APST

Asia-Pacific Journal of Science and Technology

https//:www.tci-thaijo.org/index.php/APST/index

Published by Research and Innovation Department,
Khon Kaen University, Thailand

Seed priming with spent tea leaves (*Camellia sinensis* L.) promotes early growth of black cherry tomato (*Solanum lycopersicum* L. var. *cerasiforme*) seedlings under drought stress

Luong Thi Le Tho[1], Luong Thi Thu Ngan[1] and Luu Tang Phuc Khang[2, *]

[1]Department of Ecology, Physiology Plants and Teaching Methods, Faculty of Biology, Ho Chi Minh city University of Education, Ho Chi Minh city 70000, Vietnam
[2]Department of Animal and Aquatic Sciences, Faculty of Agriculture, Chiang Mai University, Chiang Mai 50200, Thailand
[*]Corresponding author: khang_luu@cmu.ac.th

Received 18 January 2025
Revised 1 August 2025
Accepted 9 September 2025

Abstract

Black cherry tomato (*Solanum lycopersicum* L. var. *cerasiforme)* is an economically important crop valuable crop but is highly sensitive to drought, which hampers seed germination and early seedling growth. While spent tea leaves (STL) are known for their biological activity, their effects on tomato germination under drought stress remain unclear. This study evaluated STL extracts from black, green, and oolong cultivars as seed priming agents to enhance germination and early growth of black cherry tomato under polyethylene glycol (PEG-6000)-induced drought stress. Tomato seeds were surface-sterilized and then soaked in STL extracts at concentrations of 1%, 2%, or 4% (w/v) for 24 hours at 25ºC before sowing. Increasing PEG-6000 concentrations (0%, 4%, 8%, and 12%) caused significant reductions in germination percentage, shoot length, root length, seedling vigor index and fresh biomass, with the most severe declines observed at 12% PEG-6000. Priming with STL extracts mitigated these adverse effects in a tea type- and concentration-dependent manner. Black and oolong tea extracts at 2–4% improved germination percentage, germination speed, and vigor indices, while also enhancing radicle and plumule length, shoot height, and biomass under stress. In contrast, green tea exerted weaker or inhibitory effects. These findings suggest that black tea extract at 4% offers an effective and low-cost strategy approach to improve drought tolerance in black cherry tomato, promoting sustainable agricultural practices in the face of environmental stress.

Keywords: Tomato, Drought stress, Germination, Seed priming, Spent tea leaves

1. Introduction

Tomatoes are among the most extensively cultivated crops worldwide, valued for their significant economic and nutritional contributions [1]. According to food and agriculture organization of the United Nations (FAO) [2], global tomato production has reached nearly 190 million tons annually, with an average per capita consumption of 23 kg. Notably, China leads global production, contributing over one-third of the total, followed by India and the United States. In Vietnam, tomatoes are cultivated across approximately 25,000 hectares, with yields ranging from 30 to 40 tons per hectare [3]. Although productivity in Vietnam remains below global averages, stable cultivation areas have been maintained due to favorable weather and agricultural conditions, particularly in regions such as Lam Dong and the northern provinces [4].

Among tomato varieties, cherry tomatoes (*Solanum lycopersicum* var. *cerasiforme*) are notable for their compact size, vibrant colors and high nutritional content [5]. These fruits are rich in water, carbohydrates, proteins, lipids, organic acids, and essential vitamins, including A, B1, B6, and C [6]. Furthermore, they contain bioactive compounds such as phenolics, carotenoids (e.g., lycopene and β-carotene) [7] and glycoalkaloids (e.g., tomatine) [8], contributing to their potent antioxidant properties. These compounds neutralize free radicals, mitigating the risk of chronic diseases such as cardiovascular issues, diabetes, and obesity [9]. Regular tomato consumption has also been linked to anti-inflammatory and anticancer effects, with lycopene playing a potential role in slowing tumor progression [10].

Despite their importance, tomato crops are highly susceptible to abiotic stresses, particularly drought, which is becoming increasingly prevalent due to climate change [11]. In Vietnam, this issue is particularly pressing. Tomatoes are widely cultivated in the Central Highlands and southern provinces that have recently experienced increasingly severe and prolonged droughts due to shifting climate patterns [12]. Farmers in these areas often sow seeds or transplant tomato seedlings during the dry season, inadvertently exposing them to early drought stress at a critical developmental stage. Drought stress adversely affects tomatoes by disrupting key metabolic processes, leads to stunted growth and lower fruit yields, presenting considerable challenges for farmers [13], [14]. Consequently, it is essential to develop innovative and practical approaches to mitigate the effects of drought stress and sustain tomato production.

Seed priming is a pre-sowing technique in which seeds are partially hydrated to a point where germination-related metabolic activities are initiated, but radicle emergence does not occur [15]. This controlled hydration allows for the activation of enzymatic and molecular pathways that enhance seed performance upon subsequent sowing [16]. Research has demonstrated that seed priming improves germination rates and promotes robust seedling development even in drought scenarios [17]. Spent tea leaves (STL), an abundant by-product of the tea industry, offers a sustainable alternative for mitigating drought stress in crops. It is estimated that around 90% of tea leaves become waste during production and consumption, contributing to substantial waste volumes globally [18]. For instance, India generates approximately 190,000 tons of STL annually, while the Turkish Black Sea coast discards 30,0000 tons which was highlighted by Hussain, Anjali [19]. STL is rich in polyphenols, which possess antioxidant and plant growth-promoting properties [20]. Studies have demonstrated that polyphenols extracted from STL can enhance drought tolerance by improving water uptake, increasing chlorophyll content, and enhancing photosynthesis efficiency [21]. Therefore, using STL as a seed priming agent supports sustainable agricultural practices and circular economy principles by reducing waste and repurposing agricultural byproducts.

To mitigate the adverse the effects of drought stress, this study explores the use of STL extract as a natural biostimulant to improve the germination and early growth of black cherry tomato seeds (*Solanum lycopersicum* var. *cerasiforme*) under drought conditions induced by polyethylene glycol (PEG-6000). The findings of this study enable the development of a cost-effective and sustainable solution to mitigate the adverse of abiotic stress on tomato cultivation using agricultural by-product, contributed to agricultural pratices and circular economy.

2. Materials and methods

2.1 Plant materials and spent tea leaves extraction

The black cherry tomato seeds (*Solanum lycopersicum* L. var. *cerasiforme*) used in this study were provided from Rang Dong Seeds (Vietnam), while STL from the green, black, and oolong cultivars (*Camellia sinensis* L.) were obtained from Dalat Farm (Vietnam).

