Review Article

Effect of drought stress on leaf productivity and liquor quality of t~~T~~ea: A r~~R~~eview

ABSTRACT

Tea (*Camellia sinensis* (L.) Kuntze) is a highly valued plant known for its refreshing taste, medicinal properties, and health benefits. It is an evergreen shrub or small tree belonging to the Theaceae family. The productivity and quality of tea leaves and liquor are strongly influenced by edaphic ~~(soil)~~ and environmental factors. However, the cultivation of tea faces significant challenges due to the increasing occurrence of drought associated with global warming and climate change. In this review, we have summarized the potential effects of drought on the growth, productivity, and liquor quality of tea. Drought exerts substantial impacts on the physiological, biochemical, and morphological features of tea plants. For instance, under drought stress, there is a reduction in leaf activity, including chlorophyll production, photosynthetic rate, and CO_2 uptake. Drought periods also lead to decreased shoot initiation and extension rates. However, it is important to note that responses to drought can vary depending on factors such as tea variety, cultivar diversity, agricultural management practices, and study techniques. While drought-induced biochemical damage may occur, it is often reversible, and the plant can recover upon rehydration. Irrigation strategies employed during dry periods have been shown to have a significant positive effect on tea yields, making it a promising option for enhancing productivity in drought-prone regions. Furthermore, the cultivation of drought-tolerant tea cultivars, along with the application of micro and macro-nutrients, as well as hormone treatments, can contribute to improving the post-drought recovery process. Studying the influence of drought on tea productivity offers an opportunity for frontier research, aiming to understand the intricate relationship between tea leaf productivity and liquor quality. Additionally, investigating the factors that contribute to stress recovery in tea plants holds promise for enhancing cultivation practices and ensuring the sustainability of tea production in the face of changing climatic conditions.

Keywords: Abiotic stress, Camelia sinensis~~Tea~~, dry periods drought~~,~~-tolerant, rehydration *~~leaf productivity~~, ~~liquor quality~~*

1. INTRODUCTION

Camellia is a diverse genus consisting of 82 species, with the majority being native to the highlands of southeast India (Banerjee, 1992). Tea, which belongs to the *Camellia* genus, thrives in regions characterized by monsoons, where it benefits from high temperatures, a long growing season, and abundant rainfall. For optimal growth, tea plants require an average temperature of around 21 °C throughout the growing season, which ideally spans at least eight months. The combination of warm summers and frequent rainfall fosters rapid leaf reproduction, resulting in an increased number of annual pickings.

During the cool season, tea bushes enter a dormant phase hence no picking takes place;~~.~~ h~~H~~owever, in areas without distinct seasonal restrictions, such as Sri Lanka, picking can occur throughout the year. The highest yields are typically obtained in India and Bangladesh between June and September, coinciding with hot and rainy weather. However, the finest quality tea is often derived from earlier and later pickings when the climate is cooler and drier (Chand, 2014). Weather conditions play a crucial role in tea production, with droughts having a significant impact. Since tea plantations seldom rely on irrigation, droughts can lead to irreversible losses (Wijeratne, 1996).

Nowadays, drought has become a prevalent issue in tea cultivation in Bangladesh. It is considered one of the primary limiting factors that adversely affect both tea yield and quality. Climate models suggest that the frequency of drought episodes is expected to increase due to the long-term impact of global warming (Salinger et al., 2005). Each year, the productivity of tea is significantly hampered due to drought. The growth status of tea plants plays a crucial role in determining the quality and yield of tea. The yield of

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tea can be reduced by up to 40% as the leaves wilt under drought stress (Gupta et al. 2013). Wijeratne (1996) emphasizes that successful tea cultivation is highly dependent on various climatic conditions, including temperature, rainfall, humidity, and solar radiation.

Climate change is an ongoing and dynamic phenomenon with far-reaching implications. Previous research has demonstrated the value of studying individual perceptions of climate change based on seasonal patterns, providing insights into its effects. The impact of climate change extends to food and beverage crops worldwide, with significant consequences for both the environment and human well-being. While there have been numerous studies on the effects of climate change on crop yields, relatively few have focused on the impact on tea crop quality (Ahmed et al., 2019).

