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Tooba Khalil: Assistance with the pot experiment, laboratory analyses, data recording, and review and editing of the manuscript.
Arij Khalil: Supervision, validation, critical evaluation of the experimental design, interpretation of findings, manuscript review and revision, and final approval of the submitted manuscript.

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Sustainable Management of Alkaline Stress using Clove Fruit Extract in Tomato

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Abstract:
Alkalinity stress is a critical abiotic factor that affects tomato (*Solanum lycopersicum* L.) growth and productivity by inducing nutrient imbalance, oxidative damage, and physiological dysfunction. This study investigated the potential of clove (*Syzygium aromaticum*) fruit extract (CFE) as a sustainable bio-stimulant for improving tomato tolerance under alkaline conditions. A factorial pot experiment was conducted with two alkalinity treatments (0 and 100 mM $NaHCO_3$ + Na_2CO_3 in a 9:1 ratio) and five foliar CFE concentrations (0%, 0.5%, 1%, 3%, and 5%) in a completely randomized design with three replications. Plant growth, physiological characteristics, biochemical responses, antioxidant enzyme activities, and yield attributes were evaluated. Alkalinity stress significantly reduced shoot and root growth, leaf area, biomass accumulation, chlorophyll content, relative water content, and fruit yield while increasing electrolyte leakage and oxidative stress. However, CFE application substantially improved plant performance under alkaline conditions, with optimal responses observed at moderate concentrations. CFE enhanced photosynthetic stability, improved water status, and stimulated antioxidant defense mechanisms by increasing the activities of superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), thereby reducing oxidative damage. Furthermore, CFE-treated plants showed improved fruit development and yield recovery compared with untreated stressed plants. These findings demonstrate that clove fruit extract is an effective, eco-friendly bio-stimulant for mitigating alkaline stress and enhancing tomato resilience, offering a promising strategy for sustainable crop production in degraded soils.
Keywords: Clove fruit extract; Alkalinity stress; Tomato; Bio stimulant; Antioxidant defense.

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INTRODUCTION

Climate change poses a serious threat to global food security by increasing temperatures, altering precipitation patterns, and intensifying extreme climatic events that negatively influence agricultural productivity (Yuan *et al.,* 2024). Rising temperatures can shorten crop growth periods and reduce yields, particularly in developing regions where agricultural systems are already exposed to thermal stress (Sun *et al.,* 2019). Moreover, climate change accelerates pest and disease outbreaks, soil degradation, and resource limitations, creating challenges for sustainable crop production (Saleem *et al.,* 2025). Soil alkalinity is a major constraint to agricultural productivity, affecting approximately 830 million hectares worldwide by reducing soil fertility and crop performance (Hussain *et al.,* 2026).

High soil pH caused by carbonate and bicarbonate accumulation limits nutrient availability, disrupts plant metabolism, and impairs growth. Tomato (*Solanum lycopersicum* L.) is highly sensitive to alkaline stress, which causes nutrient deficiencies, reduced water uptake, oxidative damage, and yield losses (Fu *et al.,* 2026; Sediqui *et al.,* 2024). Although several mitigation strategies exist, plant-based bio-stimulants provide sustainable alternatives (Azzam *et al.,* 2026). Clove (*Syzygium aromaticum*) fruit extract, rich in phenolics, flavonoids, and eugenol, enhances antioxidant defense, reduces ROS damage, and improves tomato tolerance under alkaline conditions (Ahmed *et al.,* 2025).

Alkalinity stress is a major abiotic constraint that reduces crop productivity, particularly in arid and semi-arid regions. It is primarily caused by the accumulation of sodium carbonate (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$), which increase soil pH and limit nutrient availability. Poor drainage, excessive irrigation with sodic water, and improper fertilizer use contribute to soil alkalization (Daud *et al.,* 2025). High pH restricts essential nutrients such as phosphorus, iron, zinc, and manganese, causing nutrient deficiencies and chlorosis.

Alkalinity also disrupts water uptake, ionic balance, and physiological functions. Excess Na^+ inhibits K^+ uptake, reducing enzyme activity and photosynthetic efficiency, while reactive oxygen species (ROS) cause oxidative damage and cellular dysfunction. Consequently, root development, plant growth, fruit formation, and yield are adversely affected (Rao *et al.,* 2025).

Plants employ diverse defense mechanisms to tolerate alkaline and salt stress by regulating ion toxicity, osmotic imbalance, and oxidative damage (Yu *et al.,* 2025). The accumulation of osmoprotectants, including proline, glycine betaine, and soluble sugars, maintains cellular water balance and protects proteins. Ion transport systems, particularly Na^+/H^+ antiporters, reduce sodium toxicity through vacuolar compartmentalization. Stress conditions increase reactive oxygen species (ROS) production, activating antioxidant defenses such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), along with non-enzymatic antioxidants including phenolic compounds and glutathione. Stress-related hormones, especially abscisic acid (ABA), regulate gene expression, stomata control, and adaptive responses. Together, these physiological, biochemical, and molecular mechanisms enhance plant survival, growth, and productivity under alkaline and saline conditions.

Seaweed and plant extracts are sustainable bio stimulants that improve crop tolerance to abiotic stresses. Seaweed extracts contain bioactive compounds, including phytohormones, oligosaccharides, polyphenols, and micronutrients, which enhance plant growth, nutrient uptake, photosynthesis, and osmotic regulation (Di Sario *et al.,* 2025). Their application can improve crop growth, yield, and physiological performance under salinity and drought. Similarly, extracts from clove, basil, and smoke water contain phenolic compounds, flavonoids, and other compounds that strengthen antioxidant defense, reduce reactive oxygen species (ROS) damage, and promote stress adaptation. Clove extract, particularly rich in eugenol, can enhance antioxidant activity and stress tolerance (Desoky *et al.,* 2025). Overall, these extracts offer environmentally friendly

strategies for mitigating abiotic stress and supporting sustainable crop production.