Fresh tea leaves were initially infused in 100 mL of distilled water for 5 min to mimic standard preparation for human consumption, allowing for the extraction of water-soluble compounds. STL were prepared by steeping used tea leaves in hot water at 100°C for 5 min, followed by filtration and drying the leaves at 90°C for 48 hours in drying chamber. For extraction, each sample of STL, 1 g of each dried STL sample was steeped in 100 mL of distilled water (1% w/v) at 100°C for 5 min according to Gammoudi et al. [21]. The resulting extracts were stored at 4 °C to preserve their stability.

2.2 Drought stress induced by PEG-6000 germination tests

PEG-6000 is widely recognized for its ability to simulate osmotic stress in *controlled in vitro* conditions, owing to its effectiveness in replicating water stress conditions without exerting toxic impacts [22]. In this study, black cherry tomato seeds were surface sterilized using a 1% (v/v) NaClO solution purchased from Xilong Science Co., Ltd., China for five minutes under sterile conditions in a laminar flow hood, followed by triple rinsing with sterile distilled water to eliminate any contaminants [23]. To evaluate the impact of osmotic stress on germination, seeds were placed in Petri dishes (15 cm × 15 cm) lined with Whatman filter paper (Cytiva, England), saturated with PEG-6000 (Merck, Germany) solutions at concentrations of 0%, 4%, 8%, and 12% [24]. Seeds germinated in distilled water served as the control group. All experimental setups were maintained in complete darkness at 25 °C and 50% relative humidity to prevent the light might influence germination dynamics and seedling growth [25].

2.3 Seed priming and experimental design

The experiment followed a completely randomized design (CRD) in a factorial arrangement, consisting of two factors. Factor A is STL extract types (black, green, and oolong tea) and factor B is STL extract concentrations (1%, 2%, and 4% w/v), with an unprimed control group (CS). To test the effects of STL extracts on seed priming, tomato seeds were divided into 10 groups including CS (control) and nine treatment groups primed with black (B), green (G), or oolong (O) tea extracts at three concentrations. Each treatment had three replicates of 30 seeds. Seeds were primed in these solutions at 25 °C in darkness for 24 hours and then dried on an ultra-clean bench. Prior to germination testing, seeds were surface-sterilized with 1% NaClO for five minutes, rinsed three times with sterile water, and subjected to PEG-6000-induced drought stress following consistent experimental protocols.

2.4 Sampling measurements

The germination process of black cherry tomato seeds was monitored at 24-hour intervals, with germination defined by the emergence of a radicle measuring at least 1 mm in length. Key germination and growth parameters were assessed at three specific time points: day 7, day 14, and day 21. These evaluations were conducted using established protocols from prior research [26, 27].

Germination percentage (*%, GP*) = (*Number of seed germinated*) / (*Total number of seed*) × *100* (1)

Germination rate index (*%/day*, *GRI*) = $(G_1/1) + (G_2/2) + \ldots + (G_{21}/21)$ (2)

where G_1, G_2, G_3 and G_{21} are the number of germinated seeds.

Coefficient of germination (*CoG*) = $(A_1 + A_2 + \ldots + A_x) / (A_1T_1 + A_1T_1 + \ldots + A_xT_x) \times 100.$ (3)

Where, A = Number of germinated seeds; T = Time corresponding to A; x = Number of days to final count. Length of radical (RL) and plumule (PL): Length was measured in centimeters (cm).

Seedling vigor index (SVI) = [*Mean of root length* (cm) + *Mean of shoot length* (cm)] × *germination percentage* [28]. (4)

Fresh biomass (FB) = Radicles and plumules were cut and their fresh weight in milligrams (mg) using a digital electronic balance.

Timson index of velocity (TIM) = $\sum G_i/T = (G_{1'} + G_{2'} + G_{3'} + \ldots\ldots + G_{n'}) / T$ (5)

where $G_{1'}$, $G_{2'}$, $G_{3'}$, $G_{i'}$ and $G_{n'}$ are the cumulative germination % at the first, second, third, i^{th} and n^{th} time, respectively and T is the total germination period.

Mean daily germination (MDG, %/day) = *Total number of germinated seeds* /*Total germination periods* (6)

Mean germination time (MGT, day) = $(\Sigma g_i \times t_i)/\Sigma g_i$ (7)

Where g_i is the number of germinated seeds per day and is t_i is the number of days from the start of the count [29].

2.5 Data analysis

The dataset was first tested for normality using the Kolmogorov–Smirnov test to confirm the suitability of parametric analyses. To assess the effects of PEG-6000 on germination and early seedling growth of black cherry tomatoes under drought stress, a one-way Analysis of Variance (ANOVA) was employed. In contrast, the effects of STL extracts were analyzed using two-way ANOVA, with tea type (green, black, oolong) and concentration (1%, 2%, 4%) as fixed factors. Where significant effects were detected, mean comparisons were conducted using Tukey's post hoc test at $p < 0.05$. All statistical analyses were performed in IBM SPSS Statistics (Version 29.0.2.0, IBM Corp., Armonk, NY, USA). Data visualizations were generated in OriginPro (Origin Lab Corporation, MA, USA).

3. Results

3.1 Effect of PEG-6000 concentrations on germination parameters

Germination of black cherry tomato seeds was progressively inhibited as drought stress intensified (Table 1). Under non-stressed conditions (PEG-0), seeds achieved 100 % final germination by day 21, with a high GRI (127.95 %/day) and rapid MGT (13.53 days; Table 1). However, the imposition of 4 % PEG (PEG-4) reduced final germination to 66.67 % and slowed the GRI to 91.13 %/day, whereas at 8 % PEG (PEG-8), final germination fell further to 45.56 %, with a GRI of 62.72 %/day. The most severe drought treatment (12 % PEG) resulted in only 12.22 % of seeds germinating, accompanied by the lowest GRI (33.03 %/day) and the highest MGT (13.85 days). Correspondingly, indices of germination vigor including CoG, MDG, and TIM declined significantly with increasing PEG concentration ($p < 0.05$), indicating both slower and less uniform germination under drought stress (Table 1).

Table 1 Germination parameters of black cherry tomato seed when treated with PEG-6000.

Parameters	PEG-6000 concentration (%)			
	0	4	8	12
GP (%)	100.00±0.00[a]	66.67±3.85[b]	45.56±2.94[c]	12.22±2.94[d]
TIM (%/day)	58.94±1.09[a]	45.82±1.58[b]	29.63±1.28[c]	18.62±2.01[d]
MDG (%/day)	4.76±0.00[a]	3.17±0.09[b]	2.01±0.05[c]	1.38±0.14[d]
CoG	7.52±0.16[a]	7.39±0.09[ab]	7.39±0.10[ab]	7.22±0.13[b]
MGT (day)	13.53±0.09[b]	13.53±0.06[b]	13.29±0.17[b]	13.85±0.14[a]
GRI (%/day)	127.95±4.61[a]	91.13±3.50[b]	62.72±3.22[c]	33.03±3.18[d]

Data are presented as mean ± SD. Different letter in one row indicates significant differences between treatment with $p < 0.05$.

