sorghum plant to understand the underlying mechanism of integrated molecular and proteomic studies coupled with two-dimensional gel electrophoresis (Roy et al. 2016).

The application of proteomic analysis unveiled alterations in metabolic pathways and proteins associated with translational and transcriptional regulation in response to Cd exposure (Kamal and Ahmad 2022). The findings indicate that Cd stress generally hampers the process of carbon fixation, reduces ATP production, and modulates protein synthesis (Roy et al. 2016). Moreover, it is of great interest to explore the involvement of GST enzymes in the cellular response of C4 plants to cadmium toxicity (Roy et al. 2016). Previous research on sorghum has predominantly concentrated on its chemical composition, nutritional and medicinal properties, as well as its response to salinity and drought stress (Istrati et al. 2019; Nxele et al. 2017). Additionally, studies have delved in to the impact of metal distribution and accumulation on the photosynthetic efficiency of sorghum (Pandian et al. 2020; Xue et al. 2018). There is still little knowledge about the sorghum's mechanism for tolerating heavy metals (Kamal and Ahmad 2022). However, the sorghum's complete genome sequence being accessible renders it a feasible model plant for C4 photosynthesis. It can be utilized alongside C3 plant models like Arabidopsis and rice to explore gene products involved in adapting to HMs stress (Kamal and Ahmad 2022).

4.6 Higher Carbon Dioxide

Several studies have reported a significant decrease in the transpiration rate of the sorghum crop when exposed to elevated levels of carbon dioxide (Tovignan et al. 2023; Wall et al. 2001). This reduction in transpiration rate is particularly observed under irrigated conditions similar to those experienced by C3 cereals (Fan et al. 2023). According to Chaudhuri et al. (1986), an increase in stomatal resistance leads to reduced water consumption and improved absorption of nutrients and water from deeper soil layers. This is attributed to the increased root mass observed during each growth phase, facilitating optimal growth and development in sorghum, notably advantageous during drought. Increased CO_2 levels had a diminishing effect on water consumption under drought conditions, extending soil water availability during dehydration periods. Ottman et al. (2001) noted that elevated levels of CO_2 positively impacted growth during the grain-filling phase in the presence of drought conditions. However, it was observed that elevated CO_2 negatively affected vegetative growth. Sorghum yields increased in drought conditions due to elevated CO_2 levels, resulting in continuous carbon gain (Ottman et al. 2001).

In a study conducted by Torbert et al. (2004), they observed an approximate 30% increase in sorghum biomass production due to elevated levels of CO_2. This enrichment of CO_2 resulted in a significant increase in the carbon-to-nitrogen ratio. A limited number of studies have assessed grain quality in sorghum under elevated CO_2 conditions (Chadalavada et al. 2021). Souza et al. (2015) documented an approximate 60% rise in grain protein content of sorghum when cultivated under elevated CO_2 and water deficit conditions. Fatty acid levels in the grain showed a slight elevation while no corresponding increase in starch content was reported. Therefore, the increased levels of CO_2 were observed to have a positive impact on sorghum by aiding in alleviating drought conditions and improving the quality of the produced grain.

5 Role of Biostimulants in Alleviating Abiotic Stresses in Sorghum

Biostimulants encompass a range of substances, including both organic and inorganic compounds, as well as microorganisms. When supplied to plants, these substances elicit various physiological responses that result in enhanced growth, productivity, and stress tolerance (Ali et al. 2021; Franzoni et al. 2021). They are offered in various forms such as soluble powder, granules, or liquid, and can be delivered through foliar sprays or soil application in proximity to the root zone (Ma et al. 2022). Biostimulants exhibit minimal or negligible toxicity and do not accumulate long-term (Sangiorgio et al. 2020). There are various categories of biostimulants which can be categorized into six primary groups based on the origin of their raw materials. These groups include seaweed, protein hydrolysates, plant extracts, inorganic compounds, humic substances, and microorganisms (Franzoni et al. 2021). Over the past decade, there has been a notable increase in the prominence of biostimulants, which have emerged as a significant strategy for augmenting crop productivity and improving resilience to abiotic stresses (Nephali et al. 2020).

While research has suggested that biostimulants have priming effects (Shukla et al. 2019), there remains a lack of understanding regarding the specific mechanisms by which microbial and non-microbial biostimulants exert their effects on plants (Ma et al. 2022). Biostimulants are capable of initiating and controlling various defense mechanisms through diverse modes of action (Rai et al. 2021). Upon reaching the leaves and/or roots, biostimulants undergo translocation and subsequent distribution to various plant tissues (Rai et al. 2021). The mechanisms of action within the plant vary depending on the specific type of biostimulants, considering their nature and characteristics. The use of biostimulants, specifically those involving microbial activity, presents a promising strategy for mitigating the negative effects of drought stress in arid and semiarid regions worldwide, ultimately leading to enhanced crop productivity (Singh et al. 2021). The mitigation of drought stress has been demonstrated by several researchers through the examination of the role of bacteria (Saikia et al. 2018; Yadav and Yadav 2018).

