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Review Article **Open Access**

Latest Progress on the Effects of Drought, Salinity, and Temperature Stress on Sweet Potatoes and Their Resistance Mechanisms

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Abstract Abiotic stresses such as drought, salinity, extreme temperatures, and heavy metal toxicity pose significant challenges to global agriculture, impacting crop yields and food security. Sweet potato (*Ipomoea batatas*), an essential staple crop, is particularly affected by these stresses, necessitating enhanced tolerance mechanisms to maintain productivity. This study examines the physiological, molecular, and genetic mechanisms that support the abiotic stress tolerance of sweet potatoes, with a focus on key traits such as water use efficiency, osmotic regulation, and antioxidant defense. At the same time, specific genes and transcription factors involved in stress response pathways, including ABA and ROS signaling, as well as the role of epigenetic modifications in adapting to environmental stress, were also analyzed. Additionally, breeding strategies and biotechnological interventions such as CRISPR and marker-assisted selection are discussed, emphasizing their role in developing stress-resilient varieties. Case studies on drought and salinity-resistant sweet potato varieties highlight practical outcomes of current breeding programs. This study summarizes the limitations of existing methods and proposes directions for future research. Enhancing abiotic stress tolerance in sweet potato remains a crucial goal, with promising potential through integrated breeding and biotechnological approaches to support sustainable agriculture.

Keywords Sweet potato; Abiotic stress tolerance; Drought resistance; Salinity tolerance; Molecular mechanisms

1 Introduction

Abiotic stress, including drought, salinity, extreme temperatures, and oxidative stress, poses significant challenges to agricultural productivity worldwide (Tao and Han, 2024; Zhu and Shen, 2024). These stressors can severely limit crop growth, yield, and quality, leading to substantial economic losses and food insecurity. The increasing frequency and intensity of these stresses due to climate change further exacerbate the problem, necessitating the development of crops with enhanced tolerance to abiotic stresses (Fan et al., 2012; Demirel et al., 2020; Villalobos-López et al., 2022).

Sweet potato (*Ipomoea batatas*) is a vital staple crop globally, known for its high nutritional value and adaptability to diverse environmental conditions. It ranks as the seventh most important food crop, providing essential nutrients and calories to millions of people, particularly in developing countries (Liu et al., 2023). Despite its resilience, sweet potato production is still significantly affected by abiotic stresses such as drought, salinity, and low temperatures, which can lead to reduced yields and compromised food security (Fan et al., 2015; Ren et al., 2020). Enhancing the abiotic stress tolerance of sweet potato is therefore crucial for stabilizing its production and ensuring food availability in stress-prone regions.

This study seeks to highlight strategies for sweet potato to cope with various abiotic stresses by examining recent advancements in genetic, physiological, and molecular research, exploring the roles of specific genes and proteins-such as betaine aldehyde dehydrogenase (BADH), peroxidases (PRXs), and sucrose non-fermenting-1 related protein kinase-1 (SnRK1)-in enhancing stress tolerance, and discussing the potential of biotechnological approaches, including gene overexpression and genetic transformation, for developing stress-resistant sweet potato varieties, aiming to provide insights to guide future research and breeding programs to improve sweet potato's resilience to abiotic stress.

2 Types of Abiotic Stresses Affecting Sweet Potato

Sweet potato (*Ipomoea batatas*) is a vital crop globally, but its productivity is significantly affected by various abiotic stresses. These stresses include drought, salinity, extreme temperatures, and heavy metal toxicity. Understanding the mechanisms of tolerance to these stresses is crucial for developing resilient sweet potato cultivars.

2.1 Drought stress

Drought stress is one of the most critical factors limiting sweet potato yield. Drought conditions lead to reduced photosynthetic activity, oxidative stress, and impaired growth (Sapakhova et al., 2023). Studies have shown that the overexpression of certain genes, such as *IbSnRK1*, enhances drought tolerance by activating the reactive oxygen species (ROS) scavenging system and controlling stomatal closure via the abscisic acid (ABA) signaling pathway (Ren et al., 2020). Additionally, the IbBBX24-IbTOE3-IbPRX17 module has been identified to improve drought tolerance by scavenging ROS, thereby reducing oxidative damage (Figure 1) (Zhang et al., 2021). Transcriptomic analyses have revealed that drought-tolerant cultivars regulate flavonoid and carbohydrate biosynthesis/metabolism to mitigate drought stress (Liu et al., 2023).