Clove (*Syzygium aromaticum*) is a plant-based bio-stimulant rich in bioactive compounds, including eugenol, flavonoids, tannins, and phenolic acids, which possess strong antioxidant and stress-regulating properties (Tariq *et al.,* 2025). Eugenol, the major component of clove essential oil, enhances antioxidant defense, regulates metabolism, and improves stress tolerance. Clove extracts have improved plant performance under drought, salinity, and heavy metal stress by maintaining chlorophyll, increasing antioxidant enzyme activity, and reducing ROS. However, their role against alkaline stress remains poorly studied. Thus, clove extract may offer sustainable protection and improve tomato tolerance to alkalinity.

Bio stimulants are natural or biologically derived substances that enhance plant physiological processes, improve nutrient utilization, and strengthen tolerance to environmental stresses without directly acting as conventional fertilizers. Bio stimulants improve plant growth and stress tolerance by promoting root and shoot development, biomass production, nutrient uptake, and hormonal regulation (Islam *et al.,* 2016; Iqbal and Ashraf, 2019; Majeed *et al.,* 2017).

The study aimed to investigate the effects of alkalinity stress on the growth and yield of tomato plants. It also evaluated the effects of different concentrations of foliar-applied clove fruit extract (CFE) on the physiological and biochemical attributes of tomato plants grown under alkaline stress conditions.

MATERIALS AND METHODS

Experimental site and design

An experiment was conducted over a period of 60 days under controlled conditions at the University of Okara, Punjab, Pakistan, to evaluate the effect of foliar-applied clove (*Syzygium aromaticum*) fruit extract (CFE) on the productivity and stress tolerance of tomato (*Solanum lycopersicum* L.) grown under induced alkalinity.

The study was conducted using a pot trial arranged in a factorial experimental design within a completely randomized design (CRD), with three replications to ensure statistical reliability. The treatments consisted of two factors: alkalinity stress and clove fruit extract concentration.

Factor A included two alkalinity levels: A_0 (no stress) and A_1 (100 mM $NaHCO_3$ + Na_2CO_3 in a 9:1 molar ratio), while Factor B comprised five CFE concentrations: B_0 = 0%, B_1 = 0.5%, B_2 = 1%, B_3 = 3%, and B_4 = 5%.

The experimental layout consisted of 30 treatment combinations (2 alkalinity levels × 5 CFE concentrations × 3 replications), resulting in 30 experimental units, with an additional six pots used as buffer/control units, giving a total of 36 pots. Each pot represented an independent experimental unit and contained 5 kg of pre-sieved soil. The experiment was maintained for 60 days, during which the effects of alkalinity and foliar CFE application on tomato growth, physiological responses, biochemical attributes, and productivity were evaluated. This factorial arrangement enabled the assessment of both individual and interactive effects of alkalinity stress and CFE.

Experimental Treatments

The following are the different treatments that were used in the experiment

Factor A: Alkalinity Stress

A0 = Control (no alkalinity stress)

A1 = Alkalinity Stress (100 mM $NaHCO_3$ + Na_2CO_3 in 9:1 molar ratio)

Factor B: Clove Fruit Extract (CFE)

B0 = 0% (Control) B1 = 0.5%

B2 = 1%

B3 = 3%

B4=5%

Plant Material and Growth Conditions

Tomato plants were grown in plastic pots (15 × 10 cm) containing 5 kg of sieved soil. Soil field capacity was determined using standard procedures, and alkalinity stress was induced by applying Na_2CO_3 and $NaHCO_3$ solutions at a 9:1 ratio two months before sowing. Ten seeds were initially sown in each pot, and seven seedlings were transplanted after germination. At the three-to-four leaf stage, five uniform seedlings were maintained per pot and supplied with essential nutrients through Hoagland solution applied at sowing and every two weeks.

Clove fruit extract (CFE) treatments were applied foliarly using 500 mL solution per pot with a handheld sprayer at a 10-day interval. A commercial surfactant (1.0 mg L^{-1}) was added to improve spray adhesion. Control plants received no CFE treatment. Morphological, physiological, and biochemical parameters were recorded after harvesting.

Growth parameters

The plants were harvested, and then they were separated into roots and shoots. The height, leaf width, and length were measured. The area of the leaf can be calculated by multiplying its width and length. An analytical balance was used to measure the exact weight of both the shoots and roots in their original state. The roots and leaves were dried in an oven at a temperature of 70°C for 48 hours to ascertain the separate dry masses of the roots and leaves.

Leaf pigments were extracted using 85% acetone, and chlorophyll contents were measured spectrophotometrically at 470, 647, and 664.5 nm. Electrolyte leakage was determined by measuring electrical conductivity before and after heat treatment and calculated as EL = (EC_1/EC_2) × 100 (Berhe *et al.,* 2024).

Enzymatic Antioxidant Activities

Fresh leaf samples were extracted in phosphate buffer (pH 7.8), centrifuged, and the supernatant was used to determine the activities of antioxidant enzymes, including catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD), using standard assay methods (Al-Hakami *et al.,* 2022).

Water-Related Parameters

Leaf water potential, osmotic potential, and relative water content (RWC) were measured using standard procedures. RWC was calculated using the formula: RWC = (FW − DW)/(TW − DW) × 100 (Kafashzade *et al.,* 2024).

Yield-Related Parameters

Yield traits, including fruit number, size, and weight, were recorded at harvest following standard protocols (Arshad *et al.,* 2019; Mokria *et al.,* 2022).

Statistical Analysis

Data were analyzed using Fisher's ANOVA, and treatment means were compared using the HSD test in Graph Pad Prism version 9. Significant differences were determined among treatments.

