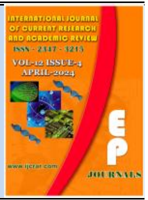
Int.J.Curr.Res.Aca.Rev.2024; 12(4): 52-59

EXCELLENT PUBLISHERS

International Journal of Current Research and Academic Review

ISSN: 2347-3215 (Online) Volume 12 Number 4 (April-2024)

Journal homepage: http://www.ijcrar.com



doi: https://doi.org/10.20546/ijcrar.2024.1204.007

Response of Coffee Plants to Drought stress: A Review Article

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Abstract

Ethiopia, the origin and diversity center of Arabica coffee is facing low national average yield due to production constraints, including drought. Drought and unfavorable temperatures significantly impact coffee production, causing water deficit or stress in plants. Environmental factors like water deficit, temperature extremes, salinity, toxic metals, and UV radiation also impact plant growth and productivity. The aim of this paper is to review the response of coffee under drought stress conditions. Plants exhibit diverse drought tolerance capacity due to their unique genetic constitution, influenced by various morphological, physiological, and biochemical mechanisms. Drought-tolerant plants decrease shoot growth, leaf area, while increasing leaf thickness, deep root and root-shoot ratio. They self-balance drought by regulating turgor and reducing water loss by using stomatal closure, utilizing adaptations like osmotic adjustment. Drought conditions in plants produce essential metabolites like sugars, amino acids, polyols, amides, and secondary metabolites, with drought-tolerant coffee genotypes having elevated biochemical composition. Plants accumulate compatible solutes and quaternary ammonium compounds. In general, drought is significantly impacts on coffee productivity. Therefore, to address this issue, research should be focused on developing drought tolerant coffee varieties.

Article Info

Received: 25 February 2024
Accepted: 30 March 2024
Available Online: 20 April 2024

Keywords

Coffee, Compatible solutes, Drought, Phytohormone, Quaternary ammonium compounds.

Introduction

Ethiopia, the origin and diversity center of Arabica coffee faces low national average yield due to production constraints, including drought (Anthony *et al.*, 2001; Gray *et al.*, 2013). Drought and unfavorable temperatures significantly impact coffee production, causing water deficit or stress in plants. This is particularly prevalent in Ethiopia, where Arabica coffee production is being affected. Environmental factors like water deficit, temperature extremes, salinity, toxic metals, and UV radiation also impact plant growth and productivity (Pinheiro *et al.*, 2005; Da Matta and Ramalho, 2006).

Plants exhibit diverse drought tolerance capacity due to their unique genetic constitution, influenced by various morphological, physiological, and biochemical mechanisms in their growth and development (Pinheiro *et al.*, 2004; Pinheiro *et al.*, 2005; Razmjoo *et al.*, 2008). Studies on Arabica and Robusta coffee's morphology, physiology, and biochemistry in relation to drought have been extensively studied. Importance of maximizing water uptake through deep roots or minimizing water loss through stomatal closure and small leaves in drought-tolerant plants (Carr, 2001; DaMatta, 2004; DaMatta and Ramalho, 2006; D'Souza *et al.*, 2009; Cheserek and Gichimu, 2012). Drought-tolerant plants decrease shoot growth, leaf area, while increasing leaf thickness and root-shoot ratio. The species self-balance drought by regulating turgor and reducing water loss, utilizing adaptations like osmotic adjustment to maintain water relations under osmotic stress (Pinheiro *et al.,* 2004; Castro *et al.,* 2007; Razmjoo *et al.*, 2008; Farooq *et al.,* 2009). According to Praxedes *et al.,* (2006) and Silvente *et al.,* (2012), drought conditions in plants produce essential metabolites like sugars, amino acids, polyols, amides, and secondary metabolites, with drought-tolerant coffee genotypes having elevated biochemical composition. Plants accumulate compatible solutes such as proline, sucrose, polyols, trehalose and quaternary ammonium compounds such as glycine betaine, alinine betaine, proline betaine to protect and maintain membrane integrity (Serraj and Sinclair, 2002; Ashraf and Foolad, 2007; Shamsul *et al.,* 2012). In addition, phytohormones are important mediators of environmental stresses such as drought (Ali *et al.*, 2020). Therefore, the objective of this paper is to review the response of coffee under drought stress conditions.