The comparative effectiveness of biostimulant microbes, as opposed to growth-controlling substances like salicylic acid and gibberellic acid in plant leaves, indicates their potential for agricultural use in sustaining crop productivity under abiotic environmental stress conditions (Sivakumar et al. 2017). Singh et al. (2021) suggested that while biostimulants have several potential, their impact may vary based on the specific host and the microbes employed. Additionally, factors such as adaptability, multiplication, and prevailing environmental conditions in natural field settings can influence their effectiveness due to the diverse chemical composition involved. Consequently, further research is needed to explore the implications of biostimulants use in agroecosystems. Singh et al. (2021) recommended utilizing biostimulants in agriculture due to their significant potential in mitigating heat stress, alongside conventional breeding, biotechnology, and the application of chemicals. The utilization of biostimulants can effectively mitigate the adverse effects of elevated temperature stress and promote environmental sustainability by reducing the use of harmful agrochemicals.

In addition to other biostimulants, the presence of salt-tolerant microbes can substantially contribute to mitigating salinity-induced stress in plants, leading to enhanced agricultural productivity. Microorganisms generally exhibit adaptability to cope with environmental stressors by undergoing alterations in crucial physiological and biochemical mechanisms. The interaction of various microorganisms with plants to enhance stress tolerance is widely recognized as a catalyst for activating host defense mechanisms (Gourion et al. 2008). In their study, Desoky et al. (2018) examined the impact of humus substances (HM) and *Moringa oleifera* leaf extract (MLE) as biostimulants on plant growth in normal and salt stress environments. They found that applying HM improved saline soil properties. Under saline conditions, both HM and MLE enhanced growth characteristics, RNA and DNA contents, photochemical activity, osmoprotectant concentrations, phytohormone levels, non-enzymatic antioxidants, and antioxidant enzyme activities in sorghum plants compared to untreated control plants. Application of moringa leaf extract to sorghum seedlings cultivated in salty soil promoted growth features, increased levels of plant hormones, chlorophyll, essential nutrients, protective compounds, and substances countering oxidative stress (Desoky et al. 2018). Rakgotho et al. (2022) examined the efficacy of zinc oxide nanoparticles (ZnO NPs) derived from Agathosma betulina in alleviating salt-induced stress in *Sorghum bicolor*. Using ZnO NPs as a priming agent enhanced sorghum plant growth, increasing shoot lengths, fresh weights, and improving anatomical structure. Additionally, the application of ZnO NPs decreased the Na^+/K^+ ratio, indicating better element distribution within plants. These findings offer compelling evidence supporting the utilization of green-synthesized ZnO nanoparticles from *A. betulina* as promising biostimulants to enhance plant growth in the presence of abiotic stressors.

Sorghum is recognized for its ability to accumulate significant levels of Cd. However, it is important to note that although sorghum species can tolerate and accumulate high levels of Cd, their overall development and growth can still be significantly impaired (Sharmila et al. 2017). To improve sorghum's resistance to Cd and mitigate its toxic effects, several strategies have been explored. One such approach involves the application of biostimulants, which has shown promise as a sustainable method to enhance crop productivity (Roussi et al. 2022a). Studies have demonstrated that plant-based bio-stimulants have the potential to enhance crop tolerance against various biotic and abiotic stresses, producing valuable outcomes (Yakhin et al. 2017). According to Roussi et al. (2022b), sorghum plants subjected to a concentration of 200 μM of Cd showed reduced growth, biomass, and chlorophyll levels compared to non-stressed plants. Nonetheless, supplementing the plants with Cistus monspeliensis extract (CME) at concentrations of 5 mg/l, 20 mg/l, and 60 mg/l effectively countered the adverse impact of Cd stress, leading to increased biomass and pigment content. The application of CME decreased the accumulation of superoxide ions (O_2^-) and increased the activities of antioxidant enzymes: glutathione peroxidase (GPx), superoxide dismutase (SOD), glutathione-S-transferase (GST), and glutathione reductase (GR). These findings suggest that CME might enhance the ability of plants to tolerate Cd-induced stress by increasing the expression of antioxidant defense enzymes, reducing the production of ROS, and enhancing carbon metabolism and nitrogen assimilation, ultimately, promoting improved growth rate. The stress alleviation effect of CME was notably more pronounced at concentrations of 5 mg/L and 20 mg/L.