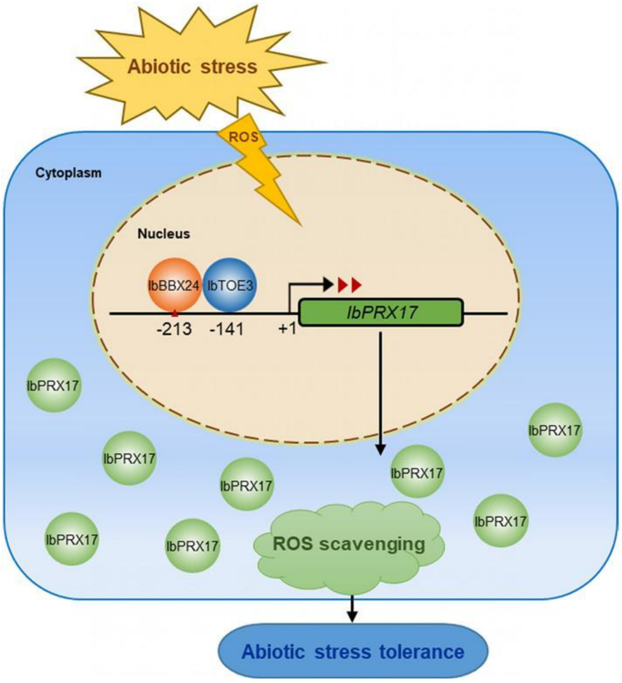

Figure 1 Proposed working model of the IbBBX24-IbTOE3-IbPRX17 regulatory module in abiotic stress responses. *IbBBX24*, *IbTOE3* and *IbPRX17* expression is induced by NaCl, polyethylene glycol 6000 (PEG6000), and H_2O_2 treatments. *IbBBX24* and *IbTOE3* bind separately to the GT-1 motif at-213 bp and the TTTGTT motif at-141 bp in the *IbPRX17* promoter and activate *IbPRX17* transcription. Interaction between *IbBBX24* and *IbTOE3* enhances the ability of *IbBBX24* to activate *IbPRX17* transcription by binding the GT-1 motif at-213 bp of its promoter. In addition, overexpression of IbBBX24, *IbTOE3* and *IbPRX17* promotes reactive oxygen species (ROS) scavenging under abiotic stress conditions, leading to abiotic stress tolerance. Brown circle, *IbBBX24*; blue circle, *IbTOE3*; green circles, *IbPRX17*; red triangles, activated transcription (Adopted from Zhang et al., 2021)

2.2 Salinity stress

Salinity stress adversely affects sweet potato by causing ionic imbalance and osmotic stress, leading to reduced growth and yield. The overexpression of genes such as *IbMIPS1* and *IbC3H18* has been shown to enhance salt tolerance by up-regulating stress-responsive genes involved in ROS scavenging, ABA signaling, and ion transport pathways (Zhai et al., 2016; Zhang et al., 2019). Furthermore, the introduction of the *AtNHX1* gene, which encodes a vacuolar Na^+/H^+ antiporter, into sweet potato has demonstrated improved salt tolerance by enhancing Na^+ compartmentalization into vacuoles, thus maintaining ionic homeostasis and reducing cellular damage.

2.3 Temperature stress (heat and cold)

Sweet potato is also susceptible to temperature extremes, including both heat and cold stress. Heat stress can lead to protein denaturation and membrane instability, while cold stress can cause cellular damage and metabolic disruptions. The overexpression of the *StnsLTP1* gene in transgenic potato plants has shown enhanced tolerance to heat stress by improving cell membrane integrity and activating antioxidative defense mechanisms (Gangadhar et al., 2016). Similarly, the overexpression of the *SoBADH* gene in sweet potato has been found to improve cold tolerance by increasing glycine betaine (GB) accumulation, which helps in maintaining cell membrane integrity and reducing ROS production (Fan et al., 2012). Additionally, the *AtNHX1* gene has been shown to confer cold tolerance by enhancing ROS scavenging and maintaining cellular homeostasis (Fan et al., 2015).

2.4 Heavy metal toxicity

Heavy metal toxicity, although less studied in sweet potato, poses a significant threat to plant health by inducing oxidative stress and disrupting cellular functions. The mechanisms of tolerance to heavy metals involve the activation of antioxidative defense systems and the sequestration of heavy metals into vacuoles. While specific studies on heavy metal tolerance in sweet potato are limited, the general principles of ROS scavenging and ion compartmentalization observed in other abiotic stresses are likely applicable.

3 Physiological Mechanisms of Abiotic Stress Tolerance in Sweet Potato

3.1 Water-use efficiency and stomatal regulation

Water-use efficiency (WUE) and stomatal regulation are critical for sweet potato’s adaptation to abiotic stresses such as drought and salinity. The *IbSnRK1* gene has been shown to play a significant role in controlling stomatal closure via the abscisic acid (ABA) signaling pathway, thereby enhancing drought and salt tolerance. Overexpression of *IbSnRK1* in transgenic sweet potato plants resulted in increased ABA content and improved stomatal regulation, which are essential for maintaining water balance under stress conditions (Ren et al., 2020). Additionally, the non-tandem CCCH-type zinc-finger protein IbC3H18 regulates the expression of stress-responsive genes involved in stomatal closure, further contributing to enhanced water-use efficiency (Zhang et al., 2019).

3.2 Osmotic adjustment and ion homeostasis

Osmotic adjustment and ion homeostasis are vital for sweet potato's resilience to abiotic stresses. The overexpression of the *IbMIPS1* gene in sweet potato has been shown to enhance osmotic adjustment by increasing the levels of inositol, proline, and other osmolytes, which help maintain cell turgor and protect cellular structures under salt and drought stress (Zhai et al., 2016). Furthermore, the *IbSnRK1* gene also contributes to ion homeostasis by increasing potassium (K^+) content and reducing sodium (Na^+) accumulation, thereby mitigating the detrimental effects of salt stress. The accumulation of glycine betaine (GB) through the overexpression of the *SoBADH* gene also aids in osmotic adjustment and ion homeostasis, enhancing the plant's tolerance to multiple abiotic stresses (Fan et al., 2012).