RESULTS

Table 1 explains that alkaline stress significantly reduced all measured growth parameters of tomato plants. Shoot length decreased from 65.11 ± 2.71 cm under A_0 to 50.86 ± 3.04 cm under A_1, while root length declined from 24.47 ± 2.63 to 17.90 ± 1.46 cm. Similarly, leaf width, leaf length, and leaf area decreased from 5.35 ± 0.34 to 4.10 ± 0.26 cm, 10.47 ± 0.37 to 8.51 ± 0.48 cm, and 56.07 ± 4.16 to 34.87 ± 2.83 cm^2, respectively. Alkaline stress also significantly reduced shoot and root fresh weights, from 109.30 ± 5.62 to 85.28 ± 6.51 g and from 30.01 ± 1.37 to 22.14 ± 1.39 g, respectively. Similar reductions were observed in shoot and root dry weights.

Application of CFE under alkaline stress partially improved growth performance. Shoot length increased to 59.40 ± 7.49 cm at B_3, while root length reached 22.62 ± 3.99 cm. Leaf length and leaf area were highest at B_4, reaching 9.71 ± 1.19 cm and 46.79 ± 11.95 cm^2, respectively. CFE treatments also partially recovered shoot and root biomass compared with untreated

stressed plants. Significant treatment effects were observed for shoot length (F = 183.80, P ≤ 0.0001), root length (F = 71.41, P = 0.0003), leaf width (F = 131.07, P = 0.0001), leaf length (F = 154.73, P ≤ 0.0001), leaf area (F = 266.33, P ≤ 0.0001), shoot fresh weight (F = 145.34, P ≤ 0.0001), root fresh weight (F = 250.61, P ≤ 0.0001), shoot dry weight (F = 145.34, P ≤ 0.0001), and root dry weight (F = 250.61, P ≤ 0.0001). Overall, alkaline stress markedly suppressed vegetative growth and biomass accumulation, whereas CFE application partially alleviated these reductions.

Table 1. Growth parameters of tomato under control and alkaline stress with different clove fruit extracts.

Parameter	Shoot Length (cm)	Root Length (cm)	Leaf Width (cm)	Leaf Length (cm)	Leaf Area (cm^2)	Shoot Fresh Wt (g)	Root Fresh Wt (g)	Shoot Dry Wt (g)	Root Dry Wt (g)
A0	65.11±2.71	24.47±2.63	5.35±0.34	10.47±0.37	56.07±4.16	109.30±5.62	30.01±1.37	21.86±1.12	7.50±0.34
A1	50.86±3.04	17.90±1.46	4.10±0.26	8.51±0.48	34.87±2.83	85.28±6.51	22.14±1.39	17.11±1.30	5.53±0.35
B0	59.08±10.07	21.21±3.81	4.73±0.71	9.61±1.30	46.23±13.16	98.47±13.12	26.72±3.80	19.69±2.62	6.68±0.95
B1	56.70 ±6.24	21.45±4.82	4.84±0.86	9.21±1.29	45.26±13.41	99.59±12.82	26.65±3.72	19.92±2.56	6.66±0.93
B2	56.96±9.83	19.72±3.26	4.70±0.65	9.62±0.89	45.57±9.92	97.65±13.58	26.20±3.52	19.47±2.72	6.55±0.88
B3	59.40±7.49	22.62±3.99	4.62±0.81	9.29±1.01	43.49±11.96	96.72±14.49	25.98±3.87	19.23±2.90	6.49±0.97
B4	57.79±7.14	20.94±4.55	4.75±0.71	9.71±1.19	46.79±11.95	96.35±12.68	26.61±3.89	19.13±2.53	6.65±0.97
F value	183.80	71.41	131.07	154.73	266.33	145.34	250.61	145.34	250.61
P value	≤0.0001	0.0003	0.0001	≤0.0001	≤0.0001	≤0.0001	≤0.0001	≤0.0001	≤0.0001

Note: A_0 = Control (no alkalinity stress); A_1 = Alkalinity stress (100 mM $NaHCO_3$ + Na_2CO_3 in a 9:1 molar ratio); B_0 = 0% clove fruit extract (control); B_1 = 0.5% clove fruit extract; B_2 = 1.0% clove fruit extract; B_3 = 3.0% clove fruit extract; B_4 = 5.0% clove fruit extract.

Effect of Alkaline Stress on Linear Growth Parameters

Alkaline stress substantially inhibited the linear growth of tomato plants compared with the control treatment (A0) (Figure 1). The mean shoot length decreased from 65.11 cm under control conditions to 50.86 cm under alkaline stress (A1), demonstrating a pronounced restriction in shoot elongation. Similarly, root length declined from 24.47 cm in A0 to 17.90 cm in A1, indicating that alkaline conditions also adversely affected root development. Leaf growth showed a comparable response, with mean leaf width decreasing from 5.35 cm in control plants to 4.10 cm under A1, while leaf length declined from 10.47 to 8.51 cm.

Overall, all evaluated vegetative growth parameters exhibited lower values under alkaline stress, confirming its detrimental influence on tomato plant development. The greatest reduction was observed in shoot length, followed by root length, whereas leaf width and leaf length showed comparatively moderate reductions. The suppression of growth under alkaline conditions may be associated with reduced water availability, impaired nutrient acquisition, ionic imbalance, and disruption of essential physiological processes. Such stress-induced limitations can restrict cell division and elongation, ultimately reducing overall plant growth. These findings demonstrate that alkaline stress negatively influences both above-ground and below-ground growth components of tomato plants, with shoot and root development appearing particularly sensitive to alkaline conditions.

