Drought Stress Management in Potatoes: Physiological, Biochemical, and Agronomic Strategies

Saira Shoukat [1*], Abida Tufail [1]

Abstract

Drought stress is a major abiotic factor limiting crop productivity worldwide, especially in drought-sensitive crops like potatoes (Solanum tuberosum L.). Potatoes are highly vulnerable to drought due to their shallow root system and physiological characteristics. Effective strategies, including genetic, biochemical, and agronomic approaches, are critical for mitigating drought-induced yield losses. A comprehensive review of existing literature was conducted, analyzing physiological and molecular pathways activated under drought stress, including ABA-dependent and ABA-independent gene expression mechanisms. This review explores the physiological, biochemical, and agronomic strategies employed by potatoes to withstand drought stress and highlights the role of abscisic acid (ABA) signaling, soil management practices, and genotype selection in enhancing drought tolerance. Drought stress induces various physiological and biochemical responses in potatoes, mediated by ABA signaling pathways. ABA promotes stomatal closure, reduces transpiration, and activates drought-responsive genes such as DREB1A and WRKY. SnRK2 kinases play a crucial role in the ABA signaling cascade, enhancing stress tolerance. Agronomic practices like mulching, residue management, and biochar application improved soil water retention and minimized evapotranspiration. Nutrient management, including the application of nitrogen (N), potassium (K), phosphorus (P), zinc (Zn), and silicon (Si), was effective in enhancing drought tolerance. Mid-maturing potato cultivars with fewer, larger leaves showed higher resilience under prolonged drought conditions, while early-maturing cultivars were advantageous in terminal drought scenarios. Drought stress remains a significant challenge for sustainable potato production, necessitating integrated strategies combining genetic and agronomic approaches. ABA signaling and its downstream pathways are pivotal in improving drought resilience in potatoes.

Keywords: Potato drought stress, Abscisic acid signaling, Agronomic management, Climate change adaptation, Soil water retention

Significance | This review explores drought stress mitigation in potatoes through physiological, biochemical, and agronomic strategies, ensuring sustainable crop production.

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1. Introduction

Environmental stresses, encompassing biotic factors such as diseases, insect infestations, and weeds, as well as abiotic influences like extreme temperature, water scarcity, solar radiation, and salinity, significantly affect plant growth and productivity. These stressors, combined with the physical and chemical characteristics of soil and air, represent major constraints on agricultural productivity, often reducing yields by over 50% for many staple crops. Global water scarcity and increasing soil salinization are particularly alarming, with projections indicating that 30% of arable land could be affected by 2021 and over 50% by 2050. Among abiotic stressors, drought is the most critical threat to global food security, disrupting plant growth, physiological processes, and overall productivity (Chaves et al., 2003). Arid and semi-arid regions, which cover approximately 40% of the Earth's land area, face the greatest challenges due to water limitations (FAO, 2019). Potato (*Solanum tuberosum*), the fourth most significant food crop after maize, rice, and wheat, is particularly sensitive to drought

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stress due to its shallow root system, which limits its water uptake capacity. Even brief periods of water deficiency during the tuberization stage can significantly reduce tuber yield and quality. Stolon development and tuberization are especially vulnerable to soil water potential below -25 kPa, which directly impacts tuber initiation and growth (Jefferies & MacKerron, 1993). Drought stress shortens the potato's growth cycle, reducing tuber size and number, while also impairing physiological functions like photosynthesis and leaf expansion. These combined effects lead to decreased productivity and compromised tuber quality (Gregory & Simmonds, 1992).

Historically, potatoes originated in the Andean regions of South America, where they were domesticated around 8,000 years ago. Spanish conquistadors introduced potatoes to Europe in the late 16th century during the Columbian Exchange. Despite initial success, monoculture practices led to the devastating Irish Potato Famine caused by late blight (*Phytophthora infestans*). Since then, breeding efforts have focused on developing high-yielding, disease-resistant cultivars (Bradshaw, 2021). Between 1961 and 2019, global potato production increased from 270 million to 370 million tonnes, despite a reduction in harvested area, primarily due to advancements in cultivar yield potential (FAO, 2020). China, India, Russia, and the United States are the leading producers, with Europe ranking second in production volume (FAO, 2020).

