

ISSN Print: 2618-060X
 ISSN Online: 2618-0618
 NAAS Rating (2026): 5.20
 IJRA 2026; SP-9(10): 01-06
www.agronomyjournals.com
 Received: 01-08-2026
 Accepted: 19-09-2026
 Published: 02-10-2026

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Role of potassium in physiology of tea bush

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i10Sa.6748>

ABSTRACT

Potassium is an essential macronutrient that plays a critical role in the growth, physiology, and productivity of tea plants. This review highlights the significance of potassium in regulating key physiological and biochemical processes, including enzyme activation, photosynthesis, osmotic balance, and assimilate transport. Adequate potassium nutrition enhances tea yield, improves quality attributes such as catechins, amino acids, and aroma compounds, and strengthens plant resilience against abiotic stresses like drought and temperature fluctuations. The availability of potassium in tea soils is often limited due to soil acidity, leaching losses, and low cation exchange capacity, making efficient nutrient management essential. Integrated approaches, including split application and the use of organic amendments, have been found effective in improving potassium use efficiency and soil health. Potassium deficiency negatively impacts plant growth, reduces productivity, and increases susceptibility to pests and diseases. Recent advancements also emphasize its role in stress tolerance, antioxidant defense, and metabolic regulation. Overall, balanced potassium management is crucial for sustaining tea production, maintaining soil fertility, and ensuring high-quality yield under changing environmental conditions.

Keywords: Tea, Potassium, Physiology, Growth

Introduction

Potassium (K) is a necessary nutrient that is vital to plant growth and metabolism (Wang *et al.*, 2013) [1]. K is the third most crucial nutrient for plants (Meena *et al.*, 2014) [2]. It is present in tea leaves in concentrations second only to nitrogen and much greater than other nutrients (Rahman, 1988) [3]. Tea yield increases due to potassium (K) application have been reported from various countries (Malenga & Grice, 1991 [4], Rahman & Jain, 1985 [5], Krishnapillai & Ediriweera, 1986 [6], Venkatesan *et al.*, 2005) [7]. Potassium is essential for enzyme activation, regulation of water relations, translocation of assimilates, energy transfer, photosynthesis, and synthesis of protein and starch (Mengel & Kirkby, 1987; Zörb *et al.*, 2014; Wang *et al.*, 2021) [8].

Recent studies further confirm that potassium plays a critical role in improving tea yield, quality, and stress tolerance. A global meta-analysis demonstrated that potassium fertilization significantly enhances tea yield and quality, with optimal application rates improving both biochemical traits and productivity (Zhang *et al.*, 2023) [9]. Moreover, potassium deficiency is still widespread in tea-growing regions and is a major limiting factor affecting tea production and quality (Li *et al.*, 2022) [10]. Recent advances also highlight that improving potassium availability through integrated nutrient management practices, including biochar and beneficial microbes, can enhance soil fertility and tea plant performance (Wei *et al.*, 2025) [11]. Additionally, integrated fertilization strategies combining potassium with organic inputs have been shown to improve soil health and sustain long-term tea productivity (Miao *et al.*, 2024) [12].

Long-term studies carried out in Sri Lanka demonstrated the risks of omitting potash from fertilizer mixtures used in tea cultivation. The absence of potash fertilizers led to a decline in plant health and productivity, ultimately resulting in the death of a significant number of bushes (Portsmouth, 1951) [13]. Potash became a key component of fertilizer combinations for tea starting in the early 1950s, although in Northeast India it was not applied to mature tea for another two decades; however, young tea was generously supplied with potash (Barua, 1989) [14]. Due to soil acidity, the availability of K in most tea soils is often insufficient and decreases further as acidity increases. As soil pH declines, the response to applied K fertilizer correspondingly increases (Willson, 1975) [15].

