Improved root-zone hydration and soil moisture conservation enhance drought resilience during the establishment of young tea plants (Camellia sinensis L.)

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RESEARCH ARTICLE

Improved root-zone hydration and soil moisture conservation enhance drought resilience during the establishment of young tea plants (*Camellia sinensis* L.)

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Abstract

Background and aims Recurrent drought and limited availability of irrigation water severely constrain the establishment of young tea plants in the tea growing regions of Bangladesh. Prolonged drought depletes root-zone soil moisture, resulting in complete mortality in newly transplanted tea saplings. This study aimed to investigate soil moisture conservation techniques capable of alleviating drought stress and maximizing the survival, growth and physiological performance of young tea plants.

Methods Ten root-zone soil water management techniques—combining scheduled watering with or without aboveground mulching, belowground mulching and the water bagging approach under limited-water conditions—were tested for the first time on newly transplanted tea saplings during winter drought from 6 December 2025 to 13 March 2026. Saplings were planted following randomized complete block design.

Results Kaplan–Meier survival analysis revealed that checked saplings without mulching and limited watering resulted in complete mortality within 18 days, whereas supplemental watering every 10- or 15-day interval without or with aboveground mulching maintained 100% survival throughout the period. Subsurface mulching with water hyacinth roots (*Pontederia crassipes*) or black polythene film under limited-water conditions maintained a final survival rate of 80–90%, whereas water bagging substantially delayed mortality and achieved a final survival rate of 65%. These strategies preserved relatively high root-zone soil moisture, accelerated shoot emergence, enhanced gas exchange, reduced root proline, and maintained a relatively low leaf-to-air VPD, indicating improved plant water status under extreme drought.

Conclusion Integrating root-zone hydration and soil moisture conservation markedly improved the survival and early establishment of young tea plants, providing water-efficient strategies for drought-resilient tea cultivation.

Keywords: Tea, root-zone, soil moisture, drought, survival

Introduction

Tea (*Camellia sinensis* L.) is one of the most widely consumed nonalcoholic beverages in the world. It is rich in bioactive compounds, particularly polyphenols, which are associated with a wide range of health benefits (Leung et al. 2001; Cabrera et al. 2006). In addition to its nutritional value, tea is an important perennial cash crop that supports the economies and livelihoods of millions of people across tropical and subtropical regions (FAO 2024a). However, tea cultivation is highly climate sensitive and requires a specific range of environmental conditions: a uniform distribution of annual rainfall between 1200 and 2500 mm, temperatures ranging from 12.7–28 °C, warm and moist environments with 70–80% relative humidity, organic matter-rich, well-drained, sandy loam to loam and acidic soils with pH values ranging from 4.5–5.5 (Sana 1989; Mwesige et al. 2026).

In the subtropical climate, prolonged dry spells are not conducive for tea cultivation, and sustained monthly rainfall below 50–60 mm causes severe moisture stress, which adversely affects the survival of tea plants (Wijeratne 1996; Sana 1989; Ahmed et al. 2019; Omer et al. 2025). Climate change is expected to exacerbate this challenge by increasing the frequency and intensity of drought events, thereby increasing the risk of drought-induced plant mortality (McDowell et al. 2008; Breshears et al. 2009; Anderegg et al. 2013; Allen et al. 2015; Choat et al. 2018). During drought, water deficit in the soil impairs key physiological functions, such as transpiration, stomatal conductance, the net photosynthetic rate, and water-use efficiency, thereby restricting plant growth, development, and ultimately survival (Haworth et al. 2012; Osakabe et al. 2014; Lamaoui et al. 2018; Gupta et al. 2020; Vadez et al. 2024).

To mitigate drought stress and soil moisture deficits, several irrigation technologies, such as drip, subsurface drip, sprinkler, microsprinkler systems, and conventional irrigation practices, have been widely adopted in tea-growing regions worldwide (Sana 1989; Yang et al. 2022; Das et al. 2023; Liang et al. 2023). Moreover, aboveground mulching using organic residues or synthetic materials and the establishment of shade trees are commonly practiced to minimize soil evaporation, moderate soil temperature and improve the microenvironment surrounding tea plants (Isaac et al. 2024; Ramos et al. 2024). These approaches have been shown to increase the soil moisture conservation, survival and physiology of tea plants under drought stress (Rokhmah et al. 2022; Das et al. 2023). Nevertheless, the widespread adoption of irrigation systems is often impeded by high installation and maintenance costs, energy requirements and relies on permanent fresh water sources (Pereira et al. 2012; Jovanovic et al. 2020). Similarly, aboveground mulching has proven to be an effective practice for conserving soil moisture and reducing evaporative water losses; however, its large-scale application is often hindered by the limited availability of suitable mulch materials (Kader et al. 2017; Ikram et al. 2025; Setsoafia et al. 2025). Despite their agronomic benefits, the application of irrigation-based drought mitigation strategies and mulching practices remains challenging in many tea-growing regions facing water scarcity and resource limitations (Bandara 2012; Daccache et al. 2014; Handique et al. 202a). In this context, sustainable management of water has become a pressing global concern in the 21st century, particularly in agriculture, which accounts for 72% of global fresh water withdrawals and is highly vulnerable to water scarcity (UN-water 2024; Gasparini et al. 2026). Therefore, improving water-use efficiency through innovative irrigation and moisture conservation practices is essential for sustaining agricultural productivity under changing climatic conditions (Pereira et al. 2002; Foley et al. 2011; FAO 2024b).

At present, the Bangladesh tea industry comprises 172 tea estates and more than 10,000 small-scale tea growers, accounting for approximately 294,081 acres of land and producing more than 100 million kilograms of tea annually (BTB 2026). Tea gardens are mostly polarized in the Sylhet, Chittagong and North Bengal regions. These areas experience a distinct seasonal pattern, with a prolonged dry period from November to April, followed by a rainy season that continues from May to October every year. Severe dry spells during winter (December–February) are often characterized by extended rainless periods, resulting in extreme soil moisture deficits (Sana 1989). Under repeated irrigation, adequate mulching and shade management, winter is considered the preferred planting time because these supportive actions promote early plant establishment and root development prior to the onset of the subsequent monsoon. In the absence of these measures, prolonged drought impedes plant establishment, resulting in complete mortality and limiting the expansion and replanting of tea. On the other hand, conventional mulching practices exhibit limited efficacy in controlling evaporation and are not technically designed to maximize moisture retention within the root zone. These challenges highlight the urgent need for affordable and efficient drought-resilient technologies capable of maximizing root-zone moisture conservation while minimizing water use during winter.