Climate change exacerbates the challenges posed by drought stress on potato cultivation. Although potatoes are relatively water-efficient, requiring only 105 liters of water per kilogram compared to rice (1,408 liters), wheat (1,159 liters), and maize (710 liters) (Renault & Wallender, 2000), they are highly susceptible to water stress. Effective irrigation strategies, soil management practices, and climate-resilient cultivars are essential to mitigate these challenges. Adaptive measures, such as mulching and optimized planting schedules, can help improve soil water retention and ensure sustainable potato production under changing climatic conditions (Vos & Haverkort, 2007).

Understanding the physiological, biochemical, and ecological responses of potatoes to drought stress is crucial for developing sustainable agricultural practices. These insights will help address the dual challenges of ensuring food security and adapting to climate change, particularly in regions where water scarcity threatens crop productivity.

2. Historical Perspective of Potato Cultivation

The cultivation of potatoes traces its roots to the New World, where wild ancestors of the *Solanum tuberosum* species still grow. Potatoes were first cultivated in South America approximately 8,000 years ago, with their domestication likely occurring in the Andean region (Spooner et al., 2004). The Spanish conquistadors introduced potatoes to Europe during the Columbian exchange in the 16th century, and by the end of the century, they reached Ireland and the United Kingdom. Despite being a staple crop for much of the 17th century, potato cultivation in Europe remained limited until the 18th century. Unfortunately, monocultural farming practices and a lack of crop diversification led to devastating outbreaks of late blight in Ireland, which decimated potato harvests (Lutaladio & Castaldi, 2009). This event spurred breeders to focus on developing high-yielding, disease-resistant potato cultivars to ensure stable production.

From 1961 to 2019, global potato production grew significantly, increasing from 270 million tonnes to 370 million tonnes, despite a reduction in the harvested area from 22.14 million hectares to 17.34 million hectares during the same period (Renault & Wallender, 2000) (Figure 1). This increase in output can be attributed to advancements in breeding and agricultural techniques, which have enhanced the yield potential of potato cultivars. Over the past 50 years, the yield potential of potato varieties has increased by 58.7%. Currently, the largest producers of potatoes are China, India, Russia, the United States, and Ukraine, with Poland, Germany, Belarus, the Netherlands, and France following closely behind. Europe produces 125.43 million tonnes of potatoes, making it the second-largest producer globally, after Asia.

Potatoes are an essential crop globally, providing significant food security and economic value, especially in both industrialized and developing countries (Lutaladio & Castaldi, 2009). One of the key reasons for their importance is the high proportion of the plant that is edible—approximately 85% of the biomass of a potato plant is consumable, compared to only 50% in grains (Spooner et al., 2004). In Europe, potatoes occupy 4.69 million hectares of land, ranking ninth in terms of area under cultivation and fourth in terms of production, following maize, wheat, and sugar beet. Notably, potatoes yield the second-highest amount per unit area in Europe, after maize (Lutaladio & Castaldi, 2009).

2.1 Climate Change and Potato Water Use Efficiency

Potatoes are considered a relatively water-efficient crop. The production of one kilogram of potatoes requires only 105 liters of water, significantly less than the other three most produced crops—rice, wheat, and maize—which require 1,408 L, 1,159 L, and 710 L of water per kilogram, respectively (Renault & Wallender, 2000). However, despite their relatively low water requirements, potatoes are highly susceptible to drought stress, which can negatively impact yield and quality (Banik et al., 2016). This vulnerability is partly due to their high water demands for optimal growth, making them sensitive to soil moisture deficits.

Water is a critical and increasingly scarce resource in agriculture, and efficient water use is crucial for crop production, particularly in regions experiencing water stress (Mansour & Abu El-Fotoh, 2018). For potatoes, maintaining adequate soil moisture is vital for maximizing yields. Different irrigation techniques, including mulching and tailored irrigation schedules, have been shown to improve potato growth and yield by minimizing moisture stress (Mansour & Abu El-Fotoh, 2018). Optimal irrigation levels have a direct impact on potato tuber output and vegetative growth, particularly when crop evaporation levels are carefully managed (Shimshi et al., 1983). Additionally, planting dates are critical for successful potato cultivation, as they determine the temperature and photoperiod that influence tuberization. Potatoes require long days for vegetative growth and short days for tuberization, with optimal temperatures ranging from 15 to 25°C for photosynthesis and canopy development. Temperatures above 29°C can inhibit tuberization, highlighting the importance of managing planting times and temperature conditions (Banik et al., 2016; Mansour & Abu El-Fotoh, 2018).