3.2 Effect of PEG-6000 concentrations on growth parameters

Seedling growth parameters exhibited a similarly negative response to increasing water deficit (Figure 1). In the absence of stress, RL, PL, and SH were 5.38 cm, 3.34 cm, and 3.75 cm, respectively: yielding a high SVI (875.71) and FB of 23.35 mg (Table 2). Under PEG-4, radicle and PL decreased to 3.77 cm and 0.51 cm, respectively, while SH fell to 3.41 cm: the SVI and FB dropped by more than 50 % relative to control. Further increases in drought severity to 8 % and 12 % PEG sharply curtailed root and shoot elongation (RL of 0.36 cm and 0.90 cm; SH of 1.38 cm and 0.00 cm, respectively), with concomitant reductions in SVI (168.51 and 7.50) and FB (14.61 mg and 6.63 mg). These results demonstrate that both germination performance and early seedling growth of black cherry tomato are highly susceptible to drought stress, particularly at PEG concentrations ≥ 8 %.

Table 2 Growth parameters of black cherry tomato seed when treated with PEG-6000.

Parameters	PEG-6000 concentration (%)			
	0	4	8	12
Radicle length (cm)	5.38±0.35[a]	3.77±0.35[b]	3.66±0.06[b]	0.90±0.06[c]
Plumule length (cm)	3.34±0.16[a]	0.51±0.01[b]	0.36±0.02[b]	0.31±0.03[b]
Shoot height (cm)	3.75±0.17[a]	3.41±0.05[b]	1.38±0.13[b]	0.00±0.00[c]
Fresh biomass (mg)	875.71±45.86[a]	478.31±42.87[b]	168.51±22.46[c]	7.50±3.03[d]
Seedling vigor index	23.35±0.82[a]	21.55±0.89[a]	14.61±0.42[b]	6.63±0.43[c]

Data are presented as mean ± SD. Different letter in one row indicates significant differences between treatment with $p < 0.05$.

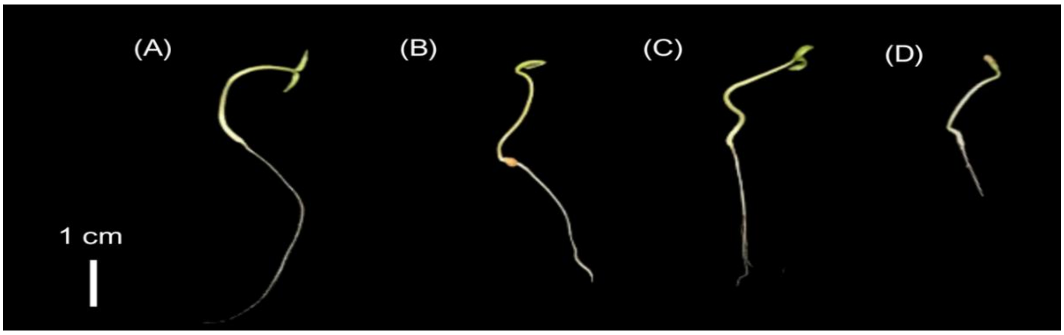

Figure 1 Black cherry tomato seeds germination at day 21 when treated with 0 % (A), 4% (B), 8% (C), and 12% (D) PEG-6000.

3.3 Effect of seed priming with spent tea leaves extract on germination parameters

The analysis of variance revealed that germination responses were differentially affected by tea type, concentration, and their interaction (Table 3). GP was significantly influenced by concentration (F = 5.65, p = 0.012) and by the interaction between tea type and concentration (F = 11.31, $p < 0.001$), while the main effect of tea type alone was not significant. Similarly, the TIM, which reflects the speed and uniformity of germination, was strongly affected by concentration (F = 13.59, $p < 0.001$) and the interaction (F = 17.41, $p < 0.001$), with tea type showing only a marginal effect (p = 0.051).

In contrast, MDG was not significantly affected by any factor. However, both the CoG and MGT were significantly influenced by tea type ($p < 0.05$), concentration ($p < 0.05$), and their interaction ($p < 0.01$), indicating that the dynamics of germination were shaped by the combined effects of the treatments. In addition, the GRI was significantly altered by all factors, with strong effects of concentration (F = 12.83, $p < 0.001$) and the interaction (F = 16.42, $p < 0.001$).

Table 3 ANOVA summary for germination-related traits under different tea types and concentrations in a CRD factorial design.

Parameter	Type of tea	Concentration (%)	Interaction (A×B)
Germination percentage (%)	ns (p = 0.64)	F = 5.65, p = 0.012	F = 11.31, $p < 0.001$
Timson index	p = 0.051 (marginal)	F = 13.59, $p < 0.001$	F = 17.41, $p < 0.001$
Mean daily germination (%/day)	ns (p = 0.85)	ns (p = 0.16)	ns
Coefficient of germination	F = 3.71, p = 0.045	F = 4.55, p = 0.025	F = 5.58, p = 0.004
Mean germination time (day)	F = 3.83, p = 0.041	F = 4.71, p = 0.023	F = 5.61, p = 0.004
Germination rate index (%/day)	F = 3.84, p = 0.041	F = 12.83, $p < 0.001$	F = 16.42, $p < 0.001$

Notes: "ns" indicates non-significant.

Seed germination responses varied considerably with tea type and concentration (Figure 2). GP was significantly reduced by higher concentrations of black tea, whereas oolong tea at 4% promoted the highest germination percentage. Green tea produced intermediate effects, with no clear concentration-dependent trend. A similar pattern was evident for the TIM, where black tea at 4% and oolong tea at 4% markedly enhanced germination speed and uniformity, while lower values were recorded at 2% green tea and 2% oolong tea. By contrast, MDG showed little variation across treatments, although black tea at 4% yielded slightly higher values compared to other combinations. The CoG remained relatively stable among treatments, with only minor differences detected in oolong tea. More pronounced effects were observed in MGT, which was significantly reduced by oolong tea at 2%, indicating accelerated germination, whereas green tea treatments maintained longer germination times. In addition, the GRI highlighted strong concentration- and tea type-dependent differences, with oolong tea at 4% and black tea at 4% producing the most rapid germination, while the lowest rates were observed in green tea at 2% and oolong tea at 2%.