Roussi et al. (2022a) demonstrated that the addition of Cistus salviifolius leaves extract (CSE) effectively mitigated the adverse impact of Cd, resulting in enhanced biomass and pigment levels. The application of CSE resulted in elevated levels of antioxidant enzymes, including isocitrate dehydrogenase (ICDH), superoxide dismutase (SOD), glutathione reductase (GR), glutathione peroxidase (GPx), and glutathione-S-transferase (GST). In addition, CSE led to a reduction in lipid peroxidation and a subsequent increase in soluble sugar and amino acid levels. Overall, the findings substantiate that the application of CSE exhibits potential as a viable approach to mitigate the detrimental impacts of Cd-induced stress in sorghum plants. According to Ennoury et al. (2023), the water extract of *Atriplex halimus* improved sorghum's tolerance to Cd by positively influencing germination index parameters, including seedling vigor index, germination percentage, and mean germination time under Cd stress. Morphological parameters such as height and weight, alongside physiological parameters like chlorophyll and carotenoid levels, showed enhanced responses in matured sorghum plants subjected to Cd-induced stress. Furthermore, *Atriplex halimus* extract (AHE) activated various antioxidant enzymes, such as superoxide dismutase, glutathione peroxidase, catalase, glutathione-s-transferase, and glutathione reductase. These findings suggest that using AHE as a biostimulant could be a more effective approach to enhance sorghum plants tolerance against Cd-induced stress.

6 Sweet Sorghum Cultivation on Marginal Lands for Biofuel Production to Mitigate Climate Change

Marginal lands are typically perceived as unproductive and unsuitable for agriculture due to factors like poor soil quality, substandard groundwater quality, unfavorable topography, drought, and adverse climatic conditions. Consequently, conventional food crops often show limited or no profits potential (Mehmood et al. 2017). However, the degree of marginality remains challenging to assess as it heavily depends on context and purpose. Marginal lands include contaminated areas, brownfields, barren agriculture land due to inappropriate conditions for crop production (Smith et al. 2013), degraded farmlands (Tilman et al. 2006), and waste disposal sites. To address the competition between food and fuels, there is growing interest in utilizing marginal lands for bioenergy feedstocks production (Mehmood et al. 2017). Given the current global scenario, it is imperative to tackle several significant challenges, including balancing between food and energy production, conserving biodiversity, safeguarding the environment, and maintaining ecosystem functions (Mehmood et al. 2017).

The cultivation of fuel crops on marginal lands presents a potentially viable option for mitigating concerns related to food scarcity and environmental degradation (Qin et al. 2011). However, the success of this approach hinges upon the availability of suitable bioenergy crops and their careful selection (Lord 2015). Similarly, it has been established that the utilization of marginal lands for the cultivation of energy crops can also contribute to the enhancement of biodiversity (Werling et al. 2014). According to Li et al. (2010), a variety of plants species have exhibited the potential to be utilized for bioenergy, contingent upon their suitability to the specific climatic and geographical conditions. Sweet sorghum is a sugar crop widely cultivated and has the potential to generate bioenergy. Plants accumulate a substantial quantity of fermented sugars within their stems, thereby enhancing the quality of biomass production. This plant exhibits a lower fertilizer requirement, making it suitable for cultivation on marginal lands. The production of sweet sorghum has the potential to yield cost savings compared to maize, while also offering superior energy benefits. According to Regassa and Wortmann (2014), sweet sorghum has the potential to produce a greater amount of ethanol per unit of land area when compared to maize and other commonly used energy crops. The increasing attention towards the utilization of biomass for energy production coupled with its potential to thrive in challenging environmental conditions such as drought, salinity, alkalinity, and water logging, positions this crop as a favorable contender in the quest for effective bioenergy crops (Rao et al. 2009). Additionally, it is worth noting that this crop exhibits a reduced growth period and necessitates lower water consumption compared to other crops such as maize, sugarcane, sugarbeet, and wheat (Ahmad Dar et al. 2018).