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Several studies, including those by Odada et al. (2008), Pachauri et al. (2014), and Campbell et al. (2016), have examined the effects of climate change on crops. Agricultural systems have experienced systematic changes in average climate conditions since 1950, including unprecedented multi-decadal warming, increased inter-annual temperature variability, changes in average precipitation, and more extreme weather conditions (Pachauri et al. 2014). Drought, a consequence of climate change, not only affects crop productivity but also alter crop quality. Crop quality encompasses various dimensions, such as nutritional and health attributes, sensory characteristics, phytonutrients, minerals, and bioactive food components (Mattos et al., 2014; Ahmed and Stepp, 2016). Tea is an excellent crop for examining the effects of climate change due to its status as a woody perennial that undergoes long-term effects spanning multiple decades. Tea, the botanical source of various tea beverages such as white, green, oolong, black, and pu-erh teas, was chosen as a study system in this review article due to its global prevalence in diets and production in over 50 countries on five continents (FAOSTAT, 2016). Overall, studying the effects of climate change on tea crop quality is crucial, as it provides valuable insights into the potential impacts on this significant agricultural product.

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2. SYSTEMATIC REVIEW METHODS

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To conduct a comprehensive review of the effect of drought stress on tea, a systematic approach was employed, focusing on two main themes: the effect of drought on tea leaf production and tea liquor quality. A total of 237 articles were initially identified and screened for relevance. After careful evaluation, 86 articles were selected and reviewed to gather relevant information for this review. To ensure a thorough search, two reputable databases, namely Google Scholar and Scopus, were utilized for article retrieval.

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The study specifically centered around tea (*C.*~~*amellia*~~ *sinensis* ~~L.~~) as the unit of analysis, investigating the effects of drought on tea leaf production and liquor quality. The search parameters employed encompassed key terms related to drought and tea, including leaf production, liquor quality, root traits, leaf traits, water potential, ABA content, micronutrients, proline, and cuticle modification. Research conducted by specialists in the respective subject areas was targeted during the search process.

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By following this systematic method and employing the specified search criteria, the review aimed to gather a comprehensive understanding of the effect of drought stress on tea, addressing both leaf production and liquor quality aspects

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3. DROUGHT STRESS AND TEA LEAF PRODUCTION

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Physiological, biochemical, and morphological changes occur in tea plants in response to water stress caused by drought (Bota et al. 2004; Zobayed et al., 2007; Damayanthi et al., 2010). These changes include a reduction in leaf water potential, photosynthesis, and stomatal conductance (Figure 1). Proline and abscisic acid (ABA) are known to

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accumulate in higher concentrations in response to water stress, aiding in the maintenance of turgor potential (Mayer, 2006).

Drought significantly limits tea productivity because~~.~~ Biggs et al. (2018) demonstrated that climate change has detrimental effects on farmer livelihoods in major tea-growing regions of Assam, India. The severity and duration of drought stress have multifaceted effects on crop plants. Studies have indicated that drought stress can lead to substantial modifications in the ultra- structural organization of plants (Stoyanova et al., 2002). To protect cells from oxidative damage, plants possess an antioxidant mechanism comprising enzymatic and non-enzymatic defense systems.

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Tea plants commonly face seasonal water deficit conditions in rain-fed ecosystems, resulting in crop yield losses (Upadhyaya et al., 2013). Drought stress increases the water loss rate (WLR) and decreases the relative water content (RWC), dry mass, chlorophyll, carotenoid, total phenolic content, ascorbate, and glutathione in tea leaves. The activities of leaf antioxidant enzymes (*e.g.*, SOD, CAT, GR) exhibit differential responses, while increased ROS and lipid peroxidation are observed alongside decreased POX activities under drought stress (Figure 1). Drought stress alters the antioxidative response and is associated with decreased mineral nutrient (Zn, Ca, Na, Fe, Mg, and K) content in tea leaves, suggesting that mineral deficiency mediates drought stress-induced oxidative damage.