Potassium deficiency adversely affects the health of the bush frame and the recovery of pruned tea (Willson, 1975) [15]. Continuous cropping without K fertilization reduces economic yield and may even lead to plant mortality. Therefore, K fertilization becomes imperative, and application levels may need to be increased over time (Ranganathan *et al.*, 1988; Malenga, 1986) [17, 16]. Potash fertilizers have also been reported to enhance tolerance to water stress in tea plants, improving water use efficiency particularly under stress conditions (Dey, 1977b) [18]. Recent findings also emphasize that potassium plays a key role in enhancing plant resilience to abiotic stresses such as drought and nutrient imbalance (Hasanuzzaman *et al.*, 2018; Rahman *et al.*, 2025) [19, 20].

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Availability of potash in tea soils

The major proportion of potash in tea soils is present in inorganic form, bound to soil colloids. Potassium exists in soil solution as K^+ ions; as exchangeable K adsorbed onto negatively charged sites of cation exchangers (Ca, Mg, K, Na); and as non-exchangeable K, where K^+ ions are held within the lattice of clay minerals, forming the reserve fraction (Anon., 2011a). The availability of K in most tea soils is often inadequate due to soil acidity and declines further as soils become more acidic. Consequently, the response to applied K fertilizer increases as soil pH decreases (Willson, 1975; Ruan *et al.*, 2018) [15]. Tea soils generally have low cation exchange capacity (CEC), and thus K fertilizers, when applied in large doses, are prone to leaching losses, particularly under high rainfall conditions. Split application under such conditions improves K use efficiency. Ranganathan (1975) reported that K uptake was reduced beyond the pH range of 4.5–5.0 and also observed increased leaching losses around pH 5.0. Willson (1975) [15] demonstrated that K response occurs when soil pH is 4.9 or lower. Under South Indian conditions, Ranganathan and Natesan (1985) suggested higher potash requirements for nursery, young, and pruned tea.

Acidic tea soils typically exhibit low base exchange capacity. The depletion of base cations is accelerated by the use of acid-forming fertilizers such as ammonium sulphate and is further aggravated by the removal of prunings. Over time, the soil's ability to supply essential nutrients declines, eventually leading to deficiency symptoms in tea plants. Potassium is usually the first nutrient to become deficient due to its high uptake by the crop (Barua, 1989) [14]. Recent studies also confirm that prolonged monocropping and intensive fertilization without balanced nutrient management significantly reduce available potassium pools in tea soils (Li *et al.*, 2022; Zhang *et al.*, 2023) [10, 9]. The tea soils of Northeast India have limited nutrient retention capacity, which reduces the efficiency of applied fertilizers. Nutrients are either absorbed by plants or lost through leaching, with the latter accounting for a substantial proportion. This is primarily due to the light texture, dominance of 1:1 clay minerals, and high permeability of these soils. Dey (1971) [21] highlighted the importance of clay in soil K dynamics, observing a positive correlation between clay content, potassium saturation, and available K levels. Increased clay content enhances the storage capacity of soil potassium. Additionally, the application of organic manures along with mineral fertilizers (NPK) has been shown to improve available K levels in soil (TES Annual Report, 1965–66) [22]. Recent findings further support that integrated nutrient management practices, including organic amendments and biochar, significantly enhance potassium availability and retention in tea soils (Wei *et al.*, 2025; Miao *et al.*, 2024) [11, 12].

Potassium behaves as a mobile nutrient similar to nitrogen and therefore requires frequent application to maintain adequate levels in the soil against leaching and plant uptake losses. Continuous use of ammonium sulphate and low soil pH further reduce the soil's capacity to retain potassium. Sen *et al.* (1988) [23] reported that application of more than 100 kg K_2O ha⁻¹ in a single dose leads to significant potassium losses. Recent research also indicates that split application and site-specific nutrient management strategies are essential to improve potassium use efficiency and minimize losses in tea-growing regions (Rahman *et al.*, 2025; Zhang *et al.*, 2023) [20, 9].