Sweet sorghum helps mitigate the food versus fuel dilemma by meeting diverse demands for food, fodder, and fuel. The plant's highly efficient photosynthetic system, known as the C4 pathway, contributes to its potential as a viable bioenergy crop. Sweet sorghum also efficiently utilizes nutrients, further enhancing its prospects in bioenergy production. This crop is commonly referred to as one that encompasses four essential components: food, fuel, fodder, and fiber (Umakanth et al. 2019). Furthermore, it has earned the nickname "the camel among crops" owing to its exceptional ability to withstand drought conditions. Its resilience against abiotic stresses such as waterlogging, salinity (Zegada-Lizarazu and Monti 2012), drought (Tesso et al. 2005), as well as its enhanced adaptation, and improved nitrogen, water, and radiation use efficiency make it a preferable biofuel feedstock compared to sugar beetroot, maize, and sugarcane (Umakanth et al. 2019). Given the anticipated limitation of water availability as a potential constraint on agricultural productivity in the future, sweet sorghum emerges as a promising alternative due to its minimal water requirements.

The utilization of sweet sorghum bioethanol has the potential to contribute to preserving depleting fossil fuel reserves and mitigating greenhouse gas emissions. According to Umakanth et al. (2019), the cultivation of sorghum for the purpose of ethanol and green electricity production could conserve approximately 3500 L of crude oil equivalents per hectare of land. Sweet sorghum juice, comprising fructose, glucose, and sucrose is suitable for direct ethanol fermentation (Sipos et al. 2009). Ou et al. (2015) suggested that this juice can also be utilized to produce other biobased compounds. In addition, the foliage, grains, and bagasse of the crop can be employed to produce biofuels and serve as a source of animal feed. Bagasse holds potential as a power source and can additionally be employed in the creation of valuable byproducts such as pulp and particle board (Somani and Taylor 2003). Besides ethanol, other fermentation byproducts that can be obtained include butanol, acetone, butyric acid, lactic acid, hydrogen, and methane (Umakanth et al. 2019). Research efforts dedicated to the genetic and molecular characterization of sorghum traits have been comparatively less extensive than those directed towards maize and sugarcane (Yadav et al. 2019). Two major challenges that hinder the utilization of sweet sorghum as a bioenergy source are the harvesting season and the need to transport and store substantial amounts of the crop. Similarly, the combination of low seed yield and the tendency for plants to grow tall contributes to the high cost of seed production.

7 Food Security and Hidden Hunger

The current climate change poses a significant threat to food security. According to the report of FAO, IFAD, UNICEF, WFP, and WHO (2021), it is projected that the global community will be unable to eradicate malnutrition and world hunger by 2030. Furthermore, the report highlights the concerning fact that current efforts are insufficient to effectively address the issue of global hunger. Similarly, the global economic downturns resulting from the COVID-19 pandemic has significantly contributed to the escalation of world hunger, exerting a severe impact on impoverished countries (FAO, IFAD, UNICEF, WFP, and WHO 2021). The COVID-19 pandemic has had a significant impact on the advancements made in the global fight against poverty and has also resulted in the regression of decades of progress towards the goal of eradicating hunger (Tanyanyiwa 2021). There has been a gradual increase in global food insecurity since 2014. However, the projected increase in food insecurity in 2020 was nearly equivalent to the cumulative increase observed over the preceding 5 years (FAO, IFAD, UNICEF, WFP, and WHO 2021). Approximately 2.37 billion individuals, accounting for one-third of the global population, experienced inadequate access to nourishing food in the year

2020 (FAO, IFAD, UNICEF, WFP, and WHO 2021). This figure represents an increase of approximately 320 million people compared to the previous year.

The anticipated milestone of achieving zero hunger by the year 2030 has been overshadowed by a concerning reversal in the trajectory. Recent projections indicate that the global population suffering from hunger could surge to approximately 840 million individuals by 2030 (Tanyanyiwa 2021). According to FAO, IFAD, UNICEF, WFP, and WHO (2019), the global population of individuals experiencing undernourishment in 2018 exceeded 820 million. Furthermore, the number of individuals facing severe food insecurity surpassed 700 million, while approximately 1.3 billion people were exposed to a moderate level of food insecurity. The global population suffering from hunger exceeds one billion individuals (Burchi et al. 2011). These individuals suffering from hunger are unable to fulfill their basic energy requirements (Ul-Allah 2018), necessary for maintaining a healthy body and overall well-being. The global prevalence of hunger in 2022 is estimated to have impacted a population ranging from 691 million to 783 million individuals. Based on the anticipated midrange estimate of approximately 735 million individuals in 2022, it is observed that an additional 122 million individuals experienced food insecurity compared to the pre-pandemic year of 2019 (Table 2) (FAO, IFAD, UNICEF, WFP, and WHO 2023).