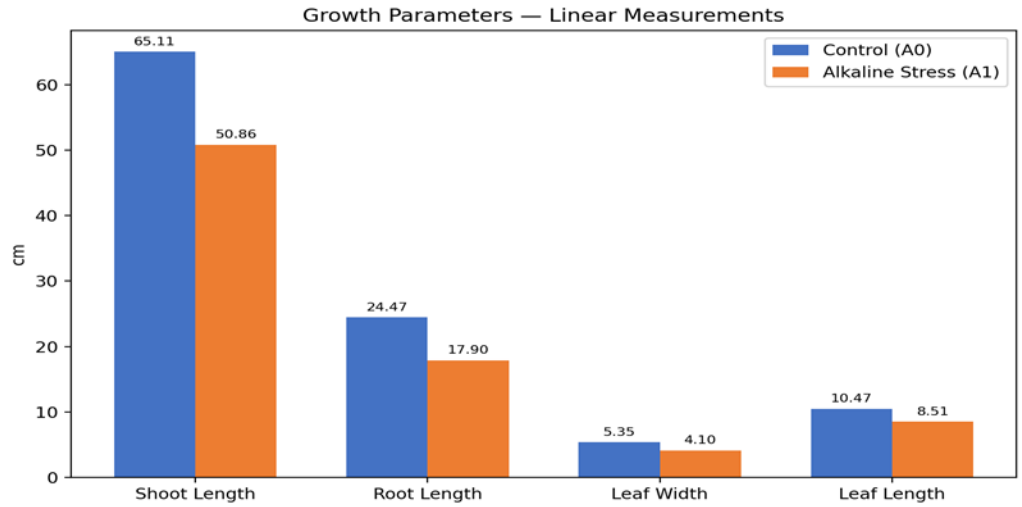


Fig. 1. Effect of alkaline stress on linear growth parameters (shoot length, root length, leaf width, leaf length) of tomato under control (A0) and alkaline stress (A1) conditions.

Effect of alkaline stress on biomass accumulation

Alkaline stress substantially reduced biomass accumulation in tomato plants compared with the control treatment (A0). Shoot fresh weight decreased from 109.30 g in A0 to 85.28 g under alkaline stress (A1), representing a reduction of approximately 22%. Similarly, root fresh weight declined from 30.01 to 21.86 g, indicating impaired biomass production under alkaline conditions. The effect was more pronounced for dry biomass. Shoot dry weight decreased from 17.11 g in control plants to 7.50 g under A1, while root dry weight declined from 5.53 to 2.36 g. These reductions correspond to approximately 56% and 57% decreases, respectively (Figure 2).

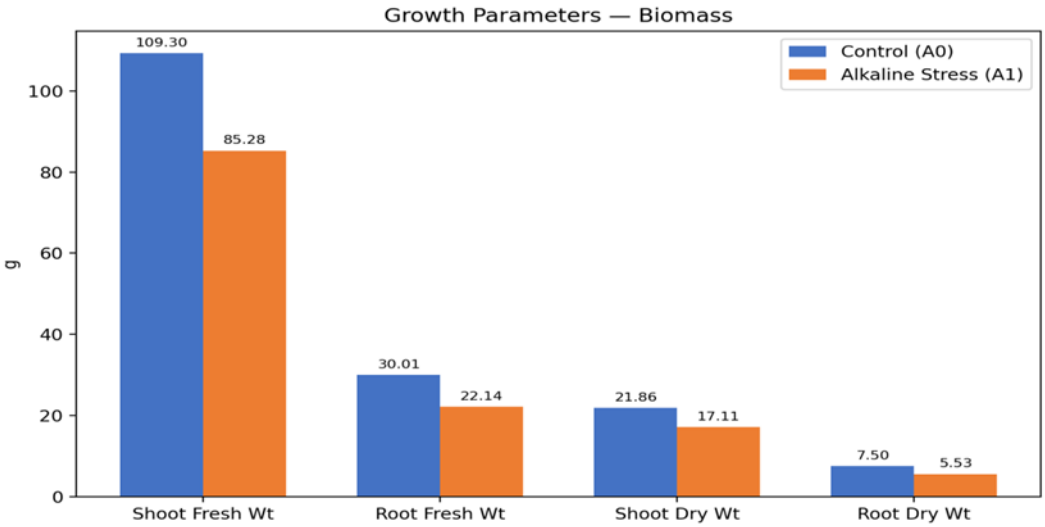


Fig. 2. Effect of alkaline stress on biomass parameters (shoot fresh weight, root fresh weight, shoot dry weight, root dry weight) of tomato under control (A0) and alkaline stress (A1) conditions.

Overall, alkaline stress negatively affected both fresh and dry biomass accumulation, with dry-weight parameters showing greater sensitivity than fresh-weight traits. The pronounced reduction in dry matter may reflect restricted nutrient uptake, disturbed ionic balance, reduced photosynthetic activity, and impaired carbon assimilation under alkaline conditions. Reduced biomass accumulation ultimately indicates suppressed plant growth and physiological performance under alkaline stress. The greater decline in shoot and root dry weights further suggests that alkaline stress substantially limits dry-matter production and partitioning in tomato plants.

Mechanisms underlying alkaline stress-mediated growth inhibition and the protective role of clove fruit extract

Alkaline stress reduces plant growth by disrupting physiological, biochemical, and structural processes. High concentrations of bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions increase soil pH, which decreases the availability and uptake of essential nutrients such as iron, phosphorus, calcium, and magnesium, resulting in nutrient deficiencies and reduced metabolic activity.

Moreover, alkaline stress causes osmotic imbalance and induces oxidative stress through excessive production of reactive oxygen species (ROS), including hydrogen peroxide, superoxide radicals, and hydroxyl radicals, which damage cellular membranes, proteins, and DNA.

Alkaline stress induces stomata closure, reduces photosynthesis, disrupts cell division and elongation, and restricts root, shoot, and biomass development. It also disturbs hormonal regulation, particularly auxins and cytokinin pathways (Figure 3). Clove fruit extract (CFE) alleviates these effects through bioactive compounds, including eugenol, flavonoids, tannins, and phenolic acids. These compounds scavenge ROS, protect cellular structures, and enhance antioxidant enzymes such as SOD, CAT, and POD. CFE may also improve nutrient uptake, photosynthetic stability, and stress-signaling responses while supporting auxins-mediated root and shoot development. Consequently, its antioxidant, osmoprotective, and growth-regulating properties help restore cellular homeostasis, enhance biomass production, and improve tomato growth under alkaline stress.