In this study, we hypothesized that, compared with conventional drought management practices that rely on repeated irrigation and adequate surface mulching; integrating root-zone hydration with targeted soil moisture conservation approaches would improve plant water status and enhance drought resilience and sapling establishment. To test this hypothesis, ten water-management strategies—combining scheduled watering with or without aboveground mulching, belowground mulching and the water bagging technique—were evaluated for the first time on newly transplanted tea saplings during winter drought. The effectiveness of these methods was assessed through comprehensive measurements of sapling survival, growth and development; root-zone moisture and temperature dynamics; gas exchange characteristics; leaf-to-air vapor pressure deficit; and root proline accumulation under prevailing environmental conditions. Overall, our study addresses an important knowledge gap in drought adaptation for tea plants by developing practical and resource-efficient management strategies that improve root–zone soil moisture availability while reducing irrigation demand. The proposed approaches have the potential to enhance the early establishment of tea saplings under water-deficient conditions and contribute to climate-resilient tea cultivation in drought-prone regions, thereby supporting the broader goal of sustainable agriculture under climate change.

Materials and methods

Study site and period

We carried out the experiment on a highly drought-prone, southwest-facing hillock (fully exposed to solar radiation) in section 13 at the Bilashcherra Experimental Farm (BEF), Bangladesh Tea Research Institute (BTRI), Srimangal, Moulvibazar, Sylhet, Bangladesh. The area of the plot was 1,200 ft^2 (60 ft * 20 ft), with a ground elevation of 166 ft. above mean sea level (MSL). The tea saplings were planted during the winter drought on 6 December 2025 and were observed continuously for 98 days, i.e., until the onset of the first rainfall on 13 March 2026 (Table 1).

Environmental conditions

Data on the temperature, rainfall, sunshine hours, evaporation, dew point and relative humidity of the study area were collected from adjacent weather station (First Class Meteorological Observatory cum Agromet, BTRI, Srimangal) to illustrate weather patterns. Throughout the observation period, no rainfall was recorded, resulting in sustained drought. Data on different weather parameters prevailing during the time are presented in Table 1.

Table 1 Monthly weather data recorded from December 2025 to March 2026

Month	Mean day temperature (°C)	Total Rainfall (mm)	Mean sunshine (hrs./day)	Total evaporation (mm)	Mean dew point (°C)	Mean relative humidity (%)
December, 25	27.08	0	5.83	68.90	14.89	71.92
January, 26	25.27	0	5.37	63.00	13.53	66.57
February, 26	29.63	0	5.62	91.00	12.90	56.40
March, 26	30.84	185 (13 March onward)	3.60	99.80	18.79	67.68

Design and techniques

The following ten strategies were evaluated, and the saplings under each option were planted randomly in the blocks (lines) following the randomized complete block design (RCBD). The number of saplings under each technique was 20, and the total population was 200. The approaches were as follows:

T0 (check) = Planting without mulching (PWM) +1-step watering. Each sapling in this treatment received 2 L of water once just after planting in the field as traditional practice.

T1= PWM+2-step watering. A single pit received 5 L of water; 12 h prior to planting, an additional 2 L of water was applied just after planting of the saplings. Each sapling in this treatment received 7 L of water in total over 98 days.

T2= PWM+ regular watering. Just after plating, each sapling received 2 L of water, and then an additional 2 L was applied every 10 days interval. A single sapling received 20 L of water throughout the study period.

T3= T0+ water bagging. A 2 L polythene water bag was buried vertically in the pit along with the sapling, and then a single lateral root consisting of multiple feeder roots entered the bag to siphon water from the water bag. The upper part of the bag was positioned horizontally with the base of the lateral root. The mouth of the bag along the root base was gently tightened, and the pit was subsequently filled with subsoil. Each sapling received only 4 L of water.

T4= T1+ water bagging. In combination with T1 and T3, each sapling in this treatment received 9 L of water in total during the period.

T5= P. with aboveground mulching (PAM) + 1-step watering. Each sapling received 2 L of water once just after planting, and then 2 kg of water hyacinth was applied as aboveground mulch in a ring style, keeping 2″ away from the plant base.

T6= PAM+2-step watering. Each sapling received 2 kg of mulch and 7 L of water, similar to those used in T1.

T7= PAM+ regular watering. A single sapling received 2 kg of mulch and 2 L of water every 15 days interval. During the 98-day period, each sapling received 14 L of water in total.

T8= P. with underground root mulch+2-step watering. Each plant received 7 L of water in the pit, similar to T1. After planting, 2 kg of well-decomposed water hyacinth roots was applied just 1″ below the ground encircling the base. Finally, the pit was filled with subsoil.

T9= P. with underground polythene film+2-step watering. Like at T1, after planting of the sapling, a square feet black polythene film (in accordance with pit size) was placed just 1″ below the soil, and then the subsoil was spread gently on the film such that it became invisible. The polythene from each test sapling was removed after the first rainfall.

Before being transplanted in the plot, the tea saplings were not subjected to a hardening process for field adaptation but were transplanted immediately after removal from the nursery. Supplemental irrigation was not provided to any treatment except T2 and T7. All the treatments were free from chemical fertilizer and any other nutrient supplements or drought retardants. The saplings were fully exposed to solar radiation, and no shade trees were planted in the study plot. Necessary intercultural operations, such as fencing, staking and hand weeding, were performed whenever needed.

Soil conditions

The soil of the study plot was characterized as well drained, sandy loam and light brown in color. The estimated soil pH value was 4.81, which falls within the optimum acidic range (pH 4.5–5.5) recommended for tea cultivation. The electrical conductivity (EC) of the soil was 35.18 μS cm^{-1}, indicating nonsaline soil conditions. The recorded organic carbon (%) of the soil was 0.082, while the available nitrogen, phosphorus and potassium contents were 0.093, 13.05 and 97.33 ppm (mg kg^{-1}), respectively. The soil physicochemical properties were analyzed at the Laboratory of Agro-product Analysis, Department of Agricultural Chemistry, Patuakhali Science and Technology University, Bangladesh.

Planting pits

The size of each plating pit was square in shape, and the dimensions for each pit were as follows: length, 1 ft; width, 1 ft; and depth, 1 ft. There were 20 lines along the length of each plot, and each line comprised 10 pits for ten approaches. Therefore, the total number of pits was 200. The line-to-line distance and pit-to-pit distance were 3 ft and 2 ft, respectively. During pit preparation, the subsoil of the pit was separated from the topsoil. The topsoil was then mixed with 2 kg of well decompost cow dung (as traditional practice), and two-thirds of the mixture was returned to the pit. Finally, the pit was filled with subsoil. No chemical fertilizers were applied to the soil mixture. For treatments T1, T4, T6, T8 and T9, there were 100 planting pits, and each pit received 5 L of water approximately 12 h prior to planting of the test saplings.