3.3 Antioxidant defense system

The antioxidant defense system is crucial for scavenging reactive oxygen species (ROS) generated under abiotic stress conditions (Golldack et al., 2014). The IbBBX24-IbTOE3-IbPRX17 module has been identified as a key player in enhancing the antioxidant defense system in sweet potato. Overexpression of *IbBBX24* and *IbPRX17* leads to increased peroxidase activity and reduced H_2O_2 accumulation, thereby improving tolerance to salt and drought stresses (Zhang et al., 2021). Similarly, the *IbSnRK1* gene enhances the activities of ROS-scavenging enzymes, such as superoxide dismutase (SOD) and catalase (CAT), which are essential for mitigating oxidative damage (Figure 2). The overexpression of the *IbC3H18* gene also upregulates genes involved in the ROS scavenging system, further bolstering the plant's antioxidant defenses.

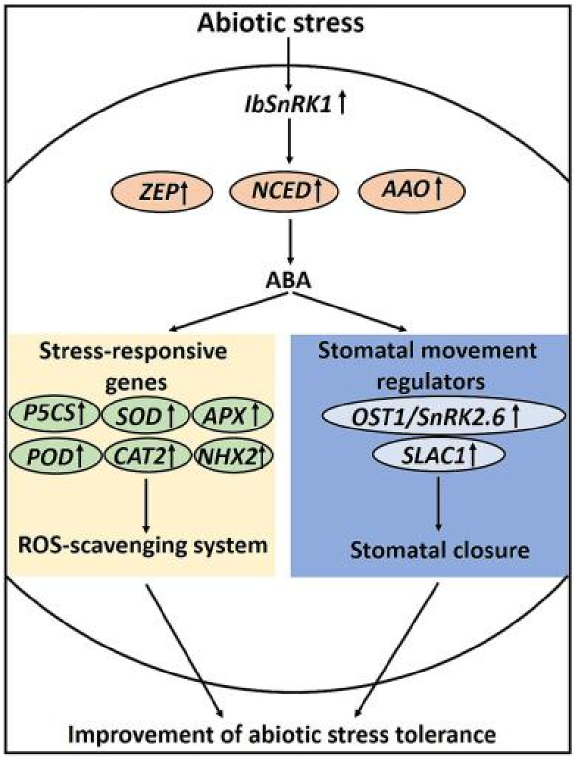

Figure 2 Diagram of a proposed model for regulation of *IbSnRK1* in abiotic stress tolerance in transgenic sweet potato. ↑ indicates up-regulation of genes coding these enzymes (proteins) (Adopted from Ren et al., 2020)

3.4 Heat shock proteins and molecular chaperones

Heat shock proteins (HSPs) and molecular chaperones play a pivotal role in protecting sweet potato from abiotic stresses by maintaining protein stability and preventing aggregation. HSPs are dynamically regulated in response to stress and are involved in the detoxification of ROS, thereby enhancing membrane stability and overall stress tolerance (Haq et al., 2019). The expression of HSPs is often induced by ROS signaling, which acts as a trigger for their production. This regulatory mechanism ensures that HSPs are available to counteract the damaging effects of abiotic stresses, such as heat and drought. The role of HSPs in sweet potato is further supported by the upregulation of stress-related genes, including those encoding HSPs, in transgenic plants overexpressing various stress-responsive genes (Gangadhar et al., 2016).

4 Molecular and Genetic Mechanisms Underpinning Stress Tolerance

4.1 Key genes involved in abiotic stress response

Several key genes have been identified in sweet potato that contribute to abiotic stress tolerance. The gene *IbC3H18*, a non-tandem CCCH-type zinc-finger protein, is one such gene that enhances tolerance to salt, drought, and oxidative stresses by regulating the expression of stress-responsive genes involved in ROS scavenging, ABA signaling, photosynthesis, and ion transport pathways. Another important gene is *IbSnRK1*, which confers tolerance to salt, drought, and cold by activating the ROS scavenging system and controlling stomatal closure via the ABA signaling pathway (Ren et al., 2020). Additionally, *IbMIPS1* enhances salt and drought tolerance by up-regulating genes involved in inositol biosynthesis, PI and ABA signaling pathways, and the ROS-scavenging system (Zhai et al., 2016).

4.2 Role of transcription factors

Transcription factors (TFs) play a crucial role in regulating gene expression in response to abiotic stress. The ItfWRKY70 transcription factor from Ipomoea trifida has been shown to increase drought tolerance in sweet potato by up-regulating genes involved in ABA biosynthesis, stress response, and the ROS-scavenging system (Sun et al., 2022). The IbMYB73 transcription factor regulates root growth and stress tolerance by influencing the transcription of genes in the ABA pathway and forming homodimers to activate the transcription of the abscisic acid-responsive protein IbGER5. Another significant TF is IbBBX24, which activates the expression of the class III peroxidase gene *IbPRX17* to enhance salt and drought tolerance by scavenging ROS (Zhang et al., 2021).