Hidden hunger arises from an inadequate intake of essential minerals and vitamins through dietary means. Insufficient consumption of vital vitamins and minerals significantly impacts the ability to resist diseases, cognitive development, physical growth, work productivity, and survival rates. Preschool-aged children and women of reproductive age are particularly susceptible to deficiencies due to their increased dietary requirements for micronutrients (UNICEF 2019). The agricultural systems in developing countries currently cannot provide an adequate supply of minerals and vitamins at affordable rates, thereby compromising the potential for optimal nutrition and overall health (Van Der Straeten et al. 2020). There is often a lack of accessibility to supplements among populations that require them (Mostafa et al. 2019). Furthermore, according to the findings

Table 2 Prevalence of severe food insecurity and number of people experiencing severe food insecurity (FAO, IFAD, UNICEF, WFP, and WHO 2023)

Regions	Prevalence of severe food insecurity (%)				Number of severely food-insecure people (millions)			
	Years				Years			
	2019	2020	2021	2022	2019	2020	2021	2022
Africa								
Northern Africa	8.7	9.5	11.2	12.0	21.5	23.8	28.7	31.1
Sub-Saharan Africa	22.8	25.4	26.6	26.6	246.6	281.2	302.4	310.6
Eastern Africa	25.0	28.1	28.7	27.7	109.3	126.2	132.1	130.9
Middle Africa	n.a	36.0	37.8	39.1	n.a.	66.5	71.9	76.7
Southern Africa	9.3	11.0	11.0	12.5	6.2	7.4	7.5	8.6
Western Africa	16.6	19.9	21.7	22.0	66.1	81.1	90.8	94.4
Asia								
Eastern Asia	1.3	2.0	1.0	1.0	21.4	33.4	17.0	16.0
Southern Asia	16.3	18.8	21.0	19.4	316.9	371.3	417.9	389.2
Central Asia	2.3	4.8	5.0	4.6	1.7	3.6	3.8	3.5
South-eastern Asia	1.8	2.1	2.6	2.6	12.2	13.9	17.7	17.8
Western Asia	8.9	9.6	10.2	10.3	25.1	27.4	29.7	30.3
Latin America and the Caribbean								
Caribbean	n.a	32.4	25.7	28.2	n.a	14.2	11.4	12.5
Latin America	8.2	11.1	13.0	11.5	49.3	67.5	79.7	70.8
Central America	7.3	7.3	8.0	8.6	12.8	12.9	14.3	15.4
South America	8.5	12.7	15.1	12.7	36.5	54.7	65.5	55.4
Europe								
Eastern Europe	0.8	1.4	1.7	2.0	2.4	4.0	4.9	5.7
Western Europe	0.7	0.8	1.7	1.8	1.4	1.6	3.2	3.6
Northern Europe	1.0	1.2	1.8	2.0	1.0	1.3	1.9	2.1
Southern Europe	1.6	2.4	2.8	1.6	2.4	3.6	4.3	2.4
Northern America	0.8	0.7	0.7	0.7	3.0	2.7	2.7	2.8

n.a, not applicable

of the Global Burden of Disease Study 2015, it has been estimated that approximately 1.5 billion individuals are affected by Fe-deficiency anemia, a condition that adversely affects the cognitive abilities of preschool-aged children (Vos et al. 2016). Approximately 1.2 billion individuals are susceptible to zinc deficiency, a condition that is linked to compromised immune systems and increased mortality rates (Black et al. 2013). Stunting, a condition highly likely caused by a deficiency in Zn has a prevalence rate of 25% among children below the age of five. There is a significant correlation between stunting and suboptimal brain development as well as impaired cognitive function (Alderman and Fernald 2017). The issue of micronutrient malnutrition presents a significant challenge to both the global well-being of individuals and the overall progress of economic development. Therefore, the eradication or at the very least limitation of its prevalence holds significant importance, aligning with the United Nations Sustainable Development Goal 2 (UNSDG2) of attaining zero hunger.

The prevalence of individuals experiencing malnutrition has increased since the year 2015 (Das et al. 2023). One of the 17 Sustainable Development Goals established by the United Nations is to eradicate hunger by the year 2030. The term "hidden hunger" pertains to the condition where individuals experience deficiencies in specific micronutrients while lacking a varied diet that provides sufficient energy and nutrients. The current imperative is to develop a sustainable and economically viable approach to address the issue of hidden hunger, ensuring its reach extends to the most remote and marginalized areas. The implementation of a comprehensive system approach that encompasses all components of the food value chain is imperative to facilitate the attainment of food security that is both safe and sustainable while also being resilient to external market shocks. Although hidden hunger is most prevalent in developing countries, it is important to recognize that dietary deficiencies can impact individuals of any age and ethnic background worldwide (Lowe 2021).