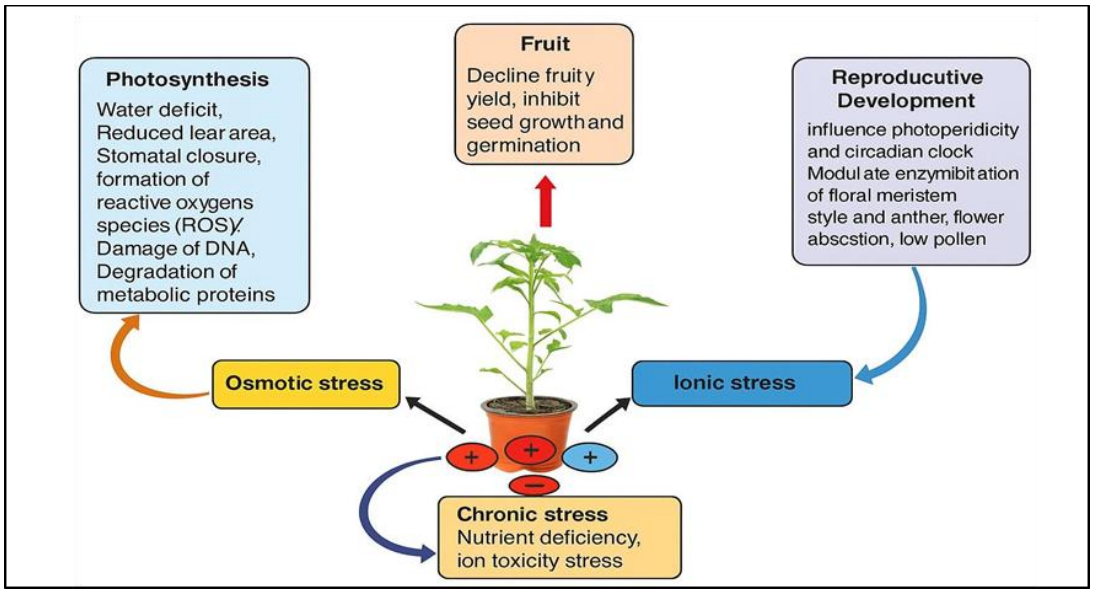


Fig. 3. Proposed Mechanism of Clove Fruit Extract-Mediated Alleviation of Alkaline Stress-Induced Growth Reduction.

Biochemical Parameters

Alkaline stress and foliar application of clove fruit extract (CFE) significantly influenced the biochemical characteristics of tomato plants, including pigment composition and membrane stability. Plants exposed to alkaline stress (A_1) showed a significant reduction in chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid contents compared with non-stressed control plants (A_0). Chlorophyll a declined from 1.739 ± 0.091 mg/g FW in A_0 to 1.298 ± 0.076 mg/g FW in A_1, while total chlorophyll decreased from 2.618 ± 0.105 to 1.921 ± 0.084 mg/g FW, indicating disruption of photosynthetic activity under alkaline conditions.

In contrast, electrolyte leakage increased significantly under stress (A_1: 44.319 ± 5.386%) compared with the control (A_0: 25.093 ± 3.650%), reflecting enhanced membrane damage and oxidative stress.

Foliar application of CFE effectively alleviated these adverse effects in a concentration-dependent manner. CFE-treated plants exhibited improved chlorophyll and carotenoid retention, with the highest concentration (5%) restoring pigment levels close to those of unstressed plants. Moreover, CFE significantly reduced electrolyte leakage, suggesting improved membrane stability and reduced oxidative injury. ANOVA results confirmed the significant effects of alkaline stress and CFE treatments on all measured biochemical parameters ($P < 0.05$), demonstrating that CFE enhances antioxidant defense mechanisms and mitigates alkaline stress-induced physiological disturbances in tomato plants.

Table 2 presents the effects of alkaline stress and clove fruit extract (CFE) application on key biochemical parameters in tomato plants. Alkaline stress significantly reduced chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid contents compared with control conditions. Chlorophyll a decreased from 1.739 ± 0.091 mg/g FW under A_0 to 1.298 ± 0.076 mg/g FW under A_1, while total chlorophyll declined from 2.618 ± 0.105 to 1.921 ± 0.084 mg/g FW. Similarly, carotenoid content decreased from 0.642 ± 0.036 to 0.471 ± 0.045 mg/g FW under alkaline stress.

In contrast, electrolyte leakage increased markedly from 25.093 ± 3.650% in control plants to 44.319 ± 5.386% under stress, indicating increased membrane damage. CFE application under stress showed partial recovery of photosynthetic pigments and a reduction in electrolyte leakage, particularly at 3% and 5% CFE. All measured parameters showed statistically significant differences ($p < 0.001$), confirming the substantial effects of alkalinity and CFE treatments on tomato biochemical responses.

Table 2. Biochemical Parameters under Control and Alkaline Stress Conditions.