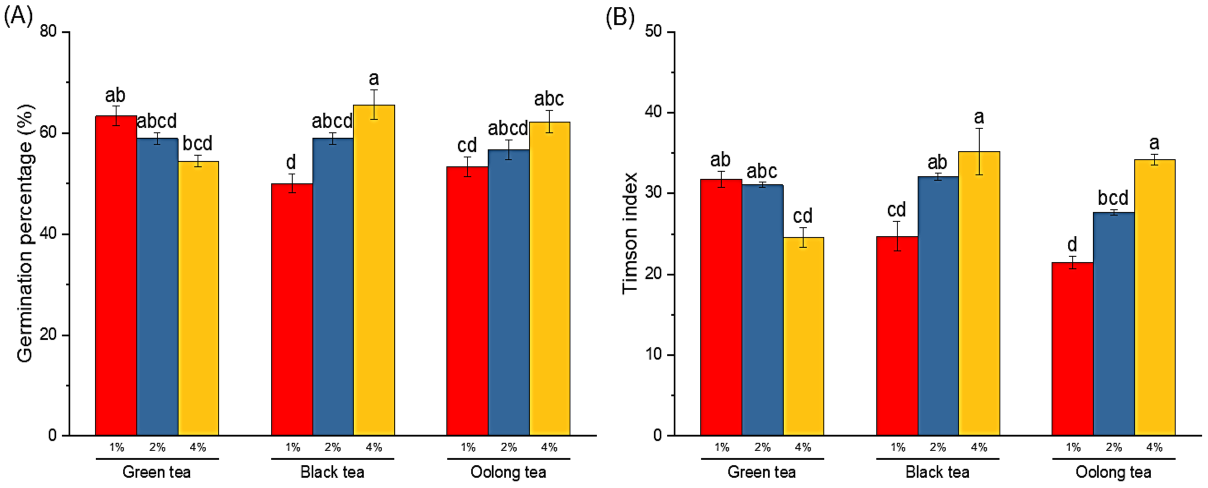

Figure 2 Effects of tea extracts on germination-related parameters under different concentrations. (A) Germination percentage, (B) Timson index, (C) mean daily germination, (D) coefficient of germination, (E) mean germination time, and (F) germination rate index of seeds treated with green, black, and oolong tea extracts at 1%, 2%, and 4%. Values represent means ± SD. Different letters above bars indicate significant differences among treatments according to Tukey's test ($p < 0.05$).

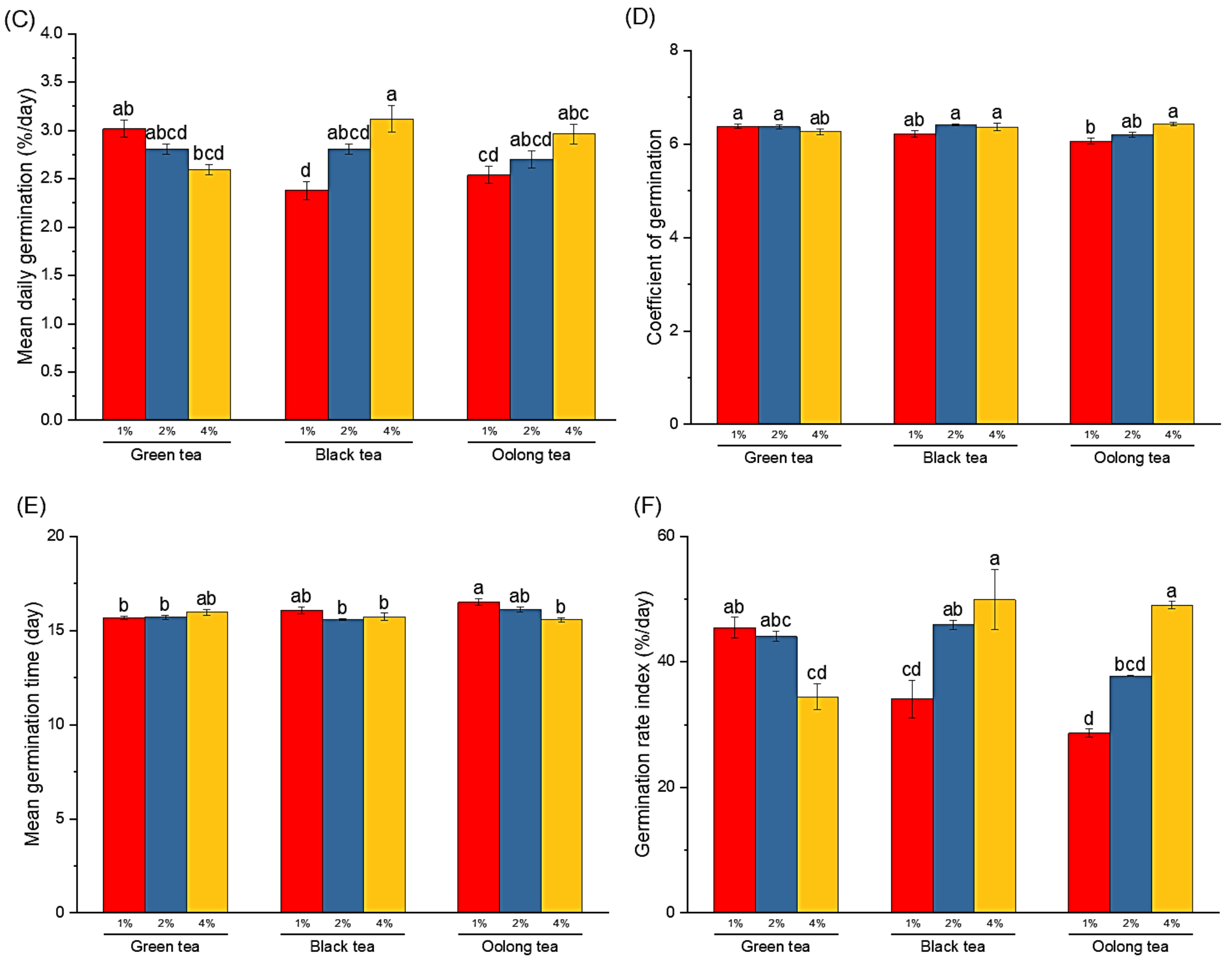

Figure 2 (cont.) Effects of tea extracts on germination-related parameters under different concentrations. (A) Germination percentage, (B) Timson index, (C) mean daily germination, (D) coefficient of germination, (E) mean germination time, and (F) germination rate index of seeds treated with green, black, and oolong tea extracts at 1%, 2%, and 4%. Values represent means ± SD. Different letters above bars indicate significant differences among treatments according to Tukey's test ($p < 0.05$).