4.3 Signaling pathways in stress response

Signaling pathways such as ABA and ROS play pivotal roles in the abiotic stress response in sweet potato. The *IbSnRK1* gene activates the ROS scavenging system and controls stomatal closure via the ABA signaling pathway, thereby enhancing tolerance to salt, drought, and cold stresses. The *IbCAR1* gene, a C2-domain abscisic acid-related protein, improves salt tolerance by relying on the ABA signal transduction pathway and activating the ROS-scavenging system (You et al., 2022). Additionally, the IbNAC3 transcription factor modulates combined salt and drought stresses by promoting the transcription of genes involved in ABA signaling and ROS scavenging (Meng et al., 2022).

4.4 Epigenetic modifications and gene regulation

Epigenetic modifications and gene regulation are essential for the adaptation of sweet potato to abiotic stress. The *IbC3H18* gene functions as a nuclear transcriptional activator and regulates the expression of a range of abiotic stress-responsive genes (Zhang et al., 2019). The IbMYB73 transcription factor influences the transcription of genes involved in the ABA pathway, demonstrating the importance of transcriptional regulation in stress tolerance (Wang et al., 2023). Furthermore, the *IbBBX24-IbTOE3-IbPRX17* module elucidates the mechanism of transcriptional regulation in response to abiotic stress by modulating the expression of genes encoding ROS scavenging enzymes.

5 Breeding and Biotechnological Approaches for Enhancing Stress Tolerance

5.1 Conventional breeding techniques

Conventional breeding techniques have been instrumental in developing sweet potato varieties with enhanced tolerance to abiotic stresses. These methods involve selecting and cross-breeding plants that exhibit desirable traits such as drought and salinity tolerance. The genetic diversity within the genus Solanum, for example, has been a valuable resource for breeding programs aimed at improving stress tolerance in related crops like sweet potato (Tiwari et al., 2022). However, the multigenic nature of abiotic stress tolerance poses a significant challenge, often requiring the integration of multiple traits to achieve the desired level of resilience (Esmaeili et al., 2022).

5.2 Genetic engineering and CRISPR technology

Genetic engineering has emerged as a powerful tool for enhancing abiotic stress tolerance in sweet potato. Techniques such as the overexpression of stress-related genes have shown promising results. For instance, the introduction of the *Spinacia oleracea* betaine aldehyde dehydrogenase (*SoBADH*) gene into sweet potato has significantly improved its tolerance to salt, oxidative stress, and low temperatures by enhancing glycine betaine biosynthesis (Fan et al., 2012). Additionally, CRISPR-Cas9 technology offers precise genome editing capabilities, allowing for the targeted modification of genes involved in stress responses. This approach has the potential to create novel quantitative trait loci for abiotic stress tolerance by targeting regulatory sequences and promoters (Zafar et al., 2020).

5.3 Marker-assisted selection and genomic approaches

Marker-assisted selection (MAS) has revolutionized the breeding process by enabling the rapid and accurate selection of stress-tolerant traits. This technique utilizes molecular markers linked to desirable traits, thereby accelerating the breeding cycle and increasing the precision of selection (Wani et al., 2018). Advances in genomics, such as high-throughput genotyping and multi-omics platforms, have further enhanced the effectiveness of MAS. These tools facilitate the identification of key genes and pathways involved in stress tolerance, enabling the development of sweet potato varieties with improved resilience to abiotic stresses (Villalobos-López et al., 2022).

5.4 Integrating biotechnology with breeding programs

The integration of biotechnological approaches with conventional breeding programs holds great promise for the development of sweet potato varieties with enhanced abiotic stress tolerance. By combining the strengths of genetic engineering, CRISPR technology, and marker-assisted selection, it is possible to achieve more robust and resilient crops. For example, the overexpression of transcription factors such as IbBBX24 and IbTOE3 has been shown to enhance ROS scavenging and improve tolerance to salt and drought stresses in sweet potato (Zhang et al., 2021). Similarly, the manipulation of genes involved in inositol biosynthesis and ABA signaling pathways has demonstrated significant improvements in stress tolerance and resistance to biotic stresses (Zhai et al., 2016). These integrated approaches not only stabilize yield production under unfavorable conditions but also provide novel germplasm for sweet potato cultivation on marginal lands (Anwar and Kim, 2020).

6 Case Studies

6.1 Drought-resistant sweet potato varieties

Several studies have identified key genetic modifications that enhance drought resistance in sweet potato. For instance, the overexpression of the *IbBBX24* and *IbPRX17* genes has been shown to significantly improve drought tolerance by enhancing reactive oxygen species (ROS) scavenging capabilities (Zhang et al., 2021). Similarly, the *IbMIPS1* gene, which is involved in myo-inositol biosynthesis, has been found to enhance drought tolerance by upregulating stress response pathways and increasing the accumulation of protective metabolites such as proline and trehalose. Another gene, *IbC3H18*, a non-tandem CCCH-type zinc-finger protein, has also been reported to increase drought tolerance by regulating the expression of stress-responsive genes and enhancing ROS scavenging. Additionally, the IbSnRK1 gene has been shown to confer drought tolerance by activating the ROS scavenging system and controlling stomatal closure via the ABA signaling pathway (Ren et al., 2020).