Parameter	Chlorophyll a (mg/g FW)	Chlorophyll b (mg/g FW)	Total Chlorophyll (mg/g FW)	Carotenoids (mg/g FW)	Electrolyte Leakage (%)
A0	1.739±0.091	0.880±0.054	2.618±0.105	0.642±0.036	25.093±3.650
A1	1.298±0.076	0.623±0.056	1.921±0.084	0.471±0.045	44.319±5.386
B0	1.500±0.251	0.742±0.148	2.242±0.392	0.548±0.098	34.629±10.452
B1	1.513±0.226	0.776±0.132	2.289±0.349	0.559±0.127	36.153±13.051
B2	1.503±0.258	0.738±0.169	2.241±0.418	0.563±0.104	36.095±11.858
B3	1.529±0.253	0.765±0.164	2.294±0.412	0.560±0.121	34.62±13.080
B4	1.579±0.291	0.775±0.164	2.354±0.433	0.564±0.108	34.341±10.296
F value	70.16	70.99	97.26	59.75	73.12
P value	0.0004	0.0004	0.0002	0.0006	0.0003

Note: A_0 = Control (no alkalinity stress); A_1 = Alkalinity stress (100 mM $NaHCO_3$ + Na_2CO_3 in a 9:1 molar ratio); B_0 = 0% clove fruit extract (control); B_1 = 0.5% clove fruit extract; B_2 = 1.0% clove fruit extract; B_3 = 3.0% clove fruit extract; B_4 = 5.0% clove fruit extract.

Table 3 shows the effects of alkaline stress and clove fruit extract (CFE) application on antioxidant enzyme activities in tomato plants. Alkaline stress increased the activities of peroxidase (POD), catalase (CAT), and superoxide dismutase (SOD), with POD increasing from 30.15 ± 1.56 under control conditions (A_0) to 33.78 ± 1.24 under stress (A_1). Similarly, CAT increased from 24.51 ± 2.11 to 29.06 ± 2.12, while SOD increased from 19.04 ± 1.82 to 24.27 ± 2.20. These increases indicate activation of the antioxidant defense system in response to alkaline stress. Application of CFE under stress modified enzyme activities, with moderate concentrations, particularly 1% CFE (B_2), maintaining relatively higher antioxidant activity. Significant differences were observed for POD ($F = 49.39$, $p = 0.0001$), CAT ($F = 34.73$, $p = 0.0002$), and SOD ($F = 50.47$, $p = 0.0001$), demonstrating significant treatment effects on antioxidant responses.

Table 3. Effect of clove fruit extract (0–5%) on enzymatic antioxidant activities (Peroxidase, Catalase and Superoxide Dismutase) in tomato plants under control (A_0) and alkaline stress (A_1) conditions.

Parameter	A0	A1	B0	B1	B2	B3	B4	F value	P Value
Peroxidase (POD)	30.15±1.56	33.78±1.24	32.95±1.20	32.16±2.54	30.80±2.27	31.86±3.17	32.05±2.22	49.39	0.0001
Catalase (CAT)	24.51± 2.11	29.06±2.12	26.16±1.50	26.23±4.00	27.32±3.63	27.58±3.04	26.64±3.68	34.73	0.0002
Superoxide Dismutase (SOD)	19.04±1.82	24.27±2.20	22.64±3.07	21.05±3.18	22.72±4.36	20.45±2.48	21.42±3.79	50.47	0.0001

Note: A_0 = Control (no alkalinity stress); A_1 = Alkalinity stress (100 mM $NaHCO_3$ + Na_2CO_3 in a 9:1 molar ratio); B_0 = 0% clove fruit extract (control); B_1 = 0.5% clove fruit extract; B_2 = 1.0% clove fruit extract; B_3 = 3.0% clove fruit extract; B_4 = 5.0% clove fruit extract.

Table 4 presents the effects of alkaline stress and foliar application of clove fruit extract (CFE) on water-related physiological parameters in tomato plants.

Alkaline stress markedly disrupted water relations in tomato plants compared with the non-stressed control. Water potential (Ψw) decreased from −0.616 ± 0.045 to −0.890 ± 0.041, while osmotic potential (Ψs) declined from −1.221 ± 0.067 to −1.501 ± 0.089, indicating increased osmotic stress and reduced capacity to maintain cellular hydration. Relative water content (RWC) also decreased from 86.757 ± 2.909% to 75.735 ± 3.811%, confirming substantial dehydration under alkaline conditions. Application of clove fruit extract (CFE), particularly at moderate concentrations (0.5–3%), partially alleviated these effects by improving RWC and maintaining less negative Ψw and Ψs. The non-linear response indicates that moderate CFE concentrations were more effective than very low or high treatments.

The response to CFE was not necessarily proportional to the concentration, indicating that moderate concentrations may provide a more effective physiological response than very low or high applications. The improvement in RWC is particularly important because maintenance of tissue hydration is essential for photosynthesis, membrane stability, nutrient transport, and other metabolic processes under abiotic stress.

Table 4. Water-Related Parameters under Control and Alkaline Stress Conditions

Parameter	A0	A1	B0	B1	B2	B3	B4
Water Potential (Ψw)	–0.616±0.045	–0.890±0.041	–0.735±0.165	–0.757±0.180	–0.764±0.132	–0.768±0.152	–0.743±0.147
Osmotic Potential (Ψs)	–1.221±0.067	–1.501±0.089	–1.378±0.193	–1.379±0.162	–1.309±0.174	–1.386±0.133	–1.352±0.191
Relative Water Content (RWC) %	86.757±2.909	75.735±3.811	78.975±8.730	82.300±6.286	82.865±3.509	82.558±6.932	79.532±7.366

Note: A_0 = Control (no alkalinity stress); A_1 = Alkalinity stress (100 mM $NaHCO_3$ + Na_2CO_3 in a 9:1 molar ratio); B_0 = 0% clove fruit extract (control); B_1 = 0.5% clove fruit extract; B_2 = 1.0% clove fruit extract; B_3 = 3.0% clove fruit extract; B_4 = 5.0% clove fruit extract.

Overall, the results demonstrate that alkaline stress significantly disrupted water relations in tomato plants, whereas CFE application, especially at moderate concentrations, partially alleviated these effects and contributed to improved maintenance of plant water status under alkaline stress.

Yield Parameters

Alkaline stress and clove fruit extract (CFE) treatments significantly altered the yield traits of tomato plants in terms of the number of fruits produced, fruit weight, the yield per plant, the diameter of fruits, and length. Under controlled conditions (A0), plants showed better performance in terms of yield compared to plants exposed to stress (A 1).