8 Sorghum in the Context of Food Insecurity and Hunger

Asia is home to over half of the global population suffering from undernourishment, totaling 418 million individuals affected. In Africa, more than one-third of the undernourished population amounting to 282 million people can be found (FAO, IFAD, UNICEF, WFP, and WHO 2021). A significant proportion of children under the age of five globally do not receive adequate nutrition to support optimal growth. Additionally, about half of all children experience hidden hunger, characterized by deficiencies in essential micronutrients (UNICEF 2019). There has been a significant increase in the number of individuals experiencing food insecurity across various regions. Specifically, Asia has witnessed an additional 57 million people affected by hunger compared to the previous year, while Africa has seen an increase of 46 million individuals facing the same predicament. Additionally, the Caribbean and Latin America have observed a rise of 14 million more people experiencing hunger in comparison to 2019 (FAO, IFAD, UNICEF, WFP, and WHO 2021). The ongoing efforts to improve global food security persist, necessitating the prompt discovery of novel technologies and food resources to effectively address food insecurity within the context of changing climate.

Orphan crops possess the potential to address food insecurity due to their high nutritional content and resilience to adverse climatic conditions (Faucher and Revoredo-Giha 2019). Among these orphan crops, sorghum, stands out as particularly noteworthy. Orphan crops are designated as such because of their historical neglect and lack of substantial attention from the scientific community in terms of research and development (Goron and Raizada 2015). Acknowledged for their remarkable nutritional, environmental, and economic characteristics, orphan crops are considered a crucial element in tackling food insecurity (Faucher and Revoredo-Giha 2019). While it is accurate to state that not all orphan crops can be classified as perfect crops or superfoods, they have gained recognition for their ability to thrive in challenging environments and adapt to the impacts of climate change (Faucher and Revoredo-Giha 2019). Therefore, their capacity to withstand adverse conditions significantly contributes to addressing food insecurity in regions facing environmental difficulties (Assefa 2014; Revoredo-Giha et al. 2022).

Sorghum possesses nutritional characteristics that make it significant in addressing global food security concerns (Saleh et al. 2013). According to Dube (2008), the utilization of small grains in meals provide adequate nutritional content, promoting prolonged satiety and increased energy levels in the human body. Sorghum has the potential to substantially contribute to enhancing food security in numerous impoverished and vulnerable countries concerning sustenance and nutritional needs globally. Its ability to thrive in arid conditions makes sorghum a potential enhancer of household food security in semi-arid regions (Taylor 2003). Enhancing small grain productivity is imperative in addressing the challenges posed by climate change, playing a crucial role in ensuring both nutritional well-being and food security (Ndlovu et al. 2019).

The use of small grains such as sorghum, as a strategy to bolster food security in arid regions, has gained considerable attention recently. However, it is worth noting that a significant proportion of farmers have expressed opposition towards the adoption of small grains to address food security concerns (Sakadzo and Kugedera 2020). Tackling the issue of food insecurity in the world's most impoverished regions can be accomplished through the cultivation of sorghum and millet (Masara 2015). These crops have been found to significantly reduce the likelihood of complete crop failure, resulting in a minimal probability of zero yield. As a result, cultivating small grains like sorghum and millet contributes to enhancing food security (Alumira and Rusike 2005). Sorghum's utilization as a primary cereal crop in arid and semi-arid regions holds promise for addressing food insecurity in these areas (Sakadzo and Kugedera 2020).

Rural populations and impoverished communities are the primary demographic affected by global-scale food insecurity and malnutrition (Awobusuyi et al. 2020). Food security is a multifaceted issue that encompasses the global economy. Contemporary agricultural practices prioritize crops that require substantial inputs, leading to a reduction in agricultural crop diversity worldwide (Chivenge et al. 2015). On a global scale, there has been a notable decrease in the cultivation of conventional crops, and this trend is expected to persist. Nevertheless, it is important to note that these crops display a broad range of genetic diversity and have the potential to enhance both nutritional quality and food security (Chivenge et al. 2015). Therefore, prioritizing these crops is imperative in addressing global food and nutritional insecurity, considering the limited availability of resources.

9 Health Benefits and Nutritional Profile of Sorghum

In addition to its several agronomic benefits, sorghum serves as a valuable source of nutrients (Table 3). Its grain is gluten-free and contains high levels of resistant starch. Sorghum is recognized for its diverse array of phenolic compounds and flavonoids, with simple phenolic acids and tannins being the most prevalent (Dykes and Rooney 2007). The presence of these nutrients in sorghum has been found to positively impact human health, proving beneficial for individuals with conditions such as obesity, celiac disease, and diabetes (Pontieri et al. 2013). According to Lemlioglu-Austin (2014), individuals with celiac disease can benefit from consuming sorghum-based food products like biscuits, pasta, bread, porridge, and pastry. Yang et al. (2015) reported that sorghum contains various bioactive compounds, including phenolic compounds, which possess notable properties contributing to the prevention of cardiovascular diseases, cancer, as well as the reduction of oxidative stress and chronic inflammation. Compared to other similar products, sorghum typically undergoes a longer duration of protein and starch digestion. This delayed digestion process results in a lower glycemic index (GI), which is beneficial for individuals with diabetes (Zhang and Hamaker 2009).