Impact of drought on coffee

Water is a crucial limiting factor affecting crop productivity, affecting physiological and biochemical processes like photosynthesis and solute transport and accumulation. Water stress significantly impacts crop productivity by limiting physiological and biochemical processes, including photosynthesis and solute transport, and decreasing plant growth and productivity by reducing cell division and elongation. Water deficit stress significantly impedes the growth of leaves in plants, resulting in a range of morphological alterations. These alterations encompass a reduction in shoot growth and the production of dry matter in shoots, consequently impacting leaf expansion, lifespan, and the overall well-being of the plant. This phenomenon has been documented in research conducted by Davies *et al.,* (2000) and Hassan *et al.,* (2003), as well as in studies carried out by Zegbe *et al.,* (2004) and Wakrim *et al.,* (2005) concerning the yield of dry matter in shoots. Coffee, despite its economic importance in developing countries like Ethiopia, suffers from low productivity due to water deficit stress, a major factor contributing to low yields and poor crop quality, similar to other crop (Rena *et al.,* 1994; Barros *et al.,* 1997). Drought significantly impacts coffee plant growth and development, decreasing soil water potential and hydraulic conductivity, affecting physiological and biochemical functions, and causing changes in coffee's chemical composition (Divya, 2008).

Water depletion can cause damage, growth inhibition, and death. Biochemical constraints from photo inhibition and photo oxidation can limit photosynthetic CO_2 fixation, but drought-tolerant genotypes may reduce oxidative damage and cell death due to increased antioxidant system activity, including enzymatic antioxidants, which may decrease chlorotic or necrotic lesions on damaged leaves. Water shortages during prolonged dry spells impact coffee crop growth and development. Short-term soil water deficits may cause reduced stomatal conductance and lower net carbon assimilation, but prolonged drought stress leads to smaller leaf area and altered assimilate partitioning, directly reducing crop yield (DaMatta, 2003; Abayneh and Masresha, 2015).

How coffee plants respond to drought stress?

In terms of morphology

Plants adjust to water stress by changing biomass allocation between roots, stems, and leaves, with decreased growth parameters being key stress avoidance and tolerance mechanisms (Dias *et al.*, 2007; Tesfaye *et al.,* 2014). Drought-adapted plants often have deep, vigorous root systems and larger root dry mass, as per a study. Coffee exhibits a deeper root system and larger root dry mass in drought-tolerant clones compared to drought-sensitive ones (Pinheiro *et al.*, 2005; DaMatta and Ramalho, 2006). Deep roots and biophysical control of water loss can help plants maintain a positive water status by increasing soil water catchment and reducing leaf area (DaMatta *et al.,* 2003; Cheserek and Gichimu, 2012) reviewed traits for drought and heat-tolerant coffee genotypes.

Stress avoidance mechanisms include decreased shoot growth, increased leaf thickness, root density, and root: shoot ratio due to increased photo assimilate allocation to the root system and soil moisture depletion (Poorter and Nagel, 2000; Kang *et al.*, 2001; Mingo *et al.*, 2004; Tesfaye *et al.*, 2014). Plant water stress develops slower in drought-tolerant clones than drought-sensitive ones, with deeper root systems allowing them to access water at the bottom of pots.

Root characteristics and growth are crucial for maintaining plant water supply. However, coffee plants with extensive root systems are vulnerable to drought due to their hydraulic system and stomatal behavior (Blum, 2005; Pinheiro *et al.*, 2005; Burkhardt *et al.*, 2006; Worku and Astatkie, 2010). Arabica coffee cultivars with open and compact crown habits were found to escape soil moisture stress (Taye, 2006) through deeper and shallow root distribution as well as leaf shedding and rolling, respectively.

In terms of physiology

Plants have physiological adaptation mechanisms, including stomatal closure and osmotic adjustment, which help maintain turgor and cell volume during soil drying, and are essential for drought tolerance (Heuer and Nadler, 1998; Sanchez *et al.*, 1998). It adapt to drought by closing stomata, regulating cell volume, and minimizing water loss. This promotes tissue volume, photosynthetic gain, and carbon balance, minimizing water loss (Stoll *et al.*, 2000; Tausend *et al.*, 2000a; Carr, 2001; Mingo *et al.*, 2004).

Arabica coffee genotypes exhibit varying drought adaptation mechanisms, including stomatal control, soil water extraction efficiency, and plant water use, and biomass allocation. Tolerance genotypes in coffee plants maintain net photosynthesis and processes during water stress, reducing transpiration loss and exhibiting better recovery rates, leaf area and steep leaf inclinations (D`Souza *et al.*, 2002; Da Matta *et al.*, 2003; Pinheiro *et al.*, 2005). Chlorophyll, a pigment responsible for photosynthesis, increases under water stress conditions (chlorophyll a), while high chlorophyll b content indicates drought tolerance (Carr, 2001; DaMatta and Ramalho, 2006; Dias *et al.*, 2007). Osmotic adjustment is a crucial survival mechanism for coffee plants under drought stress, affecting yield stability. Maintaining high relative water content under water deficit is more important than osmotic adjustment for drought tolerance. Arabica coffee has more stomatal limitations to photosynthesis, but survival may be enhanced under prolonged droughts (DaMatta and Rena, 2001; DaMatta, 2004). In addition, relative water content is a key indicator of drought tolerance, with drought-tolerant plants maintaining higher RWC levels. Coffee, for instance, exhibits high relative water content under dehydrating conditions (DaMatta *et al.*, 1993).