6.2 Salinity tolerance in sweet potato

Salinity stress is another major abiotic factor limiting sweet potato productivity. The overexpression of the *IbBBX24* and *IbPRX17* genes not only improves drought tolerance but also enhances salinity tolerance by reducing H_2O_2 accumulation and increasing peroxidase activity (Figure 3). The *IbMIPS1* gene has also been shown to confer salinity tolerance by upregulating genes involved in inositol biosynthesis and ABA signaling pathways, leading to increased accumulation of protective metabolites and reduced Na^+ content. The *IbC3H18* gene enhances salinity tolerance by regulating ion transport pathways and increasing ROS scavenging (Zhang et al., 2019). Furthermore, the overexpression of the *AtNHX1* gene, which encodes a vacuolar Na^+/H^+ antiporter, has been demonstrated to improve salinity tolerance by enhancing Na^+ compartmentalization into vacuoles, thereby maintaining high K^+/Na^+ ratios and reducing cell damage.

6.3 Results and key learnings from case studies

The case studies on drought and salinity tolerance in sweet potato reveal several key mechanisms that contribute to enhanced abiotic stress tolerance. One common theme is the importance of ROS scavenging systems. Genes such as *IbBBX24*, *IbPRX17*, *IbC3H18*, and *IbSnRK1* all play crucial roles in enhancing the plant's ability to scavenge ROS, thereby reducing oxidative damage under stress conditions. Another critical mechanism is the regulation of ion transport and compartmentalization, as demonstrated by the *AtNHX1* gene, which helps maintain ionic balance and reduce toxicity under salinity stress (Fan et al., 2015). Additionally, the accumulation of protective metabolites such as proline, trehalose, and inositol is a recurring strategy for enhancing stress tolerance, as seen with the *IbMIPS1* gene (Zhai et al., 2016).

These findings highlight the potential of genetic engineering to develop sweet potato varieties with improved tolerance to multiple abiotic stresses (Zhao et al., 2022). By targeting key genes involved in ROS scavenging, ion transport, and metabolite accumulation, it is possible to create crops that can withstand harsh environmental conditions, thereby ensuring stable yield production.

7 Challenges and Future Directions

7.1 Limitations in current breeding programs

Current breeding programs for sweet potato face several limitations in developing abiotic stress-tolerant varieties. Traditional breeding methods have primarily focused on traits such as yield and disease resistance, often neglecting abiotic stress tolerance (Kikuchi et al., 2015). The polygenic nature of stress tolerance traits complicates the breeding process, as it involves multiple genes and complex interactions (Villalobos-López et al., 2022). Additionally, the lack of comprehensive phenotyping tools to assess belowground traits, such as root and tuber development, further hampers the breeding efforts (Harsselaar et al., 2021). The integration of advanced molecular tools and high-throughput phenotyping methods is essential to overcome these limitations and accelerate the development of stress-tolerant cultivars.