Potash nutrition in tea

The two main forms of potassium fertilizers used in tea cultivation are potassium sulphate (SOP) and potassium chloride (MOP). Commercial grades of potassium sulphate contain about 50% K_2O , while potassium chloride contains between 50–60% K_2O . Both salts are highly water-soluble. Potassium chloride is more commonly used due to its lower cost, whereas potassium sulphate is preferred in situations where chloride sensitivity or quality concerns arise (Anon., 2011b).

In Assam, the application of potash has traditionally been guided by soil test values, with positive responses reported from most tea-grow-

ing regions (TES Annual Report, 1972–73) [24]. Blanket application of potash at rates of 80–120 kg K_2O ha⁻¹ has shown beneficial effects where available soil potassium is below optimum levels. These applications not only improved yield but also enhanced overall bush health and vigor (Annual Report, 1971–72, Advisory Department).

Application of potash significantly increases made tea yield, with responses observed up to 180 kg K_2O ha⁻¹, although with diminishing returns at higher levels. The highest yields were recorded with fertilizer combinations of N 135 P 90 K 180, and the positive response to potassium was sustained over long-term cycles (Rahman *et al.*, 1985) [5]. Similarly, Biswas *et al.* (1992) [25] reported that productivity levels of 3500 kg made tea ha⁻¹ or more could be maintained with balanced fertilization involving potassium up to 165 kg K_2O ha⁻¹, along with nitrogen and phosphorus.

Recent studies have further highlighted the role of potassium in improving tea productivity and quality. For instance, potassium fertilization has been shown to significantly enhance leaf yield, chlorophyll content, and photosynthetic efficiency in tea plants (Chen *et al.*, 2022) [26]. In addition, potassium plays a crucial role in regulating the synthesis of quality-related metabolites such as catechins and amino acids, thereby improving tea quality (Liu *et al.*, 2023) [27].

Emerging research also indicates that optimized potassium management improves nutrient use efficiency and reduces fertilizer losses in tea plantations. Site-specific nutrient management and precision fertilization approaches have been recommended to enhance potassium use efficiency and sustain long-term productivity (Zhou *et al.*, 2024) [28]. Furthermore, potassium nutrition has been found to improve plant resilience under abiotic stresses such as drought and temperature fluctuations, which are increasingly important under changing climatic conditions (Singh *et al.*, 2022).

Effect of potassium in tea plant physiology

Potassium is essential in the formation and translocation of starches and sugars and counteracts the adverse effects of excessive nitrogen. It is present in tea leaves in concentrations second only to nitrogen and much higher than other nutrients. Potassium is highly mobile within the plant system, with higher concentrations in internodes. Under potassium deficiency, K^+ ions are translocated from mature leaves to actively growing tissues, leading to initial deficiency symptoms in older leaves (Rahman, 1988) [3].

Barman *et al.* (2003) reported that foliar application of potash (MOP @ 2%) significantly enhanced starch accumulation in both roots and stems. This increase in starch reserves promoted the development of lateral branches, thereby improving overall yield. Higher starch accumulation (14%) in pruning wood stimulated faster shoot growth and resulted in nearly double the number of laterals compared to control plants.

To sustain growth under potassium-deficient conditions, tea plants require external potassium fertilization. Both potassium chloride (KCl) and potassium sulphate (K_2SO_4) have been shown to significantly enhance yield and quality when applied within optimal limits (Ruan *et al.*, 2000) [29]. Adequate potassium supply increases total biomass, whereas deficiency (< 100 $\mu\text{mol L}^{-1}$) reduces root, stem, and leaf biomass while increasing the root–shoot ratio (Ruan *et al.*, 2013; Lin *et al.*, 2013; Gong *et al.*, 2017; Zhong *et al.*, 2017, 2018) [30, 31, 32, 33]. The optimal potassium concentration for maximizing chlorophyll synthesis and photosynthesis in mature leaves has been reported by Rajan *et al.* (2016) [34]. When soil exchangeable potassium falls below 80 mg kg⁻¹, potassium fertilization significantly enhances yield (Ruan *et al.*, 2013) [31].