Tea saplings

Saplings of the popular BT2 clonal variety were collected from the BEF nursery, BTRI. The saplings, aged approximately 18 months, were transplanted in the plot under each treatment. Almost all the saplings were single stemmers. The average number of leaves per sapling was 15. The mean shoot height, root length and girth diameter were recorded as 58.5 cm, 16.39 cm and 4.13 mm, respectively.

Parameters evaluated

A number of parameters, including survival time, survival rate, mortality rate, shoot induction time, growth rate, soil moisture, soil temperature, leaf-to-air vapor pressure deficit, stomatal conductance, transpiration rate, net photosynthetic rate, water-use efficiency and root proline accumulation in relation to prevailing environmental factors (Table 1), were recorded during the testing phase of the study.

Survival time, survival rate and mortality rate

The saplings that survived in the study plot were confirmed to be alive by the presence of green leaves, viable stems, and active axillary buds and by their ability to resume growth under field conditions. The dead saplings were determined on the basis of their phenotypic traits (foliar browning and subsequent desiccation or drying and wrinkling of leaves and bark), as described by Blum and Tuberosa (2018) and Hammond et al. (2019). We also considered the soil moisture content (≤ 8.5% with the exception of T3 and T4) in the planting pits at which the saplings reached the permanent wilting point, i.e., at that stage, stressed saplings died completely in the field. The survival rate and mortality rate were calculated by applying the following formulae:

$$\text{Survival rate (\%)} = \frac{\text{Number of plants alived}}{\text{Total plants originnaly planted}} \times 100$$

$$\text{Mortality rate (\%)} = \frac{\text{Number of plants died}}{\text{Total plants originnaly planted}} \times 100$$

The survival time, survival rate and mortality rate of the test saplings for each option were also assessed by Kaplan–Meier survival curves.

Shoot induction time

The shoot induction time was monitored daily in the study plot, and the bud response to shoot emergence was recorded during the early morning. The critical time of shoot induction was assessed by sprouting a dormant axillary bud to form a new shoot consisting of a needle and a scale-like small leaf (Tang et al. 2023).

Growth rate measurements

The shoot growth of the test saplings under drought stress was estimated as the increase in shoot length (mm $month^{-1}$). The initial shoot height was recorded at the time of planting, and the final shoot height was recorded at the end of the observation period from a fixed reference point at the stem base. The growth rate was calculated by using the following formula:

$$\text{Growth rate (mm/month)} = \frac{\text{Final shoot height (cm)} - \text{Initial shoot height (cm)}}{\text{Observation period (98 days)}} \times 30 \times 10$$

Root-zone moisture and temperature measurements

During the study period, data on soil moisture (2″ below the ground) and soil temperature (within 2″of the topsoil) were recorded at the prewilting stage by using a comprehensive soil sensor developed by Jingxuntong, China. For T2 and T7, the final soil moisture (%) and soil temperature (°C) were measured at 5 days and 7 days after watering, respectively, as each sapling in these two treatments received 2 L of water every 10 days and 15 days intervals, respectively.

Recording gas exchange parameters

The leaf-to-air vapor pressure deficit (VPD_L in mbar), stomatal conductance (gs in mmol H_2O m^{-2} s^{-1}), transpiration rate (E in mmol H_2O m^{-2} s^{-1}), net photosynthetic rate (Pn in μmol CO_2 m^{-2} s^{-1}) and water-use efficiency (WUE in μmol CO_2 $mmol^{-1}$ H_2O) were measured by using a TARGAS-1 portable photosynthesis system (USA) to evaluate the physiological responses of the test saplings for each treatment to drought stress (Tor-Ngern and Leksungnoen 2020; Yin et al. 2022). Measurements were conducted between 10:00 am and 2:00 pm during the experimental period on fully expanded leaves at the prewilting stage under clear-sky conditions to minimize diurnal variation.

Analysis of root proline

The proline test was carried out at the Laboratory of Agro-product Analysis, Department of Agricultural Chemistry, PSTU, Bangladesh. Approximately 0.5 g of fresh root sample was homogenized in a mortar and pestle, and 10 mL of 3% sulfosalicylic acid was added until a uniform extract was obtained. The homogenate was then transferred to a centrifuge tube and centrifuged at 3,000 rpm for 10 minutes. After that, 2 mL of extract was placed in a test tube, and then 2 mL of acid ninhydrin and 2 mL of glacial acetic acid were added. All the test tubes containing the test samples were incubated in a boiling water bath at 100 °C for 1 hr. The reactions were terminated by placing the tubes immediately into an ice bath and adding exactly 4 mL of toluene to each tube. The mixture was vigorously vortexed for 15–30 s, and the layers were allowed to separate completely. Later, the upper red toluene layer was pipetted into a cuvette, and the absorbance was recorded at 520 nm with a UV–visible spectrophotometer. All the reagents used were of analytical grade. Finally, the results were calculated using a standard curve from a series of standard proline solutions (Bates et al. 1973; Szabados and Savoure 2010).

Statistical analyses

Statistical analyses were performed by Python. Data on the survival time (days), survival rate (%) and mortality rate (%) of the tea saplings were analyzed by Kaplan–Meier survival analysis, and differences among the treatments were analyzed by the log-rank test. The shoot induction time was visualized by boxplots, whereas the shoot growth, water siphoned and root proline contents are presented in bar graphs. The root-zone moisture and temperature dynamics were illustrated using violin plots with embedded boxplots. Differences among the treatments were evaluated by one-way ANOVA, followed by Tukey's HSD post hoc test. Pearson correlation was conducted to examine the relationships among the measured variables, whereas multivariate analysis (PCA) was performed to evaluate the overall associations among the drought-determining parameters and the treatments. A structural equation model (SEM) was also developed to measure the direct and indirect effects of the soil water status and microclimate, physiological, biochemical and growth parameters on the survival time of young tea plants under drought stress and to test the goodness-of-fit of the observed data.

Results

Survival analysis: Kaplan–Meier estimates

The Kaplan–Meier survival analysis revealed pronounced differences in sapling survival time among the treatments throughout the observation period (98 days). The survival curves revealed that the T2 and T7 treatments resulted in complete survival (S=100%), whereas the T8 and T9 treatments resulted in survival rates exceeding 0.80 at the end of the period. The saplings in these two treatments survived until 60 days and 65 days, respectively, without any mortality (Fig. 1). On the other hand, T0 (control) experienced 100% mortality within 18 days. The saplings in T1 and T5 survived for only 35 days and 28 days, respectively, indicating high vulnerability to drought stress. The T3 treatment displayed zero mortality until 35 days, but the survival rate decreased to 40% at the end of the period. Although the saplings under T6 survived for only 45–58 days, the saplings under T4 survived for 47 days without any mortality and exhibited a final survival rate of 65% (Fig. 1).