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Drought stress is recognized as the most significant abiotic stress affecting the yield and quality of tea worldwide (Zhidong et al. 2021). Drought stress induces oxidative stress in cells due to the accumulation of reactive oxygen species (ROS). Tea catechins, acting as non-enzymatic antioxidants, play a role in scavenging excess ROS in response to drought stress.

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4. DROUGHT STRESS AND TEA LIQUOR QUALITY

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Liquor quality is important for tea as it determines the value of the product. Liquor quality is determined by the presence, absence, and concentrations of phytonutrients, minerals, primary and secondary metabolites (phytochemicals), as well as associated bioactivity, shelf life, and organoleptic properties such as color, visual appeal, aroma, taste, and texture (Mattos et al., 2014; Ahmed and Stepp 2016). The synthesis of secondary metabolites represents a metabolic cost for plants, and they tend to produce these compounds in significant concentrations when provided with ecological cues based on interactions between environmental, agricultural, genetic, and physiological factors (Fraenkel, 1959; Coley et al., 1985; Ahmed et al., 2010). Environmental factors linked to climate change, such as shifts in seasonality, drought, geography, light factors, altitude, herbivory, microbes, temperature, and soil factors, can result in both increases and decreases in secondary metabolites by up to 50% (Ahmed et al., 2019).

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The majority of studies (78%) demonstrated a decrease in phenolic compound concentrations or their bioactivity with a seasonal shift from spring and/or the first tea harvest to other seasons, while a majority of studies (70%) showed an increase in phenolic compound levels or their bioactivity with drought stress. Herbivory and soil fertility were variables that exhibited the greatest contradictory evidence on tea quality. These variables, which can be controlled by farmers, emphasize the importance of agricultural management for climate mitigation and adaptation.

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To mitigate climate impacts on crop quality and overall risk in agricultural and food systems, evidence-based management strategies and crop breeding programs for resilient cultivars are required. Seasonality studies have consistently shown that concentrations of individual catechins, phenolic secondary metabolites, and antioxidant activity decrease as the season transitions from spring to other seasons, particularly the monsoon season. Ahmed et al. (2014) found that concentrations of desirable phenolic

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catechins were up to 50% lower at the beginning of the monsoon season compared to spring, while total phenolic concentrations and antioxidant activity increased.

5. DROUGHT STRESS AND ROOT TRAITS

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Rooting depth is an important factor influencing the drought resistance of tea plants. Shallow-rooted clones of tea plants are more susceptible to drought, while deep-rooted clones exhibit greater drought resistance (Nagarajah et al., 1981). In shallow-rooted clones, the level of drought resistance increases with rooting depth. However, in deep-rooted clones, the relationship between rooting depth and drought resistance is not significant.

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As described by Tea World (2022), tea plants have two types of roots: feeding roots and extension roots. The fibrous roots of tea are thin, branched, and range in diameter from 0.3 to 3.0 mm. The feeding or feeder roots are white or cream, while the extension roots are reddish-brown. The young roots of tea are white due to the suberisation of the endodermis and primary cortex, and their absorbing capacity is the highest. As the roots age, their color changes to cream and then to reddish-brown, and their absorbing capacity gradually decreases. The reddish-brown portions of the roots have very little absorption capacity.

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In tea plants, about two-thirds of the feeding roots are concentrated in the top 30 to 40 cm of the soil, and the abundance of fibrous roots decreases with depth. The depth of the thicker roots depends on various factors such as soil properties, rainfall, water table depth, etc. Tea roots can grow up to a depth of 5 m.

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Yamashita (1994) conducted a study on tea plant root systems and found that the root system formation and annual root growth of tea plants follow a regular pattern. The skeleton of the root system is formed by several adventitious roots during the early stages of plant growth. Clonal plants tend to have shallower root systems compared to seedling plants, requiring careful management during the early stages to ensure vigorous growth and high yield. White roots play a crucial role in nutrient uptake and account for the largest proportion of all aged roots. White roots undergo a cycle of degeneration and regeneration, with the highest growth activity observed during the autumn season when shoot growth is reduced. White roots produced during this season are considered the most beneficial as they have the longest lifespan. Thicker roots act as reserve organs and are closely associated with stress tolerance. Environmental conditions and tea production practices, such as soil hardness, fertilizer application, plucking, pruning, and shading, significantly influence root growth. Therefore, it is important to prioritize studies on the effects of these factors on root growth to increase yield and improve tea plant quality.