Table 3 Nutritional value of sorghum (National Institute of Nutrition 2007)

Nutrients	Amount per (100 g)
Carbohydrates (g)	72.6
Protein (g)	10.4
Fat (g)	1.9
Energy (kcal)	349
Crude fiber (g)	1.6
Mineral matter (g)	1.6
Ca (mg)	25
P (mg)	222
Fe (mg)	4.1
Vitamins profile of sorghum (mg/100 g)	
Thiamin (mg)	0.38
Niacin (mg)	4.3
Riboflavin	0.15
Carotene (vitamin A) (mg/100 g)	47
Vitamin B6 (mg/100 g)	0.21
Folic acid (mg/100 g)	20
Pantothenic acid (vitamin B5) (mg/100 g)	1.25
Vitamin E (mg/100 g)	12
Micronutrients profile of sorghum (mg/100 g)	
Mg	171
Na	7.3
K	131
Cu	0.46
Mn	0.78
Mb	0.039
Zn	1.6
Cr	0.008
Si	54
Cl	44

Sorghum extracts have revealed a greater presence of anticancer properties compared to other cereals making it a cost-effective and efficient dietary supplement for cancer management (Xie et al. 2019). It exhibits a high concentration of phosphorus and potassium along with a notable quantity of calcium. Additionally, it contains a minor proportion of sodium and iron (Table 3). Hungwe et al. (2020) reported that sorghum exhibits a substantial content of carbohydrates, dietary fibers, and proteins. Moreover, it was observed that the digestibility of these components in sorghum is comparatively lower when compared to other cereal grains. This characteristic of sorghum presents potential benefits for individuals with diabetes. Sorghum grain possesses elevated levels of fiber, protein, minerals, and calcium, rendering it a more advantageous choice compared to rice and wheat (Dayakar Rao 2019). Table 4 presents a nutritional comparison between maize and sorghum. Food products derived from

Table 4 Comparison of sorghum and maize typical nutrients composition (Rosa et al. 2017; Faqih et al. 2020)

Nutrients	Sorghum	Maize
Crude protein (%)	7.48	7.71
Crude fiber (%)	1.80	1.40
Calcium (%)	0.14	0.01
Available phosphorus (%)	0.23	0.26
Mineral matter (%)	1.45	1.21
Protein (g/100 g)	11	8.7
Carbohydrates (g/100 g)	73	72.4
Fat (g/100 g)	3.3	4.5
Calcium (mg/100 g)	28	9
Vitamin B1 (mg/100 g)	0.38	0.27
Gross energy (kcal/kg)	3895	3855

sorghum exhibit a low GI and possess superior nutritional qualities compared to products derived from wheat and rice (Prasad et al. 2015). It is high in both zinc (>50 ppm) and iron (>4070 ppm) and thus helps in reducing stunting (Hungwe et al. 2020). As a substitute for wheat, sorghum is used to produce gluten-free products like biscuits, pastas, breads, and porridges (Chávez et al. 2018).

The absence of gluten in sorghum makes it a viable substitute grain for human consumption, reducing the risk of developing celiac disease (Xu et al. 2021). Sorghum grains are known to contain phenolic compounds, such as flavonoids, phenolic acids, and anthocyanins (Kumari et al. 2021). These bioactive constituents have been associated with potential health benefits, such as mitigating chronic ailments like cancer, diabetes, obesity, and cardiovascular diseases (Chen et al. 2021). According to Taylor and Awika (2017), this ancient grain crop possesses the unique capability to mitigate hyperglycemia, a condition characterized by high blood sugar levels. It exhibits notable concentrations of phytochemicals that have positive effects on human health including phytosterols, phenolic compounds, and policosanols (Girard and Awika 2018). The presence of bioactive compounds in sorghum has been found to contribute to its potential role in preventing chronic diseases when regularly consumed in the diet (Teferra and Awika 2019). The functional ingredients found in sorghum, namely polyphenols, are of considerable importance and can be utilized as natural food additives effectively (Girard and Awika 2018). Regrettably, global consumption of sorghum remains relatively low in comparison to staple crops like wheat, maize, and rice, relegating sorghum to the status of a crop primarily cultivated in marginal regions.