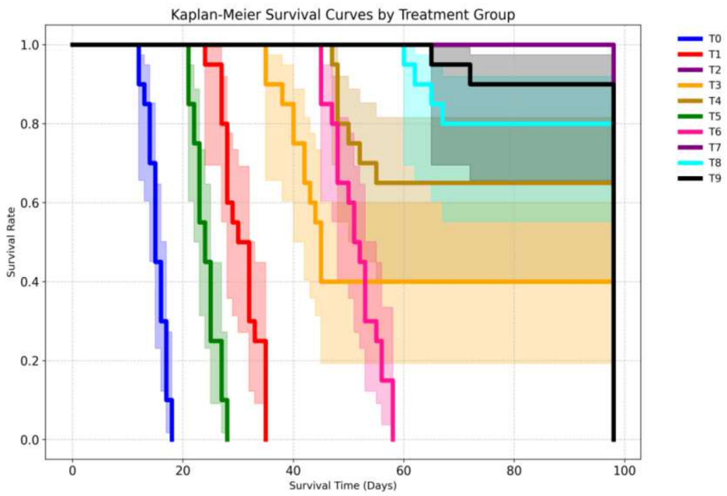

Fig. 1 Kaplan–Meier survival curves showing significant differences in survival time (days) and survival rate (1=100%) among the treatments. Pairwise comparisons using the log rank test indicated that treatment combinations (39 pairs out of 45) differed significantly (χ^2= 4.012–44.46, p<0.05), whereas six combinations (T2 vs T7, T2 vs T9, T3 vs T6, T4 vs T8, T7 vs T9 and T8 vs T9) showed statistically similar survival performance (χ^2= 0.00–2.05, p>0.05, n=20).

In this study, T2 and T7 received supplemental watering of 2 L per application every 10- and 15-day interval, without or with mulching, and each sapling received a total of 20 L and 14 L of water, respectively, over the 98-day study period. In contrast, T8 and T9 each received only 7 L of water combined with subsurface root mulch and black polythene film, respectively, whereas T4 (water bagging) received a total of 9 L of water per sapling throughout the period. The remaining approaches failed to maintain sufficient root-zone soil moisture for sapling survival.

Shoot induction time

Among all the responsive treatments, T2 resulted in earlier shoot induction at 30 days, with a median induction time of approximately 48 days, and most of the saplings in this treatment presented shoot induction within the interquartile range of 43–50 days. The remaining saplings needed up to 60 days for shoot emergence. Similarly, all the saplings in T7 produced new shoots within 40–60 days, with a median of approximately 54 days. T8 induced shoot growth within 51–67 days, and few saplings produced no shoots as they died under drought. T9 presented the highest median induction time (60.5 days), and most saplings delayed shoot initiation and responded within 55–75 days, whereas very few collapsed to zero (Fig. 2 a). The T3 and T4 treatments presented a bimodal distribution characterized by large number of saplings failing to produce shoots due to drought, and the remaining saplings produced new shoots between 63–73 and 52–65 days, respectively. However, the saplings in the T0, T1, T5 and T6 treatments presented a complete absence of shoot induction, as the plants failed to survive in the field under water stress (Fig. 2 a).

Growth rate

The saplings in the responsive treatments presented highly significant differences in shoot growth (p<0.001). According to the bar graph, the highest shoot growth (mm month^{-1}) was recorded in T7 (15.18), followed by T2 (12.34), T9 (11.57) and T8 (7.22), whereas T0 (control), T1, T5, and T6 presented no measurable shoot elongation, as the saplings died under drought stress. T3 (3.15) and T4 (5.42) were not significantly different from each other (Fig. 2 b).

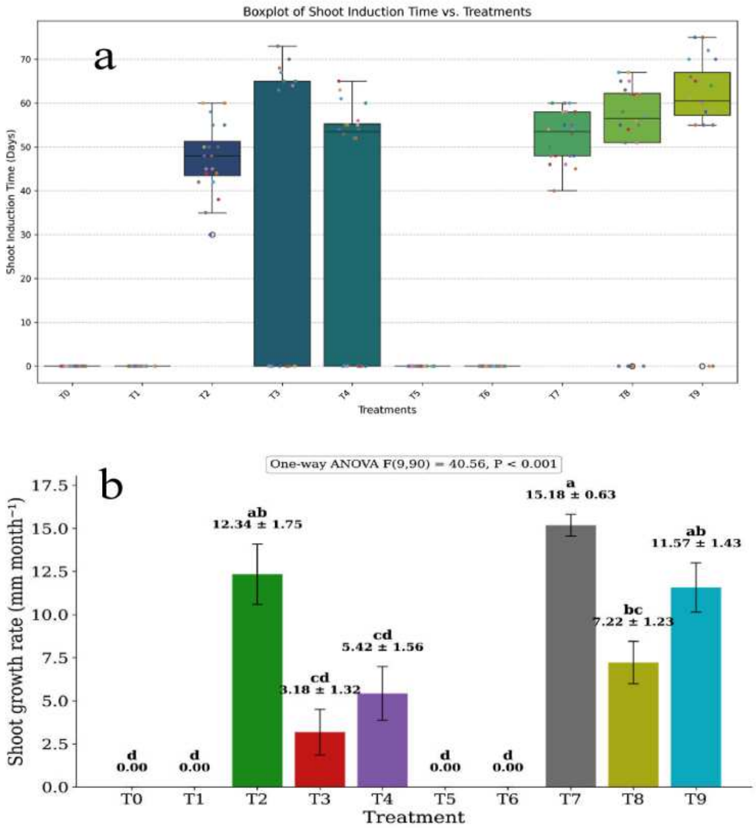

Fig. 2 Boxplot represents the (**a**) shoot induction time (days), and bar chart shows the (**b**) shoot growth (mm/month) response. (**a**) Shoot induction time differed significantly among the treatments (one-way ANOVA, F (9,190) = 39.30, p< 0.001, n=20), and Tukey's HSD post hoc test revealed insignificant differences (p>0.05) in T2, T7, T8 and T9, whereas T3 exhibited significantly delayed shoot emergence compared with T2, T4, T7, T8 and T9 (p<0.05; dot, n=20); however, T0, T1, T5 and T6 failed to induce shoot emergence. (b) Shoot growth rates are presented as the means ± SEs (n=10), and different letters denote significant differences according to Tukey's HSD test (p<0.05), followed by one-way ANOVA (F9, 90) = 40.56, p<0.001).