Climate change is expected to have a significant impact on potato production by altering temperature, precipitation, and growing seasons. Extended periods of high temperature during the potato growing season can reduce yields due to inhibited tuber development and changes in the length of the growing season (Adekanmbi et al., 2023). While potatoes are adaptable to varying conditions, extreme temperatures and excessive humidity can negatively affect their growth (Meligy et al., 2020). Conversely, the potential for drought stress in regions experiencing warmer and drier conditions may limit productivity unless adaptive strategies such as drought-tolerant varieties, efficient irrigation practices, and proper timing of cultivation are employed (Adekanmbi et al., 2023; Begna, 2021).

However, the historical significance and evolution of potato cultivation have shaped its role as a global food source. However, its productivity is increasingly influenced by climate change, which affects water availability and temperature conditions necessary for optimal growth. Research on water use efficiency and the development of drought-resistant cultivars will be crucial to ensuring potato production in the face of future climatic challenges.

3. Drought and Its Global Impact on Crops

Drought is one of the most significant abiotic stressors impacting global agricultural production. It is a key limiting factor for crop growth and yield, causing extensive losses in both developed and developing nations. Drought, caused by insufficient precipitation and irregular weather patterns, leads to moisture stress in plants, limiting their ability to perform essential metabolic processes. This phenomenon is one of the primary threats to food security globally, as crops struggle to meet their full genetic potential under water-deficit conditions (Began, 2021). Additionally, drought interacts with other stressors such as soil salinity, physical soil properties, and extreme temperatures, further exacerbating its negative effects on agricultural productivity (Jefferies & Mackerron, 1993).

Abiotic stress in crops refers to a combination of environmental factors that prevent plants from reaching their genetic potential. Among these stressors, drought stands out due to its widespread and devastating impact on crop yields worldwide (Dietz et al., 2021). Crop productivity is primarily influenced by water availability, particularly during critical growth stages such as germination, flowering, and maturation. Insufficient water not only affects plant growth but also disrupts key physiological functions, such as photosynthesis and nutrient uptake, leading to reduced crop yields (Mansour & Abu El-Fotoh, 2018). In fact, drought-related yield losses in field crops typically range from 30% to 90%, depending on the crop type and the severity of the drought (Began, 2021). Different crop parts—such as roots, shoots, leaves, fruits, and seeds—exhibit varying degrees of sensitivity to water scarcity, and drought can influence crop output differently during various developmental phases (Ibrahim et al., 2024).

One of the most notable responses to drought stress in plants is reduced leaf area, stunted root growth, and decreased photosynthetic efficiency. Water deficit leads to dehydration, which directly affects plant metabolism, stunting growth and reducing productivity (Hill et al., 2021). Water deficit also leads to a reduction in the plant's ability to regulate transpiration and the efficiency with which it uses water, further compounding stress (Nasir & Toth, 2022). The impacts of drought are particularly severe when water scarcity coincides with high temperatures, as this combination can exacerbate cellular damage and reduce water-use efficiency (Fang et al., 2024).

Effect of Drought Stress on Potato

Among the many crops vulnerable to drought, potatoes (Solanum tuberosum L.) are highly susceptible, with drought stress leading to significant yield reductions. Potatoes, which possess a shallow root system, struggle to absorb moisture from deeper soil layers, especially during prolonged dry spells. The lack of sufficient water during critical growth stages, such as tuber initiation and bulking, severely hampers the crop's productivity. Drought stress during these stages results in smaller and fewer tubers, ultimately reducing both the quantity and quality of the yield (Banik et al., 2016; Ibrahim et al., 2024).

Potatoes go through several distinct growth phases, including plant establishment, stolon initiation, tuber initiation, bulking, and maturity. Water deficits during the early stages of tuber development lead to a shorter growth cycle, adversely affecting tuber size and quality. In addition to decreased yield, drought also impairs photosynthetic activity, reduces leaf expansion, and accelerates leaf senescence (Saravia et al., 2016). The physiological effects of drought, such as a decrease in the rate of photosynthesis, negatively impact tuber bulking, one of the most critical periods for potato growth (Hill et al., 2021). As a result, the crop's ability to store energy and produce high-quality tubers is compromised, leading to significant yield losses.