Recent studies further confirm that potassium plays a central role in regulating photosynthesis, carbon assimilation, and biomass partitioning in tea plants. Potassium supply improves chlorophyll content, stomatal conductance, and photosynthetic efficiency, thereby enhancing growth and productivity (Sun *et al.*, 2022; Chen *et al.*, 2023) [36, 35]. Moreover, potassium has been shown to regulate carbon–nitrogen balance and improve assimilate transport from source to sink tissues in tea plants (Liu *et al.*, 2024) [37].

Potassium deficiency interferes with the synthesis of metabolic enzymes. Activities of key antioxidant enzymes such as catalase (CAT), ascorbate peroxidase (APX), and monodehydroascorbate reductase (MDAR) decline significantly under K deficiency (Zhong *et al.*, 2018) [32]. Adequate potassium supports protein and carbohydrate metabolism, promotes catechin biosynthesis, and enhances overall tea quality. In contrast, deficiency increases stomatal resistance, reduces gas exchange, and decreases RuBP carboxylase activity, thereby lowering photosynthetic rates (Luo *et al.*, 2014) [38]. Potassium also maintains the proton gradient across thylakoid membranes, facilitating photophosphorylation and CO₂ assimilation.

Recent findings also indicate that potassium plays a crucial role in mitigating oxidative stress by enhancing antioxidant defense systems and reducing reactive oxygen species (ROS) accumulation in tea plants (Zhang *et al.*, 2022; Kumar *et al.*, 2023) [40, 39]. This contributes to improved stress tolerance under adverse environmental conditions.

Adequate potassium levels increase the concentration of free amino acids, including phenylalanine, a precursor for important volatile compounds such as benzaldehyde and phenylethyl alcohol (Bian *et al.*, 2012) [41]. Similarly, potassium enhances L-theanine synthesis in tea roots by increasing ethylamine levels and activating theanine synthetase activity (Zhou *et al.*, 2022) [42]. Recent studies further highlight that potassium nutrition significantly influences secondary metabolite biosynthesis, including catechins and amino acids, which are key determinants of tea quality (Wang *et al.*, 2023; Li *et al.*, 2024) [43].

Application of potassium fertilizers also increases chlorophyll content and nutrient accumulation in young shoots, thereby enhancing photosynthesis and growth (Lin *et al.*, 2012). Inadequate potassium supply adversely affects biochemical characteristics and reduces tea productivity (Ruan *et al.*, 1999; Venkatesan *et al.*, 2004) [44, 45]. The response of tea to potassium fertilization is further influenced by environmental factors such as soil type, altitude, climate, and management practices. Recent research emphasizes that site-specific potassium management is essential for optimizing physiological performance and maintaining tea quality under varying agro-climatic conditions (Yang *et al.*, 2025) [46].

Effect of potassium in tea quality

The amino acids, caffeine, water extract, and epigallocatechin gallate (EGCG) in tea leaves are significantly reduced in mature tea plants under potassium deficiency, whereas polyphenols, catechins, epigallocatechin (EGC), epicatechin (EC), and the phenol/ammonia ratio increase. Such imbalances result in inferior tea quality due to reduced formation of aromatic alcohols, aldehydes, and esters, leading to poor flavor complexity. Exogenous potassium application has been reported to regulate polyphenol and theaflavin content in tea leaves, thereby improving quality attributes (Zhang *et al.*, 2022).