3.4 Effect of seed priming with spent tea leaves extract on growth parameters

The ANOVA results indicated that tea type and concentration significantly influenced all seedling growth parameters, although the interaction effects varied (Table 4). Radicle length was strongly affected by both tea type ($F = 26.54$, $p < 0.001$) and concentration ($F = 136.01$, $p < 0.001$), whereas their interaction was not significant. In contrast, plumule length and shoot height showed significant main effects of both factors as well as highly significant interactions. Similarly, fresh biomass and seedling vigor index were markedly influenced by tea type and concentration, with strong interaction effects ($F = 25.88$, $p < 0.001$ and $F = 15.86$, $p < 0.001$, respectively).

Marked variations in seedling growth responses were observed across tea types and concentrations (Figure 3). RL increased significantly with higher concentrations of all tea extracts, although the extent of stimulation differed among teas. Black tea at 4% yielded the greatest radicle elongation, followed closely by oolong tea, whereas green tea consistently produced shorter radicles at all concentrations. Similarly, PL exhibited a strong dependence on both tea type and concentration. Oolong tea at 4% resulted in the tallest plumules, while green tea extracts, particularly at 2%, restricted elongation. SH followed a comparable trend, with black tea at 2% producing the tallest shoots, whereas green tea at 2% markedly suppressed shoot elongation. The SVI was significantly enhanced by oolong tea, with 2% and 4% concentrations yielding the highest vigor values, whereas green tea-treated seedlings showed consistently lower vigor across treatments. Likewise, FB was greatest under black tea at 2% and oolong tea at 4%, contrasting with the reduced biomass recorded in green tea treatments. Representative images of seedlings under different treatments further illustrated these patterns (Figure 3F). Seedlings treated with black and oolong tea exhibited longer radicles and more developed shoots, while those exposed to green tea remained shorter and displayed limited biomass accumulation.

Table 4 ANOVA summary for seedling growth traits under different tea types and concentrations in a CRD factorial design.

Parameter	Type of tea	Concentration (%)	Interaction (A×B)
Radicle length (cm)	F = 26.54, $p < 0.001$	F = 136.01, $p < 0.001$	ns ($p = 0.24$)
Plumule length (cm)	F = 102.45, $p < 0.001$	F = 12.01, $p < 0.001$	F = 21.79, $p < 0.001$
Shoot height (cm)	F = 5.07, $p = 0.0076$	F = 29.42, $p < 0.001$	F = 22.67, $p < 0.001$
Fresh biomass (mg)	F = 38.00, $p < 0.001$	F = 13.23, $p < 0.001$	F = 25.88, $p < 0.001$
Seedling vigor index	F = 77.37, $p < 0.001$	F = 10.05, $p = 0.0012$	F = 15.86, $p < 0.001$

Notes: “ns” indicates non-significant.

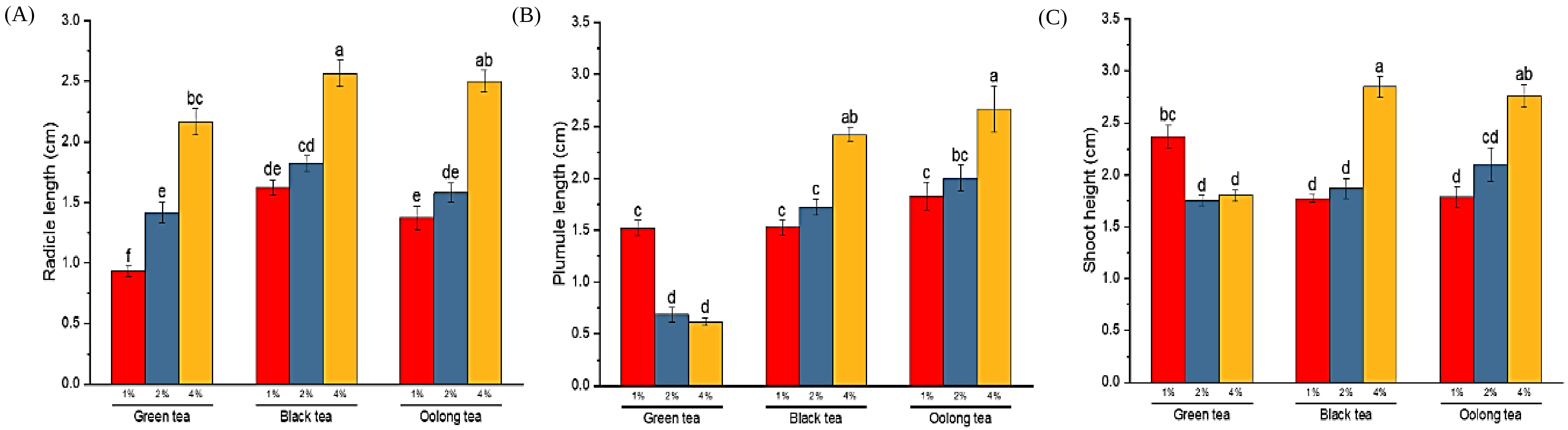

Figure 3 Effects of spent tea leaves extract on seedling growth traits under different concentrations. (A) Radicle length, (B) plumule length, (C) shoot height, (D) seedling vigor index, and (E) fresh biomass of seedlings treated with green, black, and oolong tea extracts at 1%, 2%, and 4%. (F) Representative images of seedlings grown under each treatment. Values are means ± SD. Different letters above bars indicate significant differences among treatments according to Tukey’s test ($p < 0.05$).