The drought-induced reduction in potato yield and quality is a major concern for agricultural production worldwide, especially in regions where water scarcity is a growing issue. Understanding the physiological, biochemical, and molecular mechanisms that underlie potato responses to drought is crucial for developing drought-tolerant varieties and improving agricultural sustainability (Fang et al., 2024). Moreover, breeding strategies focused on enhancing water-use efficiency and improving drought tolerance in potatoes could help mitigate the adverse effects of drought and increase yield stability in the face of climate change (Banik et al., 2016).

Drought is a global challenge that significantly affects agricultural productivity, with profound implications for food security. Its impact on crops like potatoes, characterized by reduced water availability during critical growth stages, highlights the urgent need for drought management strategies. By improving our understanding of plant responses to drought stress and developing more resilient crop varieties, it may be possible to mitigate some of the negative effects of drought and ensure a stable food supply in the future.

4. Effects of Drought on Canopy Development, Root Growth, and Tubers in Potatoes

Drought stress significantly affects potato cultivation, primarily by impacting canopy development, root systems, and tuber growth, thereby influencing overall yield and quality. Understanding these effects is essential for enhancing drought tolerance in potatoes and improving agricultural practices in water-scarce regions. This review highlights the effects of drought on potato canopy architecture, leaf responses, root and stolon development, as well as tuber mass and quality, with an emphasis on identifying cultivar-specific responses to drought stress.

4.1 Leaf and Canopy Responses

Potato canopy architecture is highly susceptible to drought stress. The primary morphological response to drought is a reduction in leaf size, which can significantly hinder photosynthesis and reduce the plant's ability to synthesize carbohydrates. Drought conditions reduce leaf expansion rates and restrict the formation of new leaves, ultimately accelerating leaf senescence (Banik et al., 2016). Leaf area reduction is particularly noticeable, and while the impact on leaf dry weight is important, changes in leaf area are more pronounced. A decrease in leaf area often correlates with an increase in vein density, which can help improve the potato plant's resistance to drought. Vein density is known to enhance photosynthetic efficiency by improving the leaf's hydraulic conductivity, thus allowing for better water transport (Banik et al., 2016).

Water stress also negatively impacts the water potential in potato leaves, leading to a reduction in leaf extension. Studies have shown that a leaf water potential below -1.0 MPa can halt leaf growth completely (Jefferies & Mackerron, 1993). Moreover, the relative water content (RWC) at -1.0 MPa can serve as a key indicator to distinguish drought-resistant from sensitive potato cultivars. For instance, the cultivar 'Raritan' exhibits higher RWC than the drought-sensitive cultivar 'Shepody', both in young and mature leaves, which contributes to better drought tolerance (Jefferies & Mackerron, 1993).

4.2 Effects of Drought on Roots, Stolons, and Tubers

Potato plants are particularly vulnerable to drought due to their shallow root systems, which have limited capacity to absorb water. Drought stress affects the growth and development of potato roots, stolons, and tubers, resulting in decreased yield and quality (Gregory & Simmonds, 1992). Water scarcity during the tuberization stage has the most significant impact, as it delays tuber formation and reduces both the number and growth of tubers (Hill et al., 2021). Research indicates that water stress during the early stages of tuber initiation results in a lower tuber count, which is detrimental to overall yield.

The root system also shows variable responses to drought. While some studies suggest an increase in total root length and dry mass under water stress conditions (Fang et al., 2024), others report a decrease or no significant change (Hill et al., 2021). Similarly, stolon growth may either increase or decrease depending on the severity and timing of the drought. These variations indicate that potato cultivars may have different strategies to cope with drought stress, and understanding these responses can help in selecting drought-resistant varieties.

4.3 Effects of Drought on Fresh and Dry Tuber Mass

Drought stress has profound effects on tuber mass and water content, which ultimately influence the quality and yield of potatoes. Tuber weight is strongly influenced by water availability, as water content accounts for up to 80% of the fresh tuber mass in some cultivars (Jefferies & Mackerron, 1993). Long-term water stress, starting at emergence and continuing through to harvest, can cause a significant reduction in tuber water content, as seen in the cultivar 'Maris Piper', where water content dropped by 69% under drought conditions (Jefferies & Mackerron, 1993).