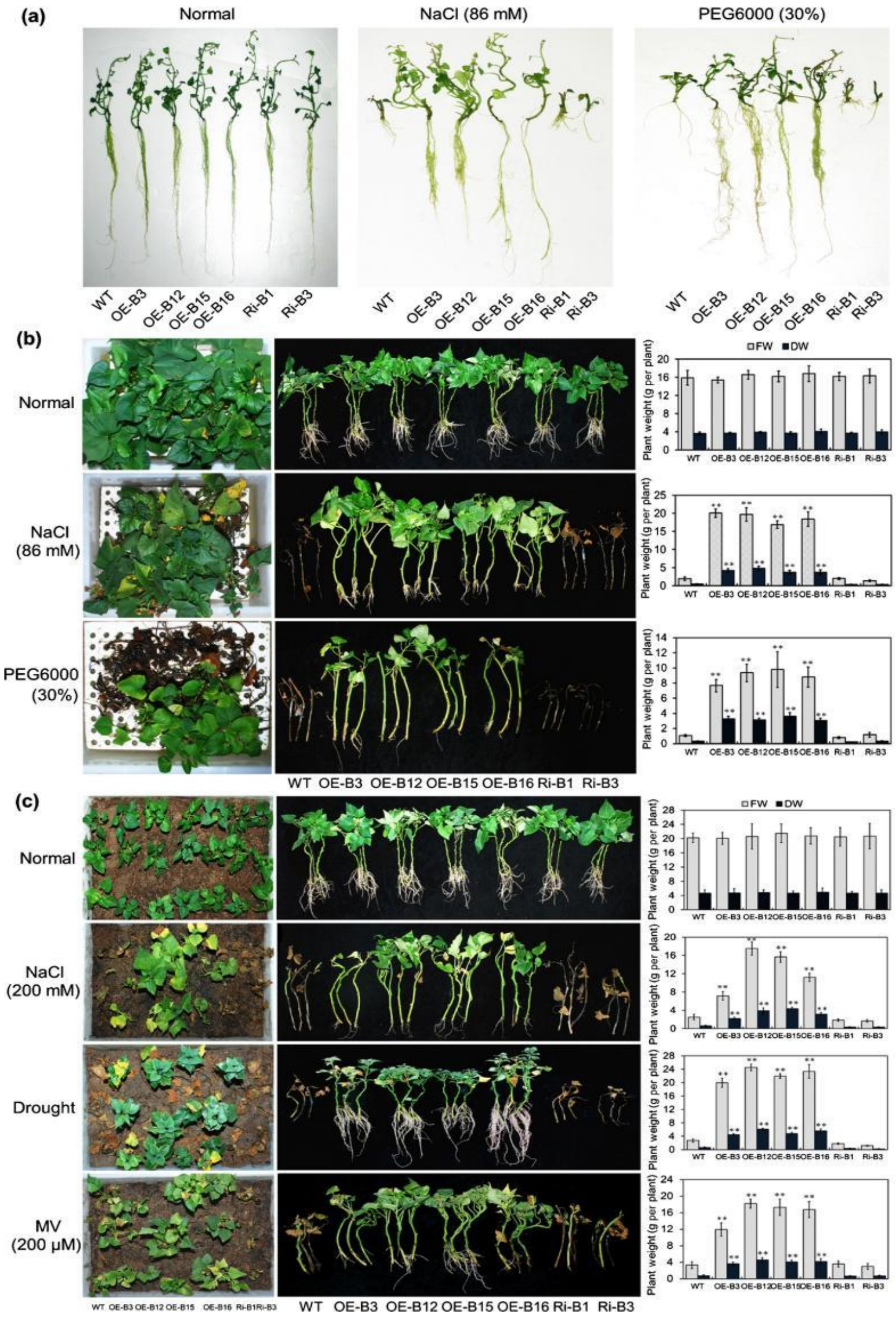

Figure 3 *IbBBX24* overexpression enhances tolerance to salt, drought and oxidative stresses in sweet potato. (a) Responses of *IbBBX24*-OE, *IbBBX24*-RNAi and wild-type (WT) sweet potato plants grown for 4 wk on Murashige & Skoog (MS) medium in control conditions (normal) or with 86 mM NaCl or 30% polyethylene glycol 6000 (PEG6000). (b) Responses of *IbBBX24*-OE, *IbBBX24*-RNAi and WT sweet potato plants grown hydroponically in half-strength Hoagland solution (normal) or half-strength Hoagland solution containing 86 mM NaCl or 30% PEG6000. (c) Responses of *IbBBX24*-OE, *IbBBX24*-RNAi and WT sweet potato plants grown in transplanting boxes under control conditions (normal) or subjected to 200 mM NaCl, drought or 200 μM methyl viologen (MV). Representative photographs were taken after stress treatment for 4 wk (salt), 8 wk (drought) or 2b wk (MV). Data are shown as means ± SD ($n = 3$). **, Significant difference from WT at $P < 0.01$ based on Student’s t-test (Adopted from Zhang et al., 2021)

7.2 Technological and funding challenges

The development of abiotic stress-tolerant sweet potato varieties is also constrained by technological and funding challenges. Advanced biotechnological approaches, such as CRISPR-Cas9 and transgenic techniques, hold promise for improving stress tolerance but require significant investment in infrastructure and expertise (Anwar and Kim, 2020). Moreover, the regulatory landscape for genetically modified organisms (GMOs) varies globally, posing additional hurdles for the commercialization of transgenic sweet potato varieties. Funding for research in this area is often limited, with a significant portion allocated to staple crops like rice and wheat, leaving root crops like sweet potato underfunded (Fan et al., 2012). Increased investment in research and development, along with streamlined regulatory processes, is crucial to harness the full potential of these technologies.

7.3 Future prospects in abiotic stress research

Future research in abiotic stress tolerance in sweet potato should focus on several key areas. First, the identification and functional characterization of stress-responsive genes, such as *IbBBX24*, *IbTOE3*, and *IbPRX17*, can provide valuable targets for genetic engineering. The overexpression of these genes has shown to enhance tolerance to salt and drought stresses by improving ROS scavenging and maintaining cellular homeostasis (Zhang et al., 2021). The integration of omics technologies, including genomics, transcriptomics, and metabolomics, can offer a holistic understanding of the stress response mechanisms and identify novel candidate genes for breeding programs (Zhai et al., 2016; Demirel et al., 2020). The development of high-throughput phenotyping platforms, such as X-ray CT imaging, can facilitate the non-invasive monitoring of tuber growth and stress responses, thereby accelerating the selection of stress-tolerant genotypes. Lastly, collaborative efforts between public and private sectors, along with increased funding, are essential to translate research findings into practical applications and develop resilient sweet potato varieties capable of withstanding the challenges posed by climate change.

8 Conclusion

The review of recent studies on abiotic stress tolerance in sweet potato highlights several key mechanisms that enhance the plant's resilience to adverse environmental conditions. The overexpression of genes such as *Spinacia oleracea* betaine aldehyde dehydrogenase (SoBADH) has been shown to improve tolerance to salt, oxidative stress, and low temperatures by increasing glycine betaine (GB) accumulation, which helps maintain cell membrane integrity and reduce reactive oxygen species (ROS) production. Similarly, the IbBBX24-IbTOE3-IbPRX17 module enhances stress tolerance by scavenging ROS, thereby improving the plant's resistance to salt and drought. The introduction of the *AtNHX1* gene, which encodes a vacuolar Na^+/H^+ antiporter, has also been effective in improving salt and cold stress tolerance by enhancing Na^+ compartmentalization and maintaining high K^+/Na^+ ratios. Additionally, the IbMYB73-IbGER5 module regulates root growth and stress tolerance through the abscisic acid (ABA) pathway, further contributing to the plant's resilience. The application of effective microorganisms (EMs) and nanomagnesium has also been shown to boost agronomic and physiological traits, enhancing the plant's defense mechanisms against salt stress.