6. DROUGHT STRESS AND LEAF TRAITS

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The rate of photosynthesis in tea leaves generally decreases with increasing drought stress. Drought stress negatively affects the physiological processes of tea plants, including photosynthesis. Chinese tea, which is grown in China, Taiwan, Japan, and parts of India's Darjeeling region, is known for its delicate flavors. It is processed to make green, white, and oolong teas. Chinese tea plants have smaller leaves compared to the Assam variety. On the other hand, Assam tea is grown in India, Sri Lanka, and other countries. The Assam tea plant produces large leaves with a strong flavor, and these leaves are primarily used to make black tea.

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During drought stress, tea plants, regardless of the variety, experience physiological, biochemical, and morphological changes that affect their overall productivity and quality (Fig. 1). The reduced rate of photosynthesis is one of the effects of drought stress on tea plants, which can subsequently affect the growth and development of the leaves and the quality of the tea produced.

7. WATER POTENTIAL AND RESPONSES OF TEA PLANT

Water stress poses a significant challenge to plant survival and growth;~~.~~ To cope with water stress, plants employ various physiological and antioxidative mechanisms. The impact of drought stress and subsequent rehydration on tea plants has been investigated, particularly concerning reactive oxygen species (ROS) metabolism. Upadhyaya et al. (2013) conducted a study on *C.~~amellia~~ sinensis* clones and found that water stress led to a reduction in nonenzymic antioxidants such as ascorbate and glutathione, while enzymic antioxidants exhibited differential responses. These findings indicate the occurrence of oxidative stress in tea plants under water stress conditions. According to Carr (2008), during periods of dry weather, seedling tea bushes were found to be less stressed compared to clones derived from vegetative propagation. Interestingly, there were variations in the responses of different clones to dry conditions, suggesting that these responses could not be predicted solely based on observations made on heterogeneous seedlings.

In the selection program for drought resistance, tests based on parameters such as xylem water potential and stomatal resistance can potentially be employed to identify drought-resistant tea clones at a later stage. These tests help in evaluating the water status and physiological responses of the clones, aiding in the identification of potentially resilient varieties