In addition to fresh tuber mass, the number of tubers produced is also affected by drought. Water stress during the entire growing season or at critical stages, such as emergence, can lead to a reduction in tuber number (Nasir & Toth, 2022). Short-term drought stress, especially when it occurs early in the growing season, can cause a marked decrease in tuber count. However, the timing of the stress is crucial—late-stage drought stress appears to have less impact on tuber count but can still affect tuber dry matter (Hill et al., 2021).

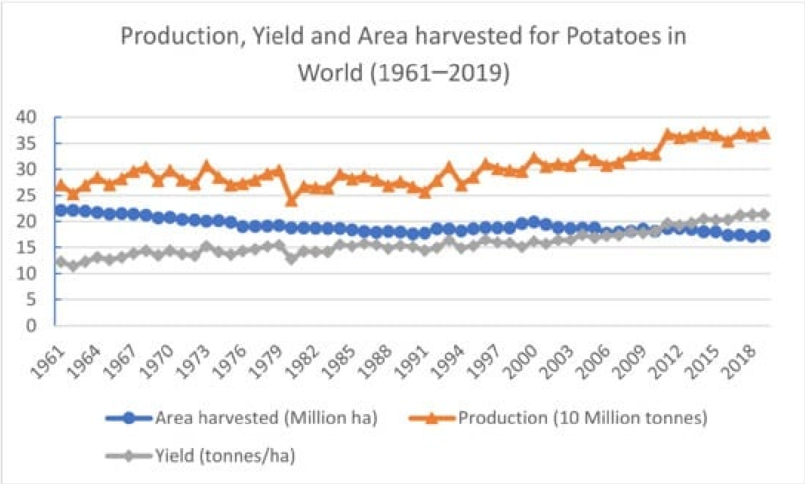

Figure 1. World potato production, yield, and area harvested during 1961–2019 [3].

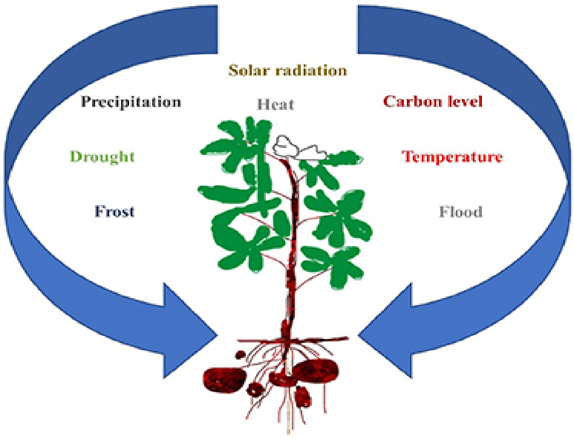

Figure 2. Variables impacting potato yields.