Compatible solutes and quaternary ammonium compounds

Plants accumulate compatible solutes, small organic metabolites soluble in water, to prevent water loss, maintain cell turgor, regulate osmo-regulation, and protect enzymes from stress (Bohnert *et al.*, 1995). Drought-tolerant coffee genotypes have higher biochemical compositions, including free proline, total protein content, epicuticular wax, soluble sugars, nitrate reductase activity, and glycine-betaine. Accumulation of compatible solute is crucial for osmoprotectants under drought conditions (Sakamoto and Murat, 2002; Khalid, 2006; Praxedes *et al.*, 2006; D' Souza *et al.*, 2009; Giri, 2011; Tesfaye *et al.*, 2014; Somashekhargouda *et al.*, 2019). In addition, phytohormones are important plant growth regulators and mediators of environmental stresses such as drought which adversely influence crop yield and pose threats to global food security (Ali *et al.*, 2020).

Compatible solutes

Plants adapt to abiotic stress through osmotic adjustment, involving inorganic ion uptake and proline accumulation. Proline, a proteinogenic amino acid, is crucial for protecting sub-cellular structures, macromolecules, and osmotic adjustment, enhancing enzyme activities, protecting nitrate reductase, and regulating development and metabolic signaling networks (Kishor *et al.*, 2005; Mishra and Dubey, 2006; Haudecoeur *et al.*, 2009; Szabados and Savoure, 2010; Wubishet, 2019). Proline, a universal osmo-protectant, is crucial for drought-tolerant coffee genotypes, acting as an osmolyte and antioxidant. Proline accumulation in coffee leaves and roots increases under oxidative stress, drought, high salinity, light, UV irradiation, and heavy metals conditions. Four Arabica coffee cultivars, Dawairi and Tessawi, exhibit higher levels of proline and favorable biochemical composition, making them better stress-tolerant. This finding supports the importance of drought tolerance in coffee production (Tounekti *et al.*, 2018). Difficult drought-tolerant Canephora coffee clones accumulate more proline (Silva *et al.*, 2010; Santos and Mazzafera, 2012; Tounekti *et al.*, 2018).

Robusta coffee clones IC-6 and IC-3 are drought-tolerant due to higher proline accumulation and leaf proline concentration. They are also more tolerant under higher light and low water conditions, with proline content increasing significantly under water stress conditions (Paulo *et al.*, 2012; Tesfaye *et al.*, 2014; Somashekhargouda *et al.*, 2019). Liu *et al.*, (2016) found that alternate and fixed drip irrigation had 69.6% and 204.6% higher proline content compared to conventional drip irrigation. Drought tolerance is correlated with increased leaf proline concentration, which is associated with decreased leaf water potential and osmotic adjustment in cells (Fabro *et al.*, 2004; Haudecoeur *et al.*, 2009; Szabados and Savoure, 2010). Proline levels in stressed coffee cultivars increased significantly, serving as a biochemical marker of drought stress. Proline accumulation is considered a tolerance mechanism and adaptation of genotypes to drought stress, playing a crucial role in osmotic adjustment in crops (Hassan *et al.*, 2003; Tesfaye *et al.*, 2014) and higher in leaves of drought-tolerant coffee canephora, indicating plant tolerance to water deficits. High proline accumulation increases bound water capacity (Divya, 2008; Renukaswamy *et al.*, 2008; Silva *et al.*, 2010; Santos and Mazzafera, 2012).

Soluble sugars, such as sucrose, glucose, and fructose, are crucial for maintaining plant growth and water content under drought stress. Arabica coffee cultivars, Dawairi and Tessawi, have higher total soluble sugar content. Fixed drip irrigation with NSAP treatment improves water use efficiency by preventing dehydration of cells and tissues. This effect is also observed in wheat (Rosa *et al.*, 2009; Akcay, 2010; Nazaarli and Faraji, 2011; Liu *et al.*, 2016; Tounekti *et al.*, 2018). Water stress significantly increases total soluble protein in coffee and sorghum, with higher accumulation observed in drought-tolerant coffee genotypes and similar changes in soluble protein content in Sorghum (Divya, 2008; D' Souza *et al.*, 2009; Somashekhargouda *et al.*, 2019). D' Souza *et al.*, (2009) reported favorable changes in biochemical composition in drought-tolerant coffee genotypes, including increased total protein content.