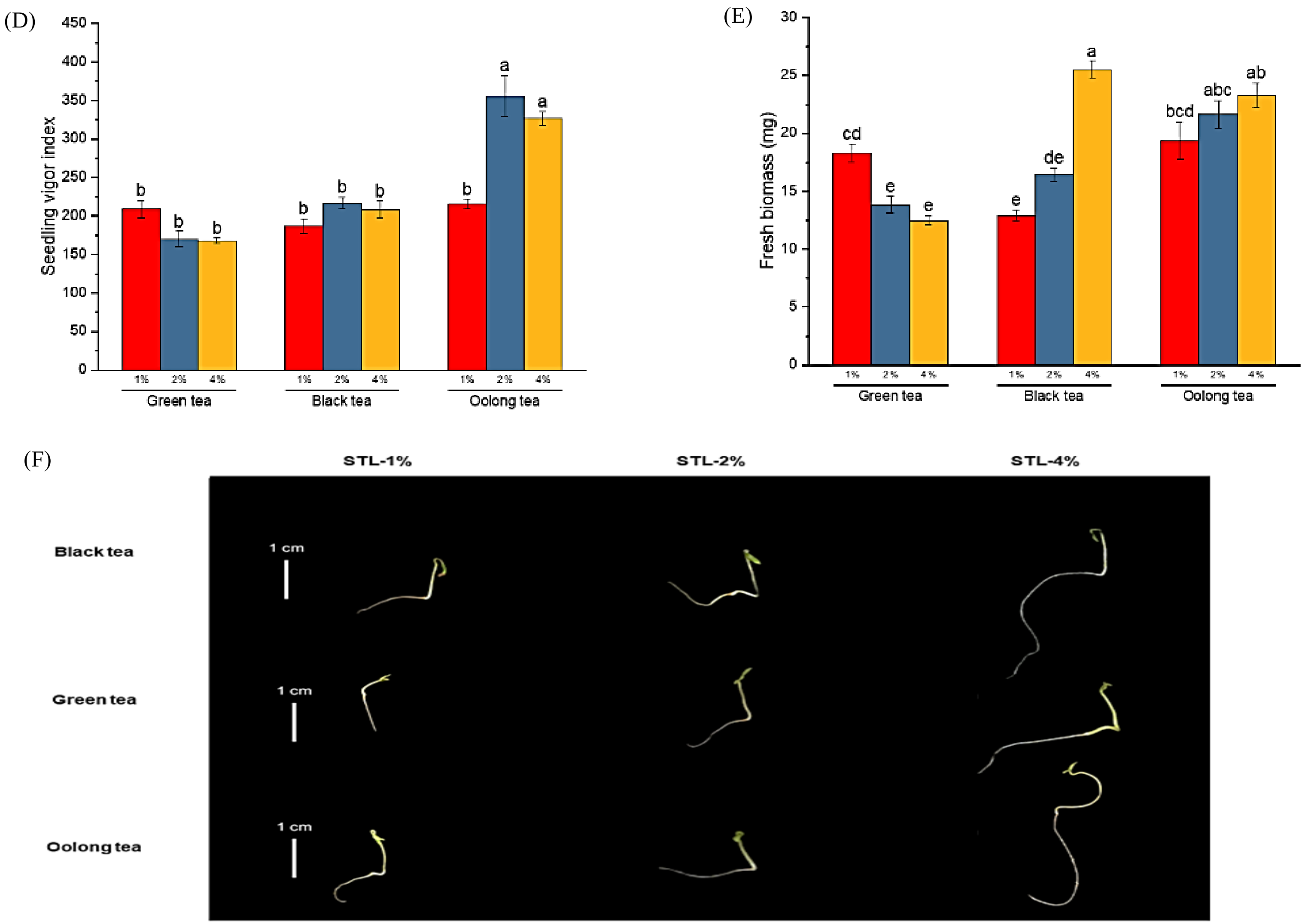

Figure 3 (cont.) Effects of spent tea leaves extract on seedling growth traits under different concentrations. (A) Radicle length, (B) plumule length, (C) shoot height, (D) seedling vigor index, and (E) fresh biomass of seedlings treated with green, black, and oolong tea extracts at 1%, 2%, and 4%. (F) Representative images of seedlings grown under each treatment. Values are means ± SD. Different letters above bars indicate significant differences among treatments according to Tukey's test ($p < 0.05$).

4. Discussions

Seed germination is a vital process ensuring plant survival, enabling species to adapt to environmental challenges over time and space [30]. Parameters such as germination percentage and days to first germination reflect the seeds' potential to transition into seedlings [31]. Metrics like germination energy and germination index also evaluate the uniformity and rate of germination, with higher values indicating enhanced seed performance [32]. Similarly, germination energy and germination index are used to evaluate the rate and uniformity of seed germination, where higher values indicate enhanced germination performance. The vigor index combines these parameters, providing a comprehensive measure of seed potential [33]. In this study, drought simulated using PEG-6000 significantly reduced GP, GRI, and SVI, while increasing MGT. These results indicate suppressed germination performance, consistent with previous findings in sunflower, wheat and hybrid corn [34]. Insufficient energy to support imbibition and slowed water absorption under stress contributed to this trend. MGT increased under drought stress, reflecting slower germination, consistent with reports in *Brassica napus* L. [35]. Drought stress, simulated by PEG-6000 in our study, primarily affects tomato seed germination and seedling growth by limiting water availability and disrupting cellular processes essential for early development. PEG-6000 creates an osmotic potential that mimics water-deficient conditions, making it harder for seeds to absorb water which is a critical first step for activating metabolism and initiating germination [22]. As a result, germination is delayed or reduced due to insufficient enzyme activity, impaired energy mobilization, and restricted cell expansion. In seedlings, continued exposure to osmotic stress can inhibit root and shoot elongation, reduce biomass accumulation, and disrupt hormonal balance [14, 22, 34].

To counteract these negative effects, seed priming with STL extracts was employed and showed marked improvements in germination speed and vigor under water-deficient conditions. Seed priming, particularly with STL extracts, emerged as an effective pre-sowing technique to mitigate drought effects. This cost-effective method enhances seedling establishment by accelerating germination and growth [30, 35]. Priming facilitates water uptake during the imbibition phase, reduces the lag phase, and boosts metabolic activities like ATP synthesis, protein production and nutrient mobilization [31]. Improved performance is linked to physiological and biochemical transformations, including enhanced enzymatic activity, osmotic regulation, and reduced lipid peroxidation [32]. In this study, STL priming significantly improved germination speed and vigor under drought conditions. Our results align closely with those of Gammoudi et al. (2020), who demonstrated that aqueous extracts of STL significantly improved in vitro germination and early growth of Capsicum annuum under PEG-induced drought stress [21]. Similar improvements in germination speed and biomass under drought stress have been recorded with green tea (*Camellia sinensis*) extract priming in mung bean (*Vigna radiata* L.) [36]. The improved performance can be attributed to the bioactive compounds in STL, particularly phenolic acids and flavonoids, which play multifaceted roles in alleviating oxidative stress, promoting hormonal balance, and enhancing metabolic activity. Phenolics such as catechins, gallic acid, and theaflavins which are abundant in black, green, and oolong STL have been shown to scavenge reactive oxygen species (ROS) and upregulate antioxidant enzymes like Superoxide Dismutase (SOD), computer-aided translation (CAT) , and Proof of Delivery (POD) thereby protecting membranes and proteins during early germination [37]. Beyond antioxidation, phenolics act as signaling molecules that influence phytohormone dynamics, particularly by suppressing ABA activity and enhancing gibberellic acid (GA) and brassinosteroid pathways that drive radicle emergence and shoot elongation through cell division [38-40]. The enhanced shoot and root elongation recorded in our results correlates with phneolics' role in activating different phytohormones as well as adjusting osmosis in the cell. Phenolics also activate mitogen-activated protein kinase (MAPK) cascades notably the ROS-activated MAPK pathway which in turn induce stress-responsive transcription factors that regulate osmolyte biosynthesis [41, 42]. STL compounds also influence early seedling growth by modulating hormonal balance and nutrient mobilization. Additionally, these compounds stimulate key metabolic enzymes such as phenylalanine ammonia-lyase and chalcone synthase which not only drive secondary metabolite synthesis but also improve the mobilization of storage proteins and carbohydrates, fueling seedling biomass accumulation [41]. The metabolic enhancement, combined with maintained water balance by phenolic compounds directly explains the higher biomass yields observed in STL-primed seedlings compared to drought-stressed controls. These compounds supported physiological adaptations akin to those induced by selenium nanoparticles, and salicylic acid, previously shown to improve drought-stressed tomato germination [43]. This enhancement can be linked to the correlations between priming-induced nuclear replication and improvements in tomato seed vigor, similar to the findings in *Capsicum anuum* L. seed [21].