Water siphoned by the saplings in T3 and T4

Young tea saplings were able to transport water from the vertically buried water bags in the root zone under 2 treatments: T3 and T4. Compared with T3 (1,064.7 ml plant^{-1}), T4 siphoned more water (1,393.7 ml plant^{-1}), as the survival percentage of the saplings under T4 (65%) was greater than that under T3 (40%). However, the difference between the two treatments was statistically insignificant (p>0.05), indicating that both treatments were able to take water equally from the water bags under drought stress (Fig. 3). All the saplings under these treatments were expected to achieve a 100% survival rate at the end of the period. However, examination of the dead saplings revealed that the feeder roots within the water bags had turned dark black and were severely damaged rather than remaining healthy and white. These nonfunctional roots were unable to transport water from the bags, which appeared to be the primary cause of sapling mortality.

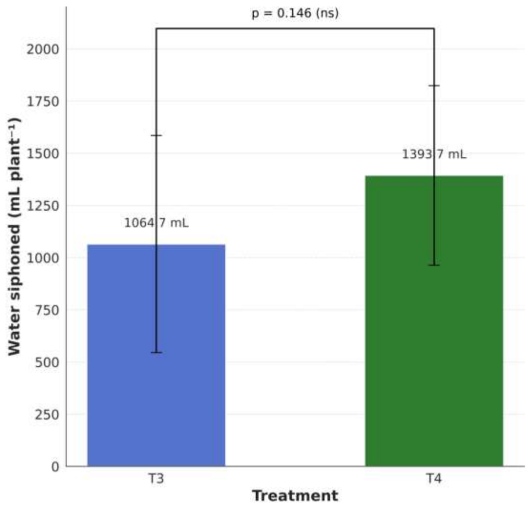

Fig. 3 Bar chart showing the average volume of water siphoned (mL) by the tea saplings from the buried water bags in treatments T3 and T4. Water uptake did not differ significantly between the two treatments ($p > 0.05$).

Root-zone moisture dynamics

The ISM percentage during the planting of the saplings varied among the treatments and was separated into two groups. Treatments T1, T4, T6, T8, and T9 maintained relatively high initial moisture (>25%) contents, as each sapling received 2-step watering during planting, whereas the saplings under T0 (control), including T2, T3, T5, and T7, received 1-step watering or lower ISM (>14%) during planting (Fig. 4 a). Greater variations in FSM were observed among the treatments during drought (Fig. 4 b). The groups T0, T1, T3, T4, and T5 presented the lowest FSM (<7%), reflecting greater depletion of available soil water during the stress period. Treatments T2 and T7 presented the highest soil moisture content (>12%), as each sapling received 2 L of water every 10 days and 15 days interval, respectively. The T8 and T9 treatments resulted in moderate moisture retention (9–10%) groups, as evaporation was partially and fully checked by underground water hyacinth root mulching and polythene film, respectively (Fig. 4 b).

Root–zone temperature dynamics

The soil temperature (°C) in the root zone significantly varied among the treatments, as the day-to-day temperature fluctuated during this period. The T3 and T4 treatments presented relatively high soil temperatures (29.24 and 29.60 °C) with broader distributions, suggesting relatively high heat accumulation within the planting pits (Fig. 4 c). In contrast, T7 maintained the lowest temperature range (25.20 °C) and presented a relatively narrow distribution, indicating more effective moderation of the thermal conditions of the root zone. Treatments T1, T5, T6, T8, and T9 resulted in moderate heat retention of approximately 27 °C (Fig. 4 c).

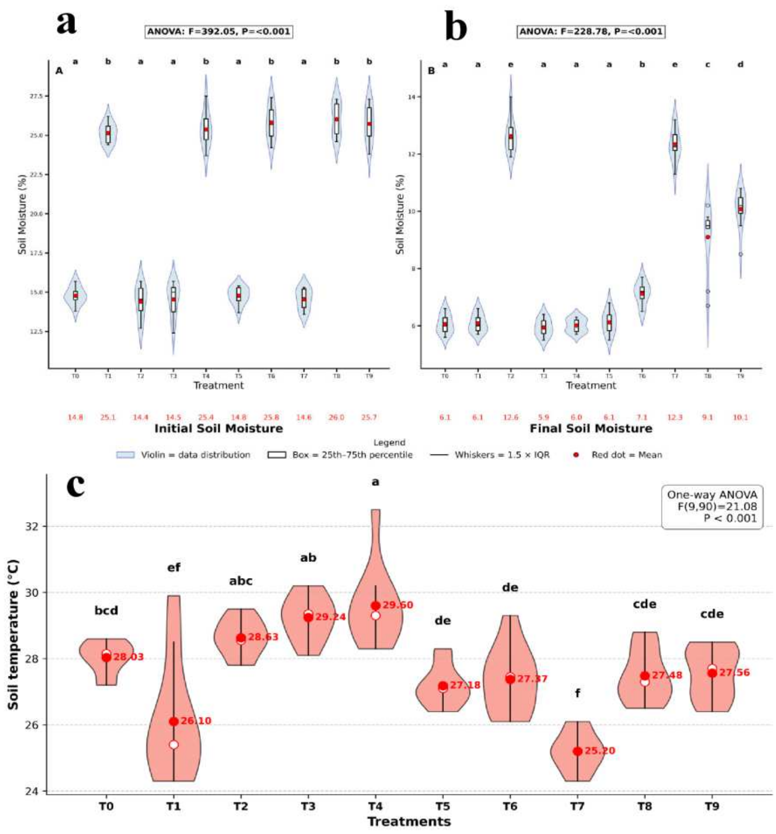

Fig. 4 Violin plots with embedded boxplots display root-zone (**a**) initial soil moisture (ISM, %); (**b**) final soil moisture (FSM, %) and (**c**) soil temperature (°C) at the prewilting stage across the 10 treatments. The red dots represent the treatment means (n=10), and the different letters denote significant differences among the treatments according to Tukey's HSD test ($p<0.05$) followed by one-way ANOVA. Significant treatment effects were detected for (**a**) ISM ($F_{(9, 90)} = 392.05$, $p<0.001$), (**b**) FSM ($F_{(9, 90)} = 228.78$, $p<0.001$) and (**c**) soil temperature ($F_{(9, 90)} = 21.08$, $p<0.001$).