Future research should focus on the integrative and multi-gene approaches to enhance abiotic stress tolerance in sweet potato. Studies should explore the combined effects of multiple gene overexpressions, such as combining *SoBADH* with *IbBBX24* and *AtNHX1*, to create transgenic lines with broad-spectrum stress tolerance. Additionally, the role of non-tandem CCCH-type zinc-finger proteins like *IbC3H18* in regulating stress-responsive genes should be further investigated to understand their potential in improving stress resilience. The application of bio- and nanofertilizers, such as EMs and MgO nanoparticles, should be expanded to other stress conditions and crop varieties to validate their efficacy and optimize their use in sustainable agriculture. Moreover, the molecular mechanisms underlying the interaction between different stress pathways, such as the ABA signaling pathway and ROS scavenging systems, should be elucidated to develop more effective stress mitigation strategies.

Enhancing abiotic stress tolerance in sweet potato is crucial for ensuring stable yield production under increasingly unpredictable climatic conditions. The integration of genetic engineering, molecular biology, and sustainable agricultural practices offers promising avenues for developing stress-resilient sweet potato varieties. By leveraging the synergistic effects of multiple stress-responsive genes and innovative agronomic practices, it is possible to create robust sweet potato cultivars capable of thriving in marginal lands and under various environmental stresses. Continued research and collaboration among scientists, agronomists, and farmers will be essential to translate these scientific advancements into practical solutions that can secure food production and improve the livelihoods of communities dependent on sweet potato cultivation.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Anwar A., and Kim J., 2020, Transgenic breeding approaches for improving abiotic stress tolerance: recent progress and future perspectives, International Journal of Molecular Sciences, 21(8): 2695.
https://doi.org/10.3390/ijms21082695

Demirel U., Morris W., Ducreux L., Yavuz C., Asim A., Tindaş I., Campbell R., Morris J., Verrall S., Hedley P., Gokce Z., Çalişkan S., Aksoy E., Çalışkan M., Taylor M., and Hancock R., 2020, Physiological, biochemical, and transcriptional responses to single and combined abiotic stress in stress-tolerant and stress-sensitive potato genotypes, Frontiers in Plant Science, 11: 169.
https://doi.org/10.3389/fpls.2020.00169

Esmaeili N., Shen G., and Zhang H., 2022, Genetic manipulation for abiotic stress resistance traits in crops, Frontiers in Plant Science, 13: 1011985.
https://doi.org/10.3389/fpls.2022.1011985

Fan W., Deng G., Wang H., Zhang H., and Zhang P., 2015, Elevated compartmentalization of Na^+ into vacuoles improves salt and cold stress tolerance in sweet potato (*Ipomoea batatas*), Physiologia Plantarum, 154(4): 560-571.
https://doi.org/10.1111/ppl.12301

Fan W., Zhang M., Zhang H., and Zhang P., 2012, Improved tolerance to various abiotic stresses in transgenic sweet potato (*Ipomoea batatas*) expressing spinach betaine aldehyde dehydrogenase, PLoS ONE, 7(5): e37344.
https://doi.org/10.1371/journal.pone.0037344

Gangadhar B., Sajeesh K., Venkatesh J., Baskar V., Abhinandan K., Yu J., Prasad R., and Mishra R., 2016, Enhanced tolerance of transgenic potato plants over-expressing non-specific lipid transfer protein-1 (*StnsLTP1*) against multiple abiotic stresses, Frontiers in Plant Science, 7: 1228.
https://doi.org/10.3389/fpls.2016.01228

Golldack D., Li C., Mohan H., and Probst N., 2014, Tolerance to drought and salt stress in plants: unraveling the signaling networks, Frontiers in Plant Science, 5: 151.
https://doi.org/10.3389/fpls.2014.00151

Haq S., Khan A., Ali M., Khattak A., Gai W., Zhang H., Wei A., and Gong Z., 2019, Heat shock proteins: dynamic biomolecules to counter plant biotic and abiotic stresses, International Journal of Molecular Sciences, 20(21): 5321.
https://doi.org/10.3390/ijms20215321

Harsselaar J., Claussen J., Lübeck J., Wörlein N., Uhlmann N., Sonnewald U., and Gerth S., 2021, X-Ray CT phenotyping reveals bi-phasic growth phases of potato tubers exposed to combined abiotic stress, Frontiers in Plant Science, 12: 613108.
https://doi.org/10.3389/fpls.2021.613108

Kikuchi A., Huynh H., Endo T., and Watanabe K., 2015, Review of recent transgenic studies on abiotic stress tolerance and future molecular breeding in potato, Breeding Science, 65(1): 85-102.
https://doi.org/10.1270/jsbbs.65.85

Liu E., Xu L., Luo Z., Li Z., Zhou G., Gao H., Fang F., Tang J., Zhao Y., Zhou Z., and Jin P., 2023, Transcriptomic analysis reveals mechanisms for the different drought tolerance of sweet potatoes, Frontiers in Plant Science, 14: 1136709.