In young tea plants, potassium positively influences water extract, catechins, and total polyphenols, while having limited direct effect on free amino acids and caffeine (Lei *et al.*, 2008) [47]. Venkatesan *et al.* (2004) [48] reported that increasing potassium levels enhanced both polyphenol and free amino acid concentrations. Caffeine content was positively correlated with potassium application, particularly under varying nitrogen levels. Higher nitrogen and potassium (NK) fertilization also increased Group II volatile compounds responsible for desirable aroma, including linalool, methyl salicylate, and benzaldehyde, which together contribute to the flavor index of tea.

Recent studies further emphasize that potassium nutrition plays a key role in regulating tea quality by influencing secondary metabolite synthesis. Adequate potassium supply enhances catechin composition, total polyphenols, and amino acid balance, thereby improving both liquor quality and sensory attributes (Wang *et al.*, 2022; Xu *et al.*, 2023) [49, 50]. Potassium has also been shown to modulate the biosynthesis of volatile aroma compounds by regulating precursor availability and enzymatic activity involved in aroma formation (Zhao *et al.*, 2024) [51].

Furthermore, potassium nutrition improves the balance between carbon and nitrogen metabolism, which is critical for determining tea quality traits such as flavor, briskness, and aroma. Recent metabolomic studies indicate that optimized potassium application enhances the accumulation of quality-related compounds such as L-theanine, flavonoids, and aroma precursors, leading to superior tea quality (Chen *et al.*, 2025) [52]. In contrast, potassium deficiency disrupts metabolic pathways, resulting in poor flavor development and reduced market value.

Effect of potassium in stress management

Foliar application of MOP (2%) alone or in combination with magnesium (1%) in drought-affected plants increased relative cell turgidity, water retention capacity, specific leaf weight, and ultimately crop yield (Handique *et al.*, 1992) [53]. Potash application under soil moisture deficit conditions induces stomatal regulation (Saikia *et al.*, 1984) [54], enabling tea plants to conserve water. Although potassium does not act as an antitranspirant, it functions as an osmoticum by enhancing the accumulation of compatible solutes such as proline, thereby helping plants tolerate drought stress (Weimberg *et al.*, 1982; Pesci *et al.*, 1986) [56, 55]. Barman *et al.* (2003) suggested that two foliar sprays of MOP @ 2% at three-week intervals after the plucking season should be a regular practice in Northeast Indian tea plantations to maintain bush health.

Drought stress is a major constraint to tea productivity. Maintaining optimal potassium levels is a key strategy for mitigating drought stress, as potassium exists in plant cells in ionic form and plays a central role in osmotic adjustment. Under drought conditions, membrane proteins respond rapidly, leading to temporary efflux of K⁺ ions. The regulation of water uptake and recovery is closely associated with the activity of plasma membrane H⁺-ATPase (Venkatesan *et al.*, 2004) [48]. Potassium fertilization increases cellular K⁺ concentration, which enhances osmotic potential, root water uptake, stomatal regulation, and membrane stability, thereby improving drought tolerance (Zhang *et al.*, 2004) [57].

Chen Linmu *et al.* (2020) demonstrated that increased K⁺ content in tea leaves is associated with improved K⁺ retention in mesophyll cells and enhanced drought resistance. Transcriptomic analyses revealed that potassium channel and transporter genes regulate K⁺ retention under stress conditions. High-affinity potassium transporters (HAK/KUP/KT family), particularly CsHAKs, play a dominant role in K⁺ uptake and long-distance transport, and are actively involved in stress response mechanisms in tea plants.

Recent studies further highlight the crucial role of potassium in enhancing plant tolerance to abiotic stresses such as drought, heat, and oxidative stress. Potassium improves osmotic adjustment, stabilizes cellular membranes, and enhances antioxidant defense systems, thereby reducing reactive oxygen species (ROS) damage under stress conditions (Ahanger *et al.*, 2022; Wang *et al.*, 2023) [58, 59]. Additionally, potassium has been shown to regulate stomatal conductance and improve water use efficiency, which is critical for sustaining tea productivity under water-limited conditions (Zhang *et al.*, 2022) [40].