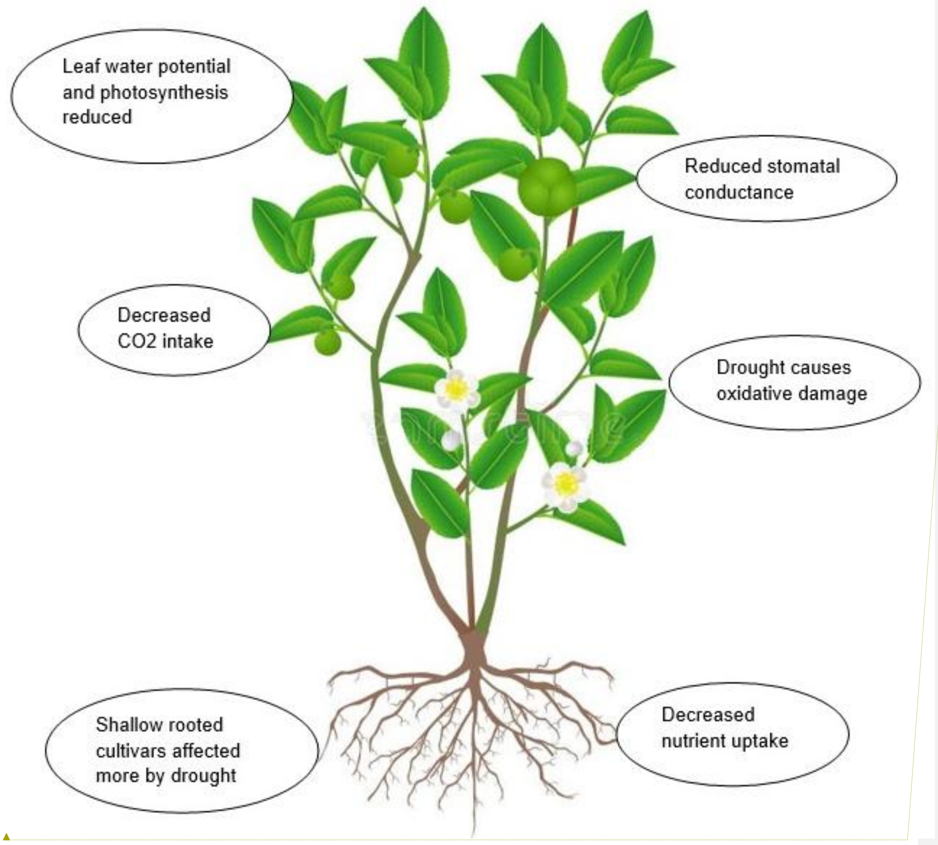

Figure 1: Schematic representation of drought effects on a tea plant.

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8. PLANT METABOLITES CONTENT IN DROUGHT STRESS

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Plant behavior involves perceiving and responding to environmental signals through physiological and morphological changes (Karban, 2008). However, plants rely on interactions with other organisms to disperse seeds, protect against herbivores and microbes, and resist diseases, as mentioned by Heil (2014). These interactions are crucial for sustaining plant populations.

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Plants produce and release volatile organic compounds (VOCs) that serve various functions during their growth and development (Jin et al., 2021);~~.~~ t~~T~~he study also found that drought-induced VOCs from tea plants could cause leaf wilting in neighboring plants. Methyl salicylate (MeSA) was identified as a key player in plant-plant interactions during early drought stress by reducing the production of abscisic acid (ABA) in nearby plants.

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The t~~T~~ea plants have been found to synthesize, accumulate, and emit numerous volatile compounds that contribute to tea quality and overall plant performance (Chen et al., 2020; Jing et al., 2019). Zhu (2016) noted that drought and cold conditions are two important environmental factors that impair plant dispersal in their native habitats.

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In response to drought stress, plants produce and store ABA, which leads to stomatal closure and reduced transpiration. The expression of proteins involved in ABA production and signal transduction pathways related to plant hormone signaling undergo significant changes under drought stress. ABA acts as a chemical messenger to induce stomatal closure through secondary messengers (Yoshida et al., 2014; Frey ~~et al.~~, 2012). Mutants deficient in ABA experience more severe drought stress effects.

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Proline is a low molecular weight osmolyte that plays a significant role in responding to osmotic stresses in plants (Delauney and Verma, 1993; Hasegawa et al., 2000). It is considered a stress indicator and is used to test plants drought tolerance capacity. Prolinecan be applied to mitigate the negative effects of drought on plant growth stages (Bekka et al., 2018).

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Under environmental stress conditions, proline tends to accumulate in many plant species. It has a fundamental biological role as a stress adapter in stress responses. Proline metabolism influences cellular signaling processes and contributes to the plant's ability to survive under stress. Liang et al. (2013) demonstrated that proline metabolism influences signaling pathways in plants by modulating the formation of ROS in the mitochondria.

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9. ROLE OF NUTRIENTS ON DROUGHT RECOVERY

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Hrishikesh et al. (2012) conducted a study on the effect of nutrients on post-drought stress recovery in tea plants. They found that water stress led to a decrease in relative water content (RWC), leaf dry mass, and antioxidants such as ascorbate and glutathione in all tested clones. However, the damage was not permanent, and foliar sprays of potassium (K), calcium (Ca), manganese (Mn), and boron (B) improved the post-drought recovery. The tested nutrients, particularly K and Ca, showed a better effect in enhancing the post-drought recovery potential of tea plants. There have been several studies on the effects of water stress and rehydration responses in plants (Upadhayaya et al., 2004), as well as the enhancement of recovery through hormone treatments (Vomacka et al., 2003).