Meng X., Liu S., Zhang C., He J., Ma D., Wang X., Dong T., Guo F., Cai J., Long T., Li Z., and Zhu M., 2022, The unique sweet potato NAC transcription factor IbNAC3 modulates combined salt and drought stresses, Plant Physiology, 191(1): 747-771.
https://doi.org/10.1093/plphys/kiac508

Ren Z., He S., Zhou Y., Zhao N., Jiang T., Zhai H., and Liu Q., 2020, A sucrose non-fermenting-1-related protein kinase-1 gene, *IbSnRK1*, confers salt, drought and cold tolerance in sweet potato, Crop Journal, 8(6): 905-917.
https://doi.org/10.1016/j.cj.2020.04.010

Sapakhova Z., Raissova N., Daurov D., Zhapar K., Daurova A., Zhigailov A., Zhambakin K., and Shamekova M., 2023, Sweet potato as a key crop for food security under the conditions of global climate change: a review, Plants, 12(13): 2516.
https://doi.org/10.3390/plants12132516

Sun S., Li X., Gao S., Nie N., Zhang H., Yang Y., He S., Liu Q., and Zhai H., 2022, A novel WRKY transcription factor from *Ipomoea trifida*, ItfWRKY70, confers drought tolerance in sweet potato, International Journal of Molecular Sciences, 23(2): 686.
https://doi.org/10.3390/ijms23020686

Tao J., and Han J.Q., 2024, Physiological mechanisms of photosynthesis and antioxidant system in rice under high temperature stress, Rice Genomics and Genetics, 15(1): 36-47.
https://doi.org/10.5376/rgg.2024.15.0005

Tiwari J., Buckseth T., Zinta R., Bhatia N., Dalamu D., Naik S., Poonia A., Kardile H., Challam C., Singh R., Luthra S., Kumar V., and Kumar M., 2022, Germplasm, breeding, and genomics in potato improvement of biotic and abiotic stresses tolerance, Frontiers in Plant Science, 13: 805671.
https://doi.org/10.3389/fpls.2022.805671

Villalobos-López M., Arroyo-Becerra A., Quintero-Jiménez A., and Iturriaga G., 2022, Biotechnological advances to improve abiotic stress tolerance in crops, International Journal of Molecular Sciences, 23(19): 12053.
https://doi.org/10.3390/ijms231912053

Wang Z., Li X., Gao X., Dai Z., Peng K., Jia L., Wu Y., Liu Q., Zhai H., Gao S., Zhao N., He S., and Zhang H., 2023, IbMYB73 targets abscisic acid-responsive *IbGER5* to regulate root growth and stress tolerance in sweet potato, Plant Physiology, 194(2): 787-804.
https://doi.org/10.1093/plphys/kiad532

Wani S., Choudhary M., Kumar P., Akram N., Surekha C., Ahmad P., and Gosal S., 2018, Marker-assisted breeding for abiotic stress tolerance in crop plants, In: Biotechnologies of Crop Improvement, Volume 3: Genomic Approaches, pp.1-23.
https://doi.org/10.1007/978-3-319-94746-4_1

You C., Li C., Ma M., Tang W., Kou M., Yan H., Song W., Gao R., Wang X., Zhang Y., and Li Q., 2022, A C2-domain Abscisic acid-related gene, *IbCAR1*, positively enhances salt tolerance in sweet potato (*Ipomoea batatas* (L.) Lam.), International Journal of Molecular Sciences, 23(17): 9680.
https://doi.org/10.3390/ijms23179680

Zafar S., Zaidi S., Gaba Y., Singla-Pareek S., Dhankher O., Li X., Mansoor S., and Pareek A., 2020, Engineering abiotic stress tolerance via CRISPR-Cas mediated genome editing, Journal of experimental botany, 71(2): 470-479.
https://doi.org/10.1093/jxb/erz476

Zhai H., Wang F., Si Z., Huo J., Xing L., An Y., He S., and Liu Q., 2016, A *myo*-inositol-1-phosphate synthase gene, *IbMIPS1*, enhances salt and drought tolerance and stem nematode resistance in transgenic sweet potato, Plant Biotechnology Journal, 14(2): 592-602.
https://doi.org/10.1111/pbi.12402

Zhang H., Gao X., Zhi Y., Li X., Zhang Q., Niu J., Wang J., Zhai H., Zhao N., Li J., Liu Q., and He S., 2019, A non-tandem CCCH-type zinc-finger protein, *IbC3H18*, functions as a nuclear transcriptional activator and enhances abiotic stress tolerance in sweet potato, New Phytologist, 223(4): 1918-1936.
https://doi.org/10.1111/nph.15925

Zhang H., Wang Z., Li X., Gao X., Dai Z., Cui Y., Zhi Y., Liu Q., Zhai H., Gao S., Zhao N., and He S., 2021, The IbBBX24-IbTOE3-IbPRX17 module enhances abiotic stress tolerance by scavenging reactive oxygen species in sweet potato, New Phytologist, 233(3): 1133-1152.
https://doi.org/10.1111/nph.17860

Zhao H., Zhao H., Hu Y., Zhang S., He S., Zhang H., Zhao N., Liu Q., Gao S., and Zhai H., 2022, Expression of the sweet potato MYB transcription factor *IbMYB48* confers salt and drought tolerance in Arabidopsis, Genes, 13(10): 1883.
https://doi.org/10.3390/genes13101883

Zhu Y.L., and Shen Z.C., 2024, Response analysis of root and leaf physiology and metabolism under drought stress in rice, Rice Genomics and Genetics, 15(3): 19-27.
https://doi.org/10.5376/rgg.2024.15.0003