The prolamins present in sorghum are commonly referred to as kafirins, and they have been found to be non-toxic for individuals with celiac disease (Chávez et al. 2017). Incorporating sorghum into the diets of countries grappling with diabetes and obesity presents an economically viable alternative (Mkandawire et al. 2015). The primary phenolic compounds found in sorghum include ferulic acid, vanillic acid, p-coumaric acid (Chávez et al. 2017), 4-coumaric acid, proanthocyanidins, 3-deoxyanthocyanins, caffeic acid, and coumaroylglycerol (Nguyen et al. 2015). According to Vázquez-Araújo et al. (2012), sorghum exhibits favorable levels of vitamins, particularly those belonging to the B complex and vitamin E, as well as minerals. Additionally, sorghum demonstrates antimutagenic and anticarcinogenic characteristics (Anunciação et al. 2017). The nutritional properties of sorghum have garnered significant attention, leading to increased emphasis on its production and consumption as a staple food for humans in various forms (Zhu 2014).

10 Sorghum Adaptability by the Community

The widespread adoption of traditional foods in society is not common and is often stigmatized (Simbarashe et al. 2010). Additionally, small grains are frequently associated with poverty and are primarily consumed by impoverished communities. Sorghum boasts higher levels of carbohydrates and protein compared to maize, suggesting its potential as a staple crop akin to maize. However, the main hindrance to adopting sorghum as a staple crop lies in individual tastes and preferences (Hungwe et al. 2020). It is plausible that the slow acceptance of sorghum among farmers may be due to the challenges associated with preparing and processing food products derived from this crop (Hungwe et al. 2020). Therefore, by effectively addressing these factors, it becomes evident that sorghum has the potential to significantly contribute to addressing food insecurity and hidden hunger. The current period necessitates the active engagement of stakeholders to fulfill their responsibilities, as the level of acceptance and integration of sorghum within the community lies on awareness campaigns conducted by these stakeholders.

11 Future Outlooks

The remarkable agronomic characteristics and health benefits of sorghum have captivated the attention of researchers, as well as drug and food industries, over recent decades (Xiong et al. 2019). The escalating demand for healthy, nutritious, and naturally derived food underscores sorghum's immense potential for use in preparing healthy foods and food products (Xiong et al. 2019). However, a notable obstacle in popularizing sorghum-based products lies in their commercialization among non-traditional consumers in the west. The adverse effects of climate change, notably drought and high temperature compounded by wrong man-made policies, necessitate a diversified approach to food productions, integrating traditional crops to address food insecurity and hunger. The key stakeholders (such as researchers, marketers, food manufacturers, and government agencies) must play a significant role in heightening public awareness regarding the benefits of sorghum (Stefoska-Needham and Tapsell 2020). Small grains, due to their resilience in challenging environments, are vital additions to the basket of food security to fulfill the food-need of a huge number of food-insecure people (Tanyanyiwa 2021). By prioritizing traditional crops, several poor countries can potentially achieve food security, and it can be assured that food being a basic human right is in access to all. The ongoing research efforts in the field of sorghum indicates that in the future, this crop will attain equal importance like other major cereals from academia and other stakeholders. According to the Washington Post "Sorghum, a whole grain that has been a staple food in Africa and India for centuries is finally getting its moment on the American table. It is well suited for our modern world because it is highly nutritious with a mildly nutty flavor, it's gluten-free and it's easy to grow even in drought conditions." (https://nulifemarket.com/sustainability/).

12 Conclusion

The escalating impacts of global climate change, including water scarcity, recurring droughts, and rising temperatures, due to heightened greenhouse gas emissions, underscore the necessity for crops resilient to these challenges. Sorghum stands as a potential and cost-effective crop amidst these adversities. With the burgeoning global population and diminishing resources, agricultural sectors face increasing pressure to bolster food production. Sorghum, renowned for its hardiness and nutritional richness, holds promise in confronting both climate change and the pressing issues of food insecurity and hidden hunger. While efforts have been made in researching and integrating sorghum into food products, further concerted research efforts and governmental support are pivotal for its widespread adoption. The impending challenge of meeting the escalating global food demand amid the detrimental effects of climate change necessitates a re-evaluation of underutilized crops like sorghum. Positioning sorghum as a star crop and a strategic choice in the global food chain's sustainability is imperative. Recognizing sorghum's tremendous potential is paramount in addressing the prevailing conditions of food insecurity, urging a paradigm shift towards leveraging its unique attributes.

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Declarations

Competing Interests The authors declare no competing interests.

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