Precisely certain fruits and yield per plant were considerably diminished under raised alkalinity; the number of fruits decreased from 21.74 to 16.17, and the value of yield per plant decreased from 1726.81 g to 1243.99 g/plant, respectively. The diameter and weight of the fruit also decreased, which indicates the negative effect of alkalinity on the development of generative processes and filling of fruits. Nevertheless, foliar application of CFE enhanced yield attributes in a concentration-response model. Treatments applied with CFE 2-3 percent under stress (A1) showed a significant recovery in the number of fruits, size, and overall yield (Table 5).

Table 5 presents the effects of alkaline stress and clove fruit extract (CFE) application on yield-related parameters of tomato plants. Alkaline stress markedly reduced tomato productivity compared with control conditions. The number of fruits decreased from 21.74 ± 1.69 under control (A_0) to 16.17 ± 2.22 under alkaline stress (A_1). Similarly, fruit weight declined from 79.92 ± 6.80 g to 66.37 ± 5.72 g, while yield per plant decreased substantially from 1726.81 ± 135.23 g to 1243.99 ± 76.94 g. Fruit diameter and length were also reduced under stress, declining from 5.54 ± 0.27 to 5.01 ± 0.29 cm and from 6.46 ± 0.36 to 6.09 ± 0.42 cm, respectively.

CFE application showed a variable but generally positive influence on yield characteristics. Among the treatments, B_2 (1.0% CFE) produced a relatively high number of fruits (20.03 ± 4.02) and fruit weight (73.12 ± 5.09 g), whereas B_3 (3.0% CFE) resulted in the highest yield per plant (1549.82 ± 293.48 g) and fruit diameter (5.44 ± 0.40 cm). Fruit length was highest under B_1 (0.5% CFE), reaching 6.55 ± 0.25 cm. The statistical analysis confirmed significant differences among treatments for all measured parameters, with P = 0.001 for number of fruits, fruit weight, yield per plant, and fruit diameter, and P = 0.014 for fruit length. Overall, CFE application partially mitigated the detrimental effects of alkaline stress and improved tomato yield and fruit development (Figure 4).

Table 5. Yield Parameters under Control and Alkaline Stress Conditions.

Parameter	Number of Fruits	Fruit Weight (g)	Yield per Plant (g)	Fruit Diameter (cm)	Fruit Length (cm)
A0	21.74±1.69	79.92±6.80	1726.81±135.23	5.54±0.27	6.46±0.36
A1	16.17±2.22	66.37±5.72	1243.99±76.94	5.01±0.29	6.09±0.42
B0	18.60±3.88	76.40±13.66	1499.33±267.45	5.30±0.50	5.99±0.63
B1	18.33±2.62	75.92±7.17	1408.83±267.62	5.30±0.25	6.55±0.25
B2	20.03±4.02	73.12±5.09	1533.45±330.50	5.06±0.32	6.36±0.33
B3	19.45±2.47	71.43±11.20	1549.82±293.48	5.44±0.40	6.29±0.29
B4	18.35±4.63	68.85±7.71	1435.55±246.87	5.29±0.43	6.18±0.46
F value	59.96	34.92	144.45	26.47	6.79
P value	0.001	0.001	0.001	0.001	0.014

Note: A_0 = Control (no alkalinity stress); A_1 = Alkalinity stress (100 mM $NaHCO_3$ + Na_2CO_3 in a 9:1 molar ratio); B_0 = 0% clove fruit extract (control); B_1 = 0.5% clove fruit extract; B_2 = 1.0% clove fruit extract; B_3 = 3.0% clove fruit extract; B_4 = 5.0% clove fruit extract.

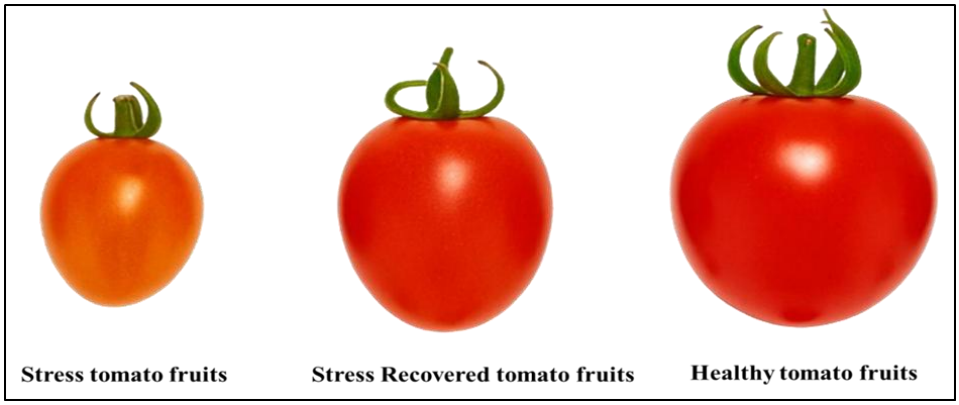


Fig. 4. Comparison of tomato fruits under control, stress, and stress-recovered conditions, showing differences in size and quality.

Heat map of Standardized Physiological, Biochemical, and Yield Traits across Treatments

The heat map provides an integrated comparison of standardized responses of tomato plants subjected to control and alkaline stress conditions with different concentrations of clove fruit extract (CFE) (Figure 5). Z-score normalization was applied to all measured traits, enabling comparison among variables with different units and scales. Yellow-to-green shades indicate relatively higher standardized trait values, whereas blue-to-purple shades represent relatively lower values. The control treatments (A_0B_0–A_0B_4) generally displayed positive standardized values for shoot and root growth, leaf dimensions, biomass accumulation, chlorophyll pigments, and carotenoids, indicating comparatively favorable physiological performance under non-stress conditions.