Root proline

The test saplings under each treatment exhibited substantial variation in proline accumulation, ranging from 1.17 to 4.17 µmol g^{-1} FW in their roots under stress conditions (Fig. 5). The highest proline content was observed in T0 (4.17), followed by T5 (4.12) and T1 (3.81). These treatments likely experienced severe water stress and activated proline biosynthesis as a protective mechanism. The T2 and T7 treatments synthesized 1.17 and 2.23 µmol g^{-1} FW of proline, respectively, indicating an improved hydration status in the root zone to mitigate drought. However, the T6, T8, T3, T9 and T4 treatments resulted in intermediate levels of proline at 3.26, 3.21, 2.78, 2.66 and 2.52 µmol g^{-1} FW, respectively (Fig. 5), in their root cells, indicating that they experienced moderate drought in the field.

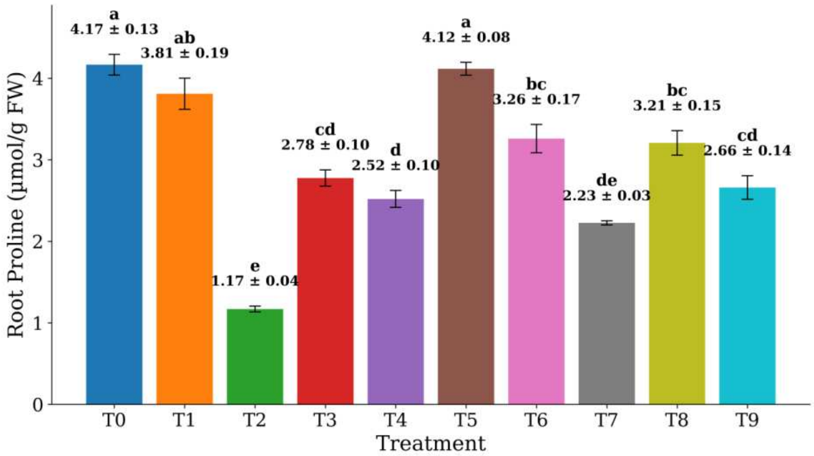

Fig. 5 Bar chart shows proline concentration in the roots of the tea saplings under different treatments. Values are presented as the means±SEs. Bars with different letters differ significantly according to Tukey's HSD test ($p<0.05$) following a significant one-way ANOVA ($F (9, 20) = 55.34$, $p<0.001$).

Correlation analysis

In the present study, Pearson correlation analysis revealed positive associations among root-zone soil moisture, survival time (ST), shoot induction time (SIT), shoot growth (SG), transpiration (T), the net photosynthetic rate (NPR), stomatal conductance (SC) and water-use efficiency (WUE). In contrast, root proline (RP) and vapor pressure deficit (VPD) were negatively correlated with the measured parameters. The soil temperature (STP) also displayed a negative correlation with the final soil moisture (FSM; Fig. 6).

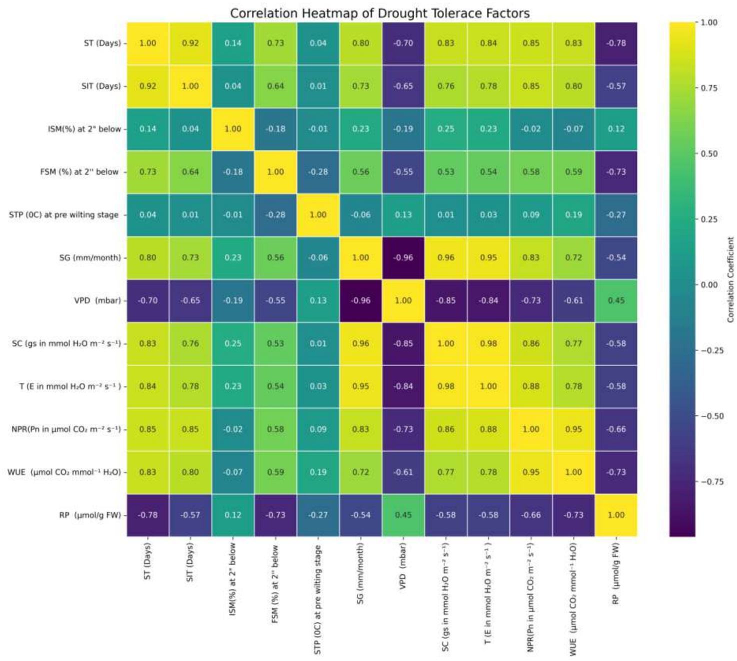

Fig. 6 Heatmap displays the Pearson correlation coefficients among the drought-determining factors. Yellow and violet indicate positive and negative correlations, respectively. Color intensity reflects the strength of the correlation; with darker shades representing stronger associations and lighter shade representing weaker associations.

Multivariate analyses: Principal component analysis (PCA)

All the measured parameters were subjected to principal component analysis (PCA) for dimensionality reduction. The first two components explained 75.81% of the total variation, with PC1 explaining 62.70% (Eigene value, 7.78) and PC2 explaining 13.11% (Eigene value, 1.63). Two major groups were observed. One cluster group consisting of T2, T7, T8 and T9 associated with SC, T, NPR, ST, SIT, WUE, SG, and FSM had high PC1 scores. This clustering suggested that these strategies promoted superior plant performance with prolonged survival, growth and physiological functions. Another cluster group consisting of T0 (control), T1, T5 and T6 with RP and VPD had low PC1 scores and was associated with stress-related characteristics (Fig. 7). The RPs and VPDs were opposite ($>90^0$) to the high-scoring PC1 variables, demonstrating strong negative correlations with plant survival, growth and physiological functions. However, treatments T3 and T4 were located close to the origin of both groups, indicating an intermediate response with no strong association with any single variable (Fig. 7). In addition, the T0, T1, T5 and T6 treatments were closely related to the RP, and the VPD exhibited a stronger association with higher values. Similarly, T2 and T7 were closely related to FSM, and SG was more strongly associated. In terms of vector lengths, almost all the variables were influential in separating the treatments except for STP and SIT; SIT contributed more than did STP (Fig. 7).