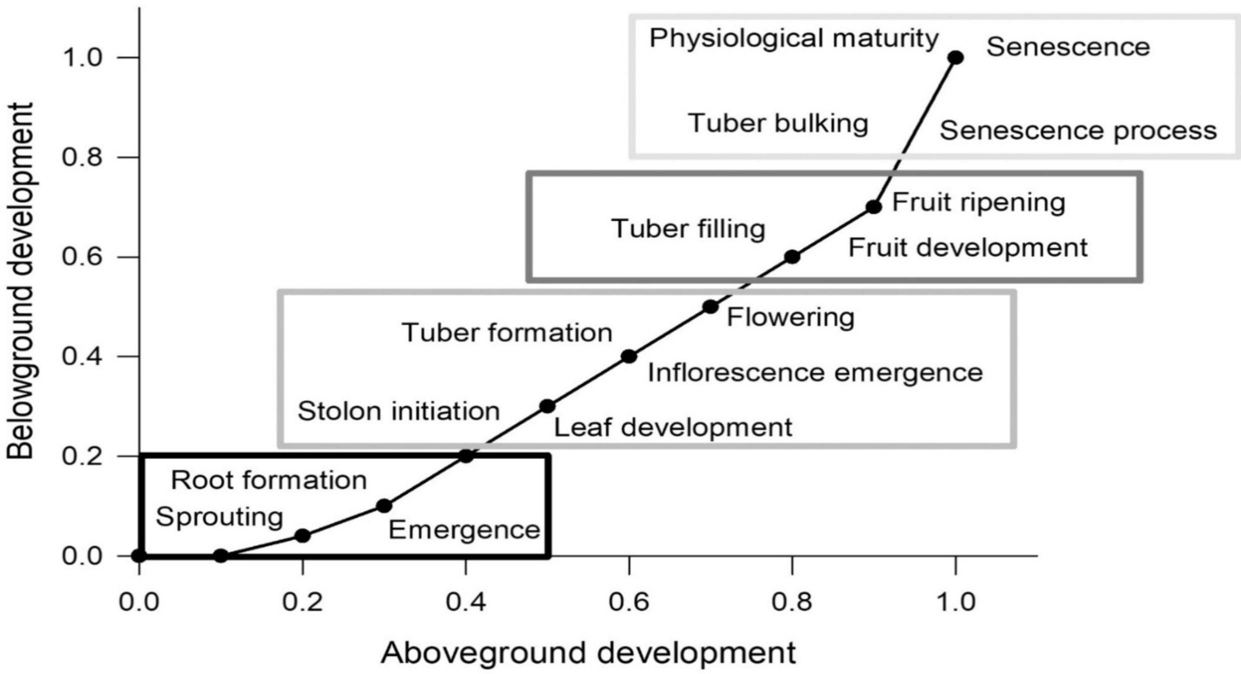

Figure 3. Above ground and Below ground development

Drought also indirectly impacts the dry mass of tubers by reducing photosynthetic activity in the leaves, which limits the translocation of assimilates to the tubers. The dry mass of tubers is a critical indicator of both yield and quality, particularly for processing cultivars. Drought stress leads to a decrease in the total dry mass of tubers, which ultimately reduces the tuber's suitability for processing (Banik et al., 2016). Furthermore, water stress impairs the ability of potato plants to efficiently distribute assimilates from the canopy to the tubers, which diminishes both the quantity and quality of the tuber crop (Nasir & Toth, 2022).

Drought stress severely affects various aspects of potato growth, including canopy architecture, leaf physiology, root and stolon development, and tuber quality. While some potato cultivars exhibit better resilience to drought than others, the effects of water scarcity are profound across all growth stages. Understanding the morphological and physiological responses of different potato cultivars to drought stress is crucial for breeding and selecting drought-resistant varieties. Moreover, improving irrigation practices and enhancing drought acclimation mechanisms can help mitigate the negative effects of water stress on potato production, ensuring stable yields and high-quality tubers in water-limited environments.

5. Drought Stress Avoidance Strategies in Potato Crops: Mechanisms and Mitigation Techniques

Drought stress is a major challenge for crop production, particularly in regions prone to terminal droughts, which occur late in the growing season. One of the primary strategies for coping with such environmental stress is drought escape, a mechanism whereby plants complete their life cycle quickly enough to avoid prolonged exposure to drought. This technique, common among natural plant populations, is particularly relevant for crops like potatoes (Solanum tuberosum), where early flowering and a shorter vegetative phase are crucial for successful yield under terminal drought conditions. Over the last century, breeders have developed cultivars that flower earlier, thereby improving productivity in regions with Mediterranean climates that experience recurrent drought. As global climate change accelerates, early-blooming crops may become more common as they help mitigate the risks associated with terminal drought stress (Saravia et al., 2016). These advances in crop breeding are likely to become more widespread in agricultural systems worldwide.

In potatoes, drought stress triggers a series of physiological and biochemical responses controlled by genes encoding regulatory and functional proteins. These responses are essential for maintaining healthy plant development, preventing wilting, and reducing water loss. A key player in the drought stress response is abscisic acid (ABA), a plant hormone involved in stress signaling. ABA promotes the expression of genes associated with drought resistance and facilitates the closure of stomata, reducing water loss through transpiration. Additionally, ABA is linked to seed dormancy, fruit development, and general growth. In response to drought stress, plants typically increase ABA production or sensitivity, which initiates a cascade of physiological adaptations. The activation of both ABA-dependent and ABA-independent pathways influences gene expression that contributes to stress tolerance (Mansour & Abu El-Fotoh, 2018).