Alkaline stress without CFE (A_1B_0) produced a clear shift toward lower standardized values for most growth and photosynthetic traits. Shoot length, root length, leaf width, leaf length, leaf area, shoot and root fresh weights, dry weights, chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids were generally reduced relative to the control treatments. This pattern indicates that alkaline stress adversely affected vegetative growth, biomass production, and photosynthetic pigment accumulation. Such reductions are consistent with the inhibitory effects of alkaline conditions on water availability, nutrient acquisition, cellular metabolism, and photosynthetic functioning.

In contrast, electrolyte leakage showed the opposite response, with higher standardized values under alkaline stress, reflecting increased membrane destabilization and cellular injury. Antioxidant enzymes, including peroxidase (POD), catalase (CAT), and superoxide dismutase (SOD), also displayed increased standardized values under several alkaline-stress treatments, particularly following CFE application. This response indicates activation of antioxidant defense mechanisms to counteract stress-induced oxidative damage.

CFE application partially moderated the adverse effects of alkalinity, although responses varied among concentrations and traits. The A_1B_2 and A_1B_3 treatments showed comparatively improved profiles for several growth, physiological, and antioxidant traits, while A_1B_4 also maintained relatively strong antioxidant responses. The clustering of improved antioxidant activity with reduced stress-associated responses suggests that CFE contributed to physiological adjustment under alkaline conditions. Overall, the heat map demonstrates that CFE application, particularly at moderate concentrations, helped rebalance growth, photosynthetic, membrane-stability, and antioxidant responses, supporting improved tolerance of tomato plants to alkaline stress.

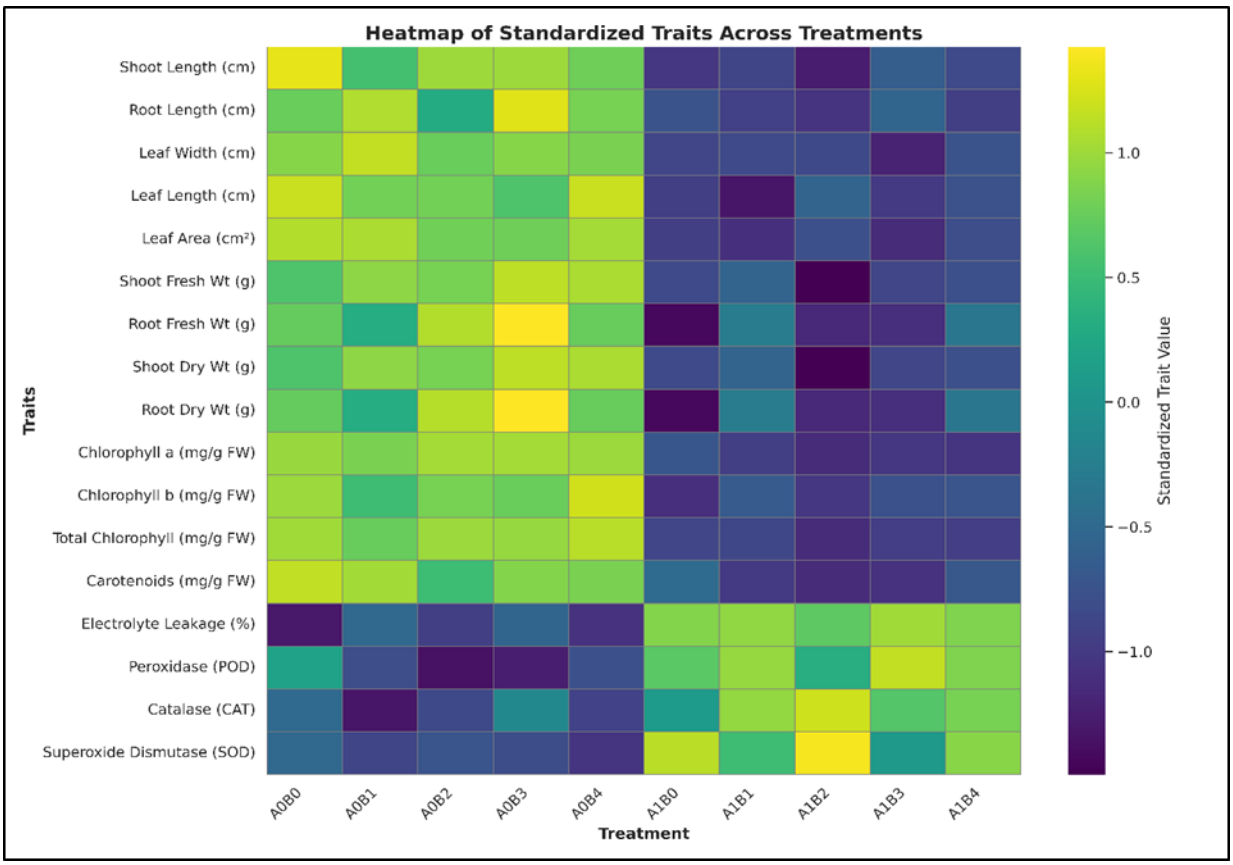


Fig. 5 . Heat map showing standardized values (Z-scores) of growth, biochemical, enzymatic, and yield-related traits in tomato plants across ten treatment combinations of control (A_0) and stress (A_1) with clove fruit extract (B_0–B_4).

DISCUSSION

Alkaline stress markedly impaired tomato growth, physiological performance, and productivity, demonstrating the multifaceted effects of elevated pH on plant functioning (Shi *et al.,* 2026). Shoot and root lengths decreased from 65.11 to 50.86 cm and 24.47 to 17.90 cm, respectively, while dry biomass declined by approximately 56–57%. The greater reduction in dry weight than fresh weight suggests that alkalinity strongly restricted dry-matter accumulation and assimilate partitioning (Hamoda *et al.,* 2026). Such growth inhibition may be associated with