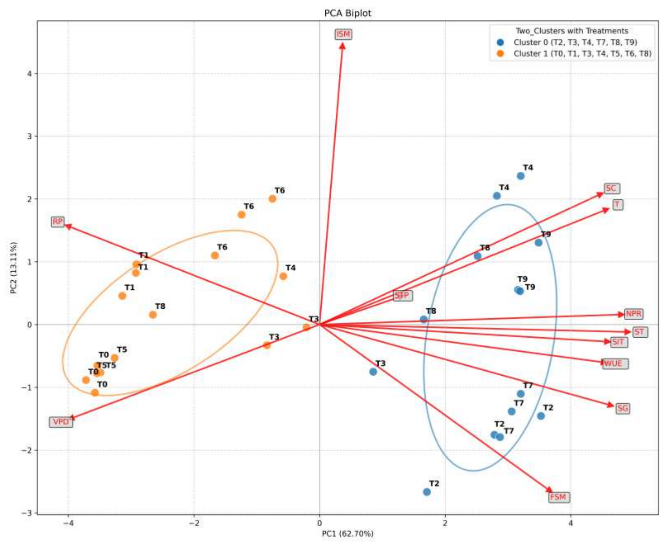

Fig. 7 PCA biplot illustrating multivariate relationships among the treatments and the drought-determining factors, including survival time (ST), shoot induction time (SIT), shoot growth (SG), root proline (RP), initial soil moisture (ISM), final soil moisture (FSM), soil temperature (STP) transpiration rate (T), net photosynthetic rate (NPR), water-use efficiency (WUE), stomatal conductance (SC) and vapor pressure deficit (VPD).

Moreover, as the angle between the vectors determined the level of association between the variables, SC and T had strong positive correlations, whereas NPR and ST, SIT and WUE, and SG and FSM had positive correlations (Fig. 7). On the other hand, the ISM, independent of the other variables, exhibited the longest vector along the positive PC2 vertical axis in the PCA biplot, indicating that it was one of the most influential variables in separating the treatments. The T1, T4, T6, T8 and T9 treatments were close to this vector and were associated with relatively high ISM values (Fig. 7). The ISM was negatively correlated with the VPD ($>90^0$) but positively correlated with SC and T ($<90^0$). Overall, the variables illustrated in the PCA biplot were well represented by

PC1 and PC2, while their vector orientations revealed both positive and negative associations among the variables. On the basis of the drought-determining parameters and performance of the test saplings in the field, the treatments were clearly separated into drought susceptible groups, which consisted of T0, T1, T5 and T6; drought tolerance groups, which consisted of T2, T7, T8 and T9; and moderate drought tolerance groups, which consisted of T3 and T4 (Fig. 7).

Structural equation modeling (SEM)

The SEM provided an excellent representation of the observed data, with all goodness-of-fit indices satisfying the recommended thresholds (χ^2/df = 1.35 (<3), comparative fit index, CFI = 0.98 (>0.95), Tucker–Lewis index, TLI = 0.97 (>0.95), root mean square error of approximation, RMSEA = 0.035 (<0.05), and standardized root mean square residual, SRMR = 0.028 (<0.08)). The SEM results indicated that the hypothesized causal pathways adequately captured the relationships among the soil moisture status and microclimate, physiological and biochemical responses, and plant growth and survival. In addition, the model exhibited high explanatory power, accounting for 93% of the variance in plant survival (R^2=0.93) and a substantial proportion of the variance (R^2) in key physiological and growth parameters (Fig. 8).

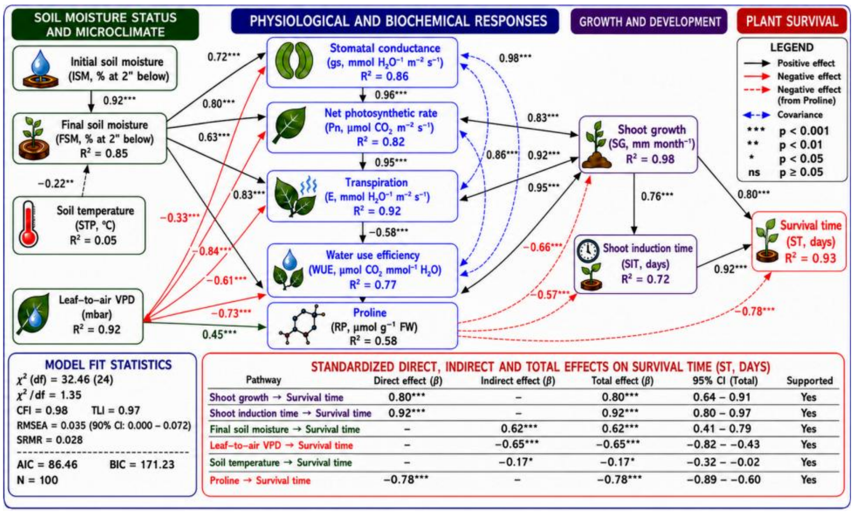

Fig. 8. Structural equation model (SEM) illustrating the direct and indirect effects of the soil water status and microclimate and physiological and biochemical responses on plant growth, development and survival under drought stress. The values on the arrows represent standardized path coefficients (ß), and R^2 indicates the proportion of variance explained in the endogenous variables.

SEM also revealed that residual soil moisture, as the principal driver, positively regulated all the observed physiological activities during drought stress. Increased soil moisture-driven physiological responses indirectly promoted prolonged plant survival (ß = 0.62), whereas enhanced vegetative development, i.e., shoot growth (ß = 0.80) and early shoot induction (ß = 0.92), were the direct determinants of prolonged plant survival under drought (Fig. 8). In this model, proline indicated that saplings whose survival time was shorter accumulated more proline in their roots under drought stress. VPD had a positive effect on the proline content (ß = 0.45), indicating that the saplings with relatively high VPD values presented high proline contents, although VPD had a negative influence on all the observed physiological activities of the test saplings (Fig. 8).

Discussion

Plant survival and mortality rates

Earlier studies revealed that supplementary irrigation during the dry period increased survival, prevented mortality and enhanced the resilience of young clonal tea (Othieno 1978; Peng et al. 2007; Sun et al. 2011; Zhang et al. 2020). The improved survival was associated with sustained root-zone soil moisture, which maintained the plant–water status, delayed hydraulic dysfunctions, triggered stomatal conductance and photosynthesis, and resulted in irreversible cellular dehydration under drought stress (Flexas et al. 2004; Chaves et al. 2009; Blum 2011; Choat et al. 2018). These physiological benefits are particularly important for young tea saplings because their fibrous and shallow root systems have limited access to deeper soil moisture, making them highly susceptible to water stress (Carr 2010; Nyarukowa et al. 2018). Although irrigation and mulching are considered effective practices for mitigating drought in tea, quantitative assessments of sapling survival under integrated root-zone moisture regimes are scarce. This study extends previous work by providing quantitative evidence for integrated root–zone moisture conservation during the critical establishment phase of tea plants (Fig. 1).