Quaternary ammonium compounds

Nitrate reductase activity is crucial for plant metabolism and is used as a biomarker for plant stress. It is used to evaluate water stress on coffee. During stress, graft combinations maintained high nitrate reductase activity compared to pure line seedlings, indicating drought tolerance and improved nitrogen assimilation (Sivakumar *et al.*, 2017; Somashekhargouda *et al.*, 2019). Research indicates that nitrate reductase activity can predict genotypes' environmental adaptability under water stress, with Catuai and Nacional cultivars showing significant differences in nitrate reductase activity activity (Meguro and Magalhães, 1983). Glycine betaine is an amphoteric compound, stabilizes enzyme and protein complex structures, maintains membrane integrity, and plays a crucial role in plant cell responses to various stresses (Sakamoto and Murata, 2002). It is crucial in plants as a compatible solute under various environmental stress conditions, according to physiology, genetics, biophysics, and biochemistry (Farooq *et al.*, 2008). Plant cells respond to abiotic stresses by accumulating compatible solutes such as glycine-betaine in their cytosols. This accumulation of solutes plays a vital role in the plant's ability to cope with different stressors (Sakamoto and Murat, 2002; Giri, 2011).

Epicuticular wax is crucial for drought tolerance in coffee cultivars. It significantly increases in graft combinations and pure line seedlings under water stress conditions. It is also effective in drought resistance in other crops like sorghum (Somashekhargouda *et al.*, 2019). The Chandragiri variety showed higher epicuticular wax during stress conditions, possibly due to increased stress on the variety, as coffee plants typically accumulate epicuticular wax at stress. The plant cuticle, a hydrophobic layer enveloping primary plant organs, is composed of cutin and waxes. It regulates water loss, gas exchange, nutrient loss, radiation shielding, cooling, wind, and physical abrasion and epicuticular wax enhances water repellent properties. Changes in leaf cuticular wax compositions are observed in drought conditions, highlighting the importance of understanding its role under drought conditions (Bargel *et al.*, 2004; Yeats and Rose, 2013). Plants' drought tolerance is influenced by genetics, with drought-tolerant cultivars accumulating compounds like nitrogen, phosphrous, K, and Ca, increasing water capacity, regulating stomatal movement, and maintaining cell membrane integrity (Venkataramanam, 1985).

Phytohormone

Phytohormones are important plant growth regulators and mediators of environmental stresses such as drought which adversely influence crop yield and pose threats to global food security (Ali *et al.*, 2020). Abscisic acid is critical for plant development and can redesign various physiological and biochemical signal transduction cascades in plants to cope with environmental stresses particularly drought (Chaves *et al.*, 2003). Abscisic acid is a premier signal for plants to respond to drought and plays a critical role in plant growth and development.

Additionally it plays a critical role in bimolecular synthesis, senescence, seed germination, stomatal closure and root architecture modification (Trivedi *et al.*, 2016). Plants show a significant increase in abscisic acid levels under drought stress, changes in expression of genes, and induction of abscisic acid biosynthesis enzymes corresponding to mRNA level lead to enhanced abscisic acid accumulation. Abscisic acid is a prime mediator of drought (Boominathan *et al.*, 2004) and plays an important role in regulating plant growth, development, and responses to several environmental stresses (Zhu, 2002). Under water deficit, plants accelerate production of phytohormone abscisic acid to make stomatal closure and reduce transpiration rate that potentiate the crops drought tolerant (Bashir *et al.*, 2021).

Summary and Conclusion

Ethiopia, the birthplace and hub of diversity for Arabica coffee, is challenged by low national average yield due to production limitations, such as drought. Drought and adverse temperatures have a significant impact on coffee production, leading to water scarcity or plant stress. Arabica coffee varieties display a range of drought tolerance capacities due to their distinct genetic makeup, influenced by various morphological, physiological, and biochemical processes. Plants respond to water stress by altering biomass distribution among roots, stems, and leaves, with reduced growth parameters serving as crucial stress avoidance and tolerance mechanisms. Drought tolerant plants reduce shoot growth and leaf area, while increasing leaf thickness and root-shoot ratio. They manage drought stress by regulating turgor and minimizing water loss, utilizing adaptations like osmotic adjustment. Drought tolerant coffee varieties exhibit higher biochemical compositions, including free proline, total protein content, epicuticular wax, soluble sugars, nitrate reductase activity, and glycine-betaine and abscisic acid. The significant diversity in morphological, physiological, and biochemical characteristics among coffee species, which provides an opportunity to develope drought tolerance varieties.

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How to cite this article:

Wubishet Tamirat. 2024. Response of Coffee Plants to Drought stress: A Review Article. *Int.J.Curr.Res.Aca.Rev.* 12(4), 52-59. doi: https://doi.org/10.20546/ijcrar.2024.1204.007