Despite these promising findings, limitations exist. The controlled experimental setup may not fully replicate variable field conditions. The biochemical pathways and specific roles of STL compounds in drought tolerance were not fully elucidated. Furthermore, the study focused solely on germination and early seedling stages, leaving long-term impacts on growth, yield, and resilience unexplored. Future research should validate STL priming under diverse field conditions and investigate molecular mechanisms to identify bioactive compounds contributing to drought tolerance. Long-term studies assessing growth, yield, and stress resilience are needed to evaluate STL priming's agricultural potential comprehensively. Additionally, scalable extraction methods and consistent STL extract quality should be explored to integrate this sustainable approach into large-scale agricultural practices.

5. Conclusions

The present study demonstrates that black cherry tomato seeds are highly sensitive to drought stress induced by PEG-6000, with germination percentage, vigor indices, and seedling growth traits all declining sharply as PEG concentration increased. Severe stress (≥ 8% PEG) nearly suppressed germination and drastically reduced radicle and shoot elongation, fresh biomass, and overall vigor. By contrast, seed priming with spent tea leaf extracts modulated germination and seedling performance in a concentration- and tea type-dependent manner. Oolong and black tea extracts, particularly at moderate concentrations (2–4%), enhanced germination indices, promoted radicle and plumule elongation, and increased seedling vigor and biomass, whereas green tea exerted comparatively weaker or inhibitory effects. Collectively, these findings suggest that while drought stress severely restricts germination and seedling growth, priming with certain types of tea extracts, especially oolong and black tea, can improve seedling performance and potentially mitigate early stress impacts. This indicates a promising role of spent tea leaf extracts as low-cost, sustainable biostimulants for enhancing germination and vigor under suboptimal conditions. Further research is needed to explore the mechanisms behind STL efficacy and assess its broader agricultural applications.

6. Acknowledgements

The authors would like to express their sincere gratitude to the Faculty of Biology, Ho Chi Minh City University of Education, Ho Chi Minh city 70000, Vietnam for their invaluable support and assistance throughout this study.

7. References

[1] Panno S, Davino S, Caruso AG, Bertacca S, Crnogorac A, Mandić A. A review of the most common and economically important diseases that undermine the cultivation of tomato crop in the mediterranean basin. Agronomy. 2021;11(11):2188.

[2] FAO. Food and Agriculture Organization of the United Nations. 1st Edition. Overcoming water challenges in agriculture. 2020.

[3] Vuong TAT, Nguyen DT, Nguyen PTT, Hoang NT, Vu CL. Evaluation of morphological characteristics of tomato accessions at the National Plant Genebank in Vietnam. Technol Hortic. 2024;4(1):1–8.

[4] Hai Chau M, Xuan Chinh N. Effect of plant density and fertilizer application rates on growth, fruit yield and quality of tomato (*Solanum lycopersicum* L.) in greenhouse condition. Asian Plant Res J. 2021;8(3):22-31.

[5] Dong S, Zhang J, Ling J, Xie Z, Song L, Wang Y. Comparative analysis of physical traits, mineral compositions, antioxidant contents, and metabolite profiles in five cherry tomato cultivars. Food Res Intl. 2024;194:114897.

[6] Delgado-Vargas F, Sicairos-Medina LY, Luna-Mandujan AG, López-Angulo G, Salazar-Salas NY, Vega-García MO. Phenolic profiles, antioxidant and antimutagenic activities of *Solanum lycopersicum* var. *cerasiforme* accessions from Mexico. CyTA J Food. 2018;16(1):715-722.

[7] Lo C, Manurung R, Esyanti RR. Enhancement of lycopene and βcarotene production in cherry tomato fruits (*Solanum Lycopersicum* L. var. *cerasiforme*) by using red and blue light treatment. Int J Tech Res Appl. 2014;2:7-10.

[8] Venkadeswaran E, Vethamoni PI, Arumugam T, Manivannan N, Harish S. Evaluating the yield and quality characters of cherry tomato *Solanum lycopersicum* (L.) var. *cerasiforme* Mill. Genotypes. Int J Chem Stud. 2018;6(3):858-863.

[9] Pinela J, Oliveira MBP, Ferreira IC. Bioactive compounds of tomatoes as health promoters. Natural bioactive compounds from fruits and vegetables as health promoters: Part II: Bentham Science Publishers. 2016;2:48-91.

[10] Jiménez Bolaño DC, Insuasty D, Rodríguez Macías JD, Grande-Tovar CD. Potential use of tomato peel, a rich source of lycopene, for cancer treatment. Molecules. 2024;29(13):3079.

[11] Machado J, Fernandes A, Fernandes T, Heuvelink E, Vasconcelos M, Carvalho S. Drought and nitrogen stress effects and tolerance mechanisms in tomato: a review. Plant Nutr Food Secur Clim Change. 2022;3:315-359.

[12] Anh HH, Phuong DND, Ha PT, Tu LH, Hanh TMD, Loi NK. Sustainable agricultural development in Gia Lai Province, Central Highlands Vietnam: A holistic approach to addressing socio-economic and climate challenges. Environ Dev Sustain. 2024;5:1-35.

[13] Chegini SN, Jafarinia M, Ghotbi-Ravandi AA. Unraveling the impacts of progressive drought stress on the photosynthetic light reaction of tomato: Asassed by chlorophyll-a fluorescence and gene expression analysis. Cell Mol Biol. 2024;70(11):176-184.

[14] Wahab A, Abdi G, Saleem MH, Ali B, Ullah S, Shah W. Plants' physio-biochemical and phyto-hormonal responses to alleviate the adverse effects of drought stress: A comprehensive review. Plants. 2022;11(13):1620.