Plant growth and development

Adequate root-zone soil moisture promoted earlier shoot induction and sustained shoot elongation, whereas water deficit delayed or suppressed bud emergence, and in some saplings, resulted in mortality (Fig. 2). Similar responses have been reported in tea, where irrigation stimulates bud activation and drought delays shoot induction and growth (Carr, 2010; Zhang et al. 2020; Jin et al. 2026). The earlier bud break observed under favorable root-zone soil moisture conditions may reflect improved plant water status and photosynthetic carbon assimilation, which support bud activation and subsequent shoot development (Chaves et al. 2009; Blum 2011). Conversely, water deficit restricts shoot development through reduced cell turgor, stomatal closure, diminished photosynthesis, and impaired cell division and expansion, thereby limiting the water and assimilates supply required for shoot growth (Chaves et al. 2009; Blum 2011; Taiz et al. 2015). Similar observations were reported by De Costa et al. (2010) in tea and by Stanik et al. (2021) in *Arnica Montana*. Notably, the timing of shoot induction during the early establishment of tea saplings under water-limited conditions has received little attention, highlighting the relevance of the present findings for understanding early drought response in young tea plants.

Water syphoned by the saplings in T3 and T4

Several root-zone water management technologies designed to improve water-use efficiency under drought stress have been reported in previous studies. King et al. (2019) developed a radially slotted trunk irrigator, which delivers water directly to both the tap roots and the peripheral root network of the individual tree in a controlled manner, thereby minimizing water loss. Similarly, Wang et al. (2020) buried a vertical irrigation tube approximately 40 cm deep beside jujube trees, allowing water to be applied directly to the root zone. Unlike these systems, the vertically buried water bag evaluated in the present study functions as a localized water reservoir from which the feeding roots gradually syphoned water during drought (Fig. 3). This approach potentially prolongs water availability within the rhizosphere while reducing irrigation frequency and water loss. Its simple design suggests considerable potential for large-scale tea plantations where irrigation water is limited.

Soil moisture and temperature regimes

Soil moisture is a key determinant of sapling establishment because it regulates both plant water availability and root-zone temperature. The treatments that maintained higher soil moisture and mulching consistently improved survival and growth, whereas the unmulched treatments experienced rapid soil drying, elevated soil temperature, and greater mortality (Fig. 1, Fig. 2, Fig. 4). Reduced soil moisture limits root water uptake, whereas elevated root-zone temperature impairs feeder-root activity and increases respiratory demand, thereby accelerating drought injury (Kramer and Boyer 1995; Carr 2010; Taiz et al. 2015). In contrast, mulch preserves soil moisture and buffers soil temperature, creating a more favorable rhizosphere environment for root function and sapling establishment (Kader et al. 2017). These findings highlight the importance of integrated moisture conservation strategies for maintaining a stable root–zone environment during prolonged drought.

Root proline accumulation

The accumulation of proline in the roots closely reflected the degree of drought stress experienced by the tea saplings. Higher proline contents were detected in the tea saplings subjected to water deficit conditions, whereas those subjected to well-watered and mulched conditions presented significantly lower proline levels (Fig. 5). Similar responses have been reported in *Arabidopsis* (Szabados and Savoure 2010; Bhaskara et al. 2015) as well as in wheat, maize, rice and barley (Hayat et al. 2012), where proline functions as an important osmoprotectant during drought stress. Conversely, plants maintained under adequate soil moisture generally present relatively low proline concentrations (Verbruggen and Hermans 2008). Therefore, the proline accumulation observed in the present study provides physiological evidence that improved root-zone moisture management effectively alleviates drought stress during the early establishment of young tea plants (Fig. 5).

Relationships among edaphic, plant physiological, biochemical and survival parameters

The correlation analysis highlighted the importance of soil water availability in regulating physiological performance under drought conditions. Greater root-zone moisture is positively associated with stomatal conductance, transpiration, photosynthesis, water-use efficiency and growth, indicating that adequate soil water supports plant water status and carbon assimilation (Chaves et al. 2009; Flexas et al. 2014; Haworth et al. 2021). Conversely, higher root proline and VPD are associated with reduced physiological performance and growth, reflecting osmotic adjustment under water deficit and increased atmospheric evaporative demand, respectively (Farooq et al. 2009; Blum 2017). The negative association between soil temperature and final soil moisture further confirmed that increased temperature accelerated soil water depletion and aggravated drought stress (Fig. 6). The PCA integrated these relationships and clearly separated these treatments into drought-susceptible, moderately tolerant, and drought-tolerant groups (Fig. 7). Susceptible groups were characterized by lower root-zone moisture, gas exchange, failed shoot induction and survival but higher VP) and root proline contents, whereas tolerant groups presented greater soil moisture and physiological activities (Fig. 7). Similar responses have been widely reported under drought conditions by the above researchers, including Zandalinas et al. 2023. Thus, drought resilience in young tea plants appears to depend on the coupled regulation of soil water availability and plant physiological functions.

Conclusions

This study demonstrated that targeted root-zone hydration and moisture conservation approaches can substantially increase the drought resilience of newly planted tea saplings under prolonged water deficit conditions. Among the evaluated techniques, supplemental watering every 10- or 15-day interval combined without or with mulching (T2 and T7), respectively, consistently improved plant survival (100%), triggered shoot induction, maintained favorable plant water relationships and physiological performance, and reduced drought-induced stress compared with those of the control saplings. However, these strategies require high irrigation inputs, with each sapling receiving 20 L or 14 L of water over the 98-day experimental period. In contrast, saplings transplanted under limited-water conditions in combination with subsurface water hyacinth roots (T8) or black polyethylene film (T9) and water bagged with lateral roots (T4) exhibited comparable drought resilience and high survival rates (80–90% in T8 and T9; 65% in T4) while substantially reducing irrigation requirements. The total water consumption per sapling was only 7 L in T8 and T9, and 9 L in T4 throughout the study period. These findings indicate that efficient water management within the root zone, rather than frequent irrigation or surface mulching alone, is the primary factor governing the successful establishment of young tea plants during prolonged dry periods. Therefore, the root-zone hydration and soil moisture conservation strategies under limited-water conditions identified in this study offer practical, water-efficient and climate-resilient solutions for enhancing the early establishment of tea plants in drought-prone regions.

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Declarations

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Availability of data The data supporting the findings of this study will be available from the corresponding author upon reasonable request.

Authors' contributions Conceptualization, Methodology, Supervision, Investigation, Writing-Original Draft, Md. Moshiur Rahman Akonda; Resource, Laboratory Analyses, Writing-Editing, Md. Shariful Islam; Data Analysis, Visualization, Partho Sarker Dhrubo; Resources, AKM Rafikul Hoque, Md. Abdul Aziz and Toufiq Ahmed

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