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Micro and macronutrients are essential throughout all stages of plant development. Manganese is considered an essential micronutrient that plays a primary role in activating several enzymes in metabolic pathways such as the tricarboxylic acid cycle and the biosynthesis of isoprenoids (Foy et al., 1988). Manganese is also involved in the photosynthetic apparatus, including the water-splitting system associated with photosystem II, ATP synthesis, RuBP carboxylase reactions, and the biosynthesis of fatty acids, acyl lipids, and proteins.

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Boron is another essential micronutrient, and its deficiency can lead to the accumulation of chlorogenic acid and polyamines (Camacho-Christobal et al., 2004). The reduction in root and shoot growth due to boron deficiency is associated with a decrease in the biosynthesis of cytokinins and indole-3-acetic acid (IAA) in plant organs (Li et al., 2001). Calcium is an important nutrient that acts as a secondary messenger and can alleviate the effects of water stress (Nayyar et al., 2002; Rentel et al., 2004). Calcium also plays a role in various signaling pathways in plants.

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10. CUTICLE MODIFICATION IN DROUGHT STRESS

The cuticle of plants plays a crucial role in determining their drought tolerance by acting as a transpiration barrier that prevents non-stomatal water loss. Pollard et al. (2008) highlighted the multiple functions of the plant cuticle in interacting with the environment, with its main function being the prevention of excessive water loss through non-stomatal pathways. In tea leaves, there is a distinct difference in cuticular wax composition between tender leaves and fully expanded mature leaves (Zhu et al., 2018). They observed that triterpenoids, which are abundantly present in the cuticular waxes of mature leaves, were absent in tender leaves. The cuticular waxes of tea leaves were found to consist of seven chemical classes, including acids, 1-alkanols, aldehydes, alkanes, esters, glycols, and terpenoids. These differences in cuticular wax composition may contribute to variations in the drought tolerance and water loss characteristics of different leaf types in tea plants.

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11. CONCLUSION

This review highlights the significant impact of water stress on plants, specifically focusing on tea plants (*C.~~amellia~~ sinensis*). Water stress poses a significant barrier to plant survival and growth, affecting various physiological and antioxidative mechanisms. Rooting depth has been found to influence drought resistance, with shallow-rooted clones being more susceptible to drought and deep-rooted clones showing higher resistance. Tea plants have a unique root system consisting of feeding roots and extension roots, with the white roots playing a crucial role in water and nutrient absorption.

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Plants perceive and respond to drought by adapting their physiology and morphology. Plant interactions with other organisms, such as seed dispersers, herbivores, and beneficial microbes, play a vital role in their survival and population sustainability. Plant responses to drought stress involve the production and emission of volatile organic compounds (VOCs) and the synthesis of signaling molecules like abscisic acid (ABA), which regulate stomatal closure and reduce transpiration.

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Nutrient availability, including elements like potassium (K), calcium (Ca), manganese (Mn), and boron (B), plays a crucial role in plant recovery from drought stress. Foliar application of these nutrients has been shown to improve post-drought recovery potential in tea plants. Additionally, proline, a low molecular weight osmolyte, accumulates in plants under stress conditions and serves as a stress indicator and a cellular stress adapter.

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The plant cuticle, particularly the composition of cuticular waxes, plays a vital role in drought tolerance by forming a transpiration barrier and preventing non-stomatal water loss. Tea leaves exhibit different cuticular wax compositions between tender and mature leaves, with variations in triterpenoids and other chemical classes. These differences in cuticular wax composition may contribute to variations in drought tolerance and water loss characteristics among different leaf types in tea plants.

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Overall, these findings emphasize the complex responses and adaptations of tea plants to drought stress and the importance of understanding physiological, biochemical, and

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morphological mechanisms to develop strategies for enhancing drought resistance, optimizing growth, and improving tea plant quality. Further research in this field can provide valuable insights for sustainable tea cultivation practices and crop management in the face of changing environmental conditions.

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