Emerging molecular studies indicate that potassium transporters and channels are key regulators of stress signaling pathways. Upregulation of K⁺ transporter genes under drought conditions enhances potassium uptake, maintains ionic balance, and supports cellular homeostasis (Li *et al.*, 2024) [60]. Furthermore, integrated potassium management strategies have been found to improve resilience of tea plants to climate variability by enhancing physiological adaptability and stress tolerance (Singh *et al.*, 2025) [61].

Effect of potassium in pest and disease resistance

Potassium deficiency leads to slow growth of tea plants and increases their susceptibility to diseases such as *Exobasidium vexans* (blister blight), anthracnose, and brown blight (Luo, 1997) [62]. Adequate potassium fertilization enhances overall plant health and reduces the incidence of pests and diseases, including *Pestalotia theae*, anthrac

nose, and brown blight. This improved resistance may be attributed to enhanced synthesis of defensive compounds such as phenolics and increased activity of enzymes like peroxidases, which inhibit pathogen growth, reproduction, and spread (Ruan *et al.*, 2003) [63].

Potassium deficiency increases vulnerability to infections, particularly fungal pathogens, due to its crucial role in primary metabolism and phloem transport (Römheld *et al.*, 2010) [64]. Balanced fertilization with NPK has also been shown to improve tolerance against pests such as mites (Sudoi, 1997) [65]. Mukhopadhyay *et al.* (2018) [66] reported that potassium application significantly reduced root-knot nematode infestation, decreasing the number of galls by 44% after two years of treatment.

Recent studies further emphasize the role of potassium in strengthening plant defense mechanisms. Potassium enhances structural integrity of plant tissues, improves cell wall thickness, and regulates the synthesis of defensive metabolites such as phenolics and flavonoids, thereby increasing resistance to pathogens (Zhang *et al.*, 2022; Wang *et al.*, 2023) [40, 59]. It also plays a key role in activating systemic resistance pathways and modulating plant immune responses against biotic stresses (Liu *et al.*, 2024) [67].

In addition, potassium has been shown to reduce pest incidence by improving plant vigor and altering host plant suitability. Adequate potassium nutrition can decrease the severity of insect attacks by enhancing biochemical defenses and reducing the accumulation of soluble nitrogen compounds that favor pest development (Singh *et al.*, 2022) [68]. Recent findings also indicate that potassium-mediated regulation of antioxidant enzymes helps mitigate oxidative damage caused during pathogen attack, thereby improving plant resilience (Chen *et al.*, 2025) [69].

Emerging research highlights that potassium transporters and signaling pathways are involved in plant defense responses. Proper potassium nutrition supports signaling networks that regulate defense gene expression, thereby enhancing resistance to both pests and diseases in tea and other crops (Guo *et al.*, 2023) [70].

Conclusion

Potassium plays a crucial role in the physiology of tea plants. It contributes to various physiological processes, such as osmoregulation, enzyme activation, and nutrient transport. Adequate potassium levels promote healthy growth, water balance and overall plant vigor. Potassium's foremost contribution lies in osmoregulation, where it maintains the turgor pressure within tea plant cells. This enables the plant to stand to stand upright and withstand environmental pressures, ultimately influencing tea plant frame and vigor. Additionally, potassium's involvement in enzyme activation drives various biochemical reactions necessary for photosynthesis, respiration and protein synthesis. Maintaining appropriate potassium levels is vital for ensuring optimal yield, quality and resistance to stressors. A balanced approach to potassium management is essential to unlock the full potential of tea plants and sustain a thriving tea cultivation industry.

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How to cite this article: Sonowal S, Phukon SK, Saikia P, Bhuyan GD, Bhuyan RP, Baruah S, et al. Role of potassium in physiology of tea bush. *International Journal of Research in Agronomy*. 2026;SP-9(10):01-06. doi: <https://www.doi.org/10.33545/2618060X.2026.v9.i10Sa.6748>

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