Among the central components of the ABA signaling pathway are SNF1-associated protein kinases (SnRK2s), which play a critical role in the regulation of drought stress responses. When ABA binds to its receptor (PYR/PYLs/RCAR), it forms complexes that inhibit SnRK2s via PP2Cs, key negative regulators of ABA signaling. Under stress, Raf-type protein kinases activate SnRK2s, which, in turn, phosphorylate transcription factors such as ABFs and ABI5. These transcription factors regulate the expression of genes, including WRKY and heat shock proteins (HSPs), that are involved in drought stress tolerance (Fang et al., 2024). Studies have shown that upregulating the expression of DREB1A, a gene involved in the ABA-dependent pathway, enhances the drought tolerance of potatoes (Banik et al., 2016). Furthermore, transcription factors like ABF influence ABA signaling and contribute to the plant's ability to withstand both salt and drought stresses (Muñiz García et al., 2020).

To mitigate the effects of drought stress, modern agricultural practices have focused on a combination of enhanced agronomic techniques and the selection of potato genotypes that are better adapted to specific climatic conditions. Research has shown that soil management practices, such as mulching, tillage, residue management, and organic matter incorporation, can significantly reduce the negative impacts of drought on crop productivity. For instance, soil tillage affects evapotranspiration and water infiltration, with certain tillage techniques improving crop water availability (Meligy et al., 2020). Organic mulches, which control evaporation and enhance water retention, can help mitigate the effects of drought by absorbing water vapor and increasing water penetration rates. Additionally, the addition of animal manure and carbon-rich wastes to the soil improves its structure and water-holding capacity, providing further relief to crops under water stress (Sekhon et al., 2010). Compost and biochar have also been identified as effective amendments for improving soil structure, enhancing water retention, and reducing the impact of drought stress on crops like potatoes (Daccache et al., 2012).

Another critical aspect of drought stress management in potatoes is the role of nutrient management. Studies have shown that nitrogen management plays a significant role in enhancing the soil's water retention capacity, which is crucial for mitigating drought-induced stress. Furthermore, the application of inorganic nutrients such as nitrogen (N), phosphorus (P), potassium (K), and zinc (Zn) has been found to reduce the effects of drought stress and improve potato yield (Figure 2). Similarly, the foliar application of silicon has been shown to increase potatoes' resistance to drought by improving the strength of plant cell walls and enhancing root water uptake (Jefferies & Mackerron, 1993). Fertilizing with micronutrients such as boron (B) and manganese (Mn) also has positive effects on potato yield and micronutrient concentration under drought conditions (Nasir & Toth, 2022).

Climate change is expected to exacerbate the frequency and severity of abiotic stress events, including drought, in agricultural systems. This is particularly concerning for crops like potatoes, which are vulnerable to water stress due to their shallow root systems. However, recent research has shown that cultivar type and canopy growth are equally important factors influencing the drought tolerance of potatoes (Begna, 2021). While late-maturing potato cultivars may be suitable for areas that experience terminal droughts, mid-maturing cultivars with thicker, larger leaves may offer better drought tolerance in regions with prolonged dry periods (Jefferies et al., 1989). These findings underscore the importance of breeding and selecting potato cultivars that are specifically suited to the climate conditions of a given region.

6. Conclusion

In conclusion, drought stress avoidance in potatoes involves a combination of genetic, physiological, and agronomic strategies aimed at improving water use efficiency and ensuring yield stability. Genetic advances in breeding early-blooming cultivars and enhancing drought tolerance through ABA signaling pathways have shown promise in improving potato production under water-limited conditions. Additionally, the implementation of soil and nutrient management practices, as well as the careful selection of appropriate cultivars, plays a crucial role in mitigating the impact of drought stress on potato crops. As climate change continues to challenge global food production, these strategies will be essential for sustaining potato yields and ensuring food security in drought-prone regions. Agronomic practices such as biochar application, nutrient management, and genotype selection offer practical solutions for mitigating drought effects. Future research should focus on breeding stress-tolerant cultivars and refining agronomic practices to address climate change-induced challenges and ensure stable potato production under water-limited conditions.

Author contributions

S.S. conceptualized the study, defined its objectives, and supervised the research. A.T. conducted the literature review, managed references, and contributed to manuscript drafting. S.S. performed the final revisions. Both authors reviewed and approved the final manuscript for submission.

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Competing financial interests

The authors have no conflict of interest.

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