[15] Ashraf M, Foolad M. Pre-sowing seed treatment—A shotgun approach to improve germination, plant growth, and crop yield under saline and non-saline conditions. Adv Agron. 2005;88:223-271.

[16] Rhaman MS, Imran S, Rauf F, Khatun M, Baskin CC, Murata Y, et al. Seed priming with phytohormones: An effective approach for the mitigation of abiotic stress. Plants. 2020;10(1):3-7.

[17] Marthandan V, Geetha R, Kumutha K, Renganathan VG, Karthikeyan A, Ramalingam J. Seed priming: a feasible strategy to enhance drought tolerance in crop plants. Int J Mol Sci. 2020;21(21):8258.

[18] Negi T, Kumar Y, Sirohi R, Singh S, Tarafdar A, Pareek S, et al. Advances in bioconversion of spent tea leaves to value-added products. Bioresour Technol. 2022;346:126409.

[19] Hussain S, Anjali K, Hassan ST, Dwivedi PB. Waste tea as a novel adsorbent: a review. Appl Water Sci. 2018;8:1-16.

[20] González-Hernández AI, Pérez-Sánchez R, Plaza J, Morales-Corts MR. Compost tea as a sustainable alternative to promote plant growth and resistance against Rhizoctonia solani in potato plants. Sci Hortic. 2022;300:111090.

[21] Gammoudi N, Nagaz K, Ferchichi A. Potential use of spent coffee grounds and spent tea leaves extracts in priming treatment to promote *In Vitro* early growth of salt-and drought-stressed seedlings of *Capsicum annuum* L. Waste Biomass Valor. 2021;12:3341-3353.

[22] Wang C, Zhou L, Zhang G, Xu Y, Gao X, Jiang N, et al. Effects of drought stress simulated by polyethylene glycol on seed germination, root and seedling growth, and seedling antioxidant characteristics in Job's Tears. Agric Sci. 2018;9(8):991-1006.

[23] Rutkowski M, Krzemińska-Fiedorowicz L, Khachatryan G, Bulski K, Kołton A, Khachatryan K. Biodegradable silver nanoparticles gel and its impact on tomato seed germination rate in *in vitro* cultures. Appl Sci. 2022;12(5):2722.

[24] Basha PO, Sudarsanam G, Reddy MMS, Sankar S. Effect of PEG induced water stress on germination and seedling development of tomato germplasm. Inter J Recent Sci Res. 2015;6(5):4044-4049.

[25] Nawaz A, Amjad M, Pervez MA, Afzal I. Effect of halopriming on germination and seedling vigor of tomato. Afr J Agric Res. 2011;6(15):3551-3559.

[26] Rofekuggaman M, Kubra K, Mahmood S. Effect of different salt concentrations (NaCl) on seed germination and seedling growth of tomato cv. BINA Tomato-10. Asian Plant Res J. 2020;5(3):38-44.

[27] Ranal MA, Santana DGd. How and why to measure the germination process. Braz J Bot. 2006;29:1-11.

[28] Abdul-Baki AA, Anderson JD. Vigor determination in soybean seed by multiple criteria 1. Crop Sci. 1973;13(6):630-633.

[29] Abou El-Nour HH, Attia RM. Evaluate the effects of rare earth elements on sweet pepper seeds germination process, seedlings growth and plants productivity. GSC Adv Res Rev. 2022;13(1):23-38.

[30] Gul B, Ansari R, Flowers TJ, Khan MA. Germination strategies of halophyte seeds under salinity. Environ Exp Bot. 2013;92:4-18.

[31] Donohue K, Rubio de Casas R, Burghardt L, Kovach K, Willis CG. Germination, postgermination adaptation, and species ecological ranges. Annu Rev Ecol Evol Syst. 2010;41(1):293-319.

[32] Reed RC, Bradford KJ, Khanday I. Seed germination and vigor: ensuring crop sustainability in a changing climate. Heredity. 2022;128(6):450-459.

[33] Zhang T, Fan S, Xiang Y, Zhang S, Wang J, Sun Q. Non-destructive analysis of germination percentage, germination energy and simple vigour index on wheat seeds during storage by Vis/NIR and SWIR hyperspectral imaging. Spectrochim Acta Part A Mol Biomol Spectrosc. 2020;239:118488.

[34] Khodarahmpour Z. Effect of drought stress induced by polyethylene glycol (PEG) on germination indices in corn (*Zea mays* L.) hybrids. Afr J Biotechnol. 2011;10(79):18222-18227.

[35] Lombardi T, Bedini S. Seed germination strategies of Mediterranean halophytes under saline conditions. Handbook of halophytes: From molecules to ecosystems towards biosaline agriculture. Handb Halophytes. 2020;8:1-19.

[36] Mahmoud R, Al-Hayani E, Mohammed R. Effect of seed priming with green tea (*Camellia sinensis* L.) aqueous extract on germination and growth traits of mung bean (*Vigna radiata* L.). Sabrao J Breed Genet. 2023;55(6):2250-2255.

[37] Waqas M, Korres NE, Khan MD, Nizami AS, Deeba F, Ali I. 7th edition. Advances in the concept and methods of seed priming. Priming and pretreatment of seeds and seedlings: Implication in plant stress tolerance and enhancing productivity in crop plants. Springer Nature Singapore Pte Ltd. 2019.

[38] Ahmad S, Belwal V, Punia SS, Ram M, Dalip, Rajput SS. Role of plant secondary metabolites and phytohormones in drought tolerance: A review. Gesunde Pflanz. 2023;75(4):729-746.

[39] Wu J, Lv S, Zhao L, Gao T, Yu C, Hu J. Advances in the study of the function and mechanism of the action of flavonoids in plants under environmental stresses. Planta. 2023;257(6):108-109.

[40] Corso M, Perreau F, Mouille G, Lepiniec L. Specialized phenolic compounds in seeds: Structures, functions, and regulations. Plant Sci. 2020;296:110471.

[41] Sharma A, Shahzad B, Rehman A, Bhardwaj R, Landi M, Zheng B. Response of phenylpropanoid pathway and the role of polyphenols in plants under abiotic stress. Molecules. 2019;24(13):2452.

[42] Park YJ, Kwon DY, Koo SY, Truong TQ, Hong S-C, Choi J. Identification of drought-responsive phenolic compounds and their biosynthetic regulation under drought stress in Ligularia fischeri. Front Plant Sci. 2023;14:1140509.

[43] Shah A, Smith DL. Flavonoids in agriculture: Chemistry and roles in, biotic and abiotic stress responses, and microbial associations. Agronomy. 2020;10(8):1209.

[44] Shi R, Tong L, Du T, Shukla MK. Response and modeling of hybrid maize seed vigor to water deficit at different growth stages. Water. 2020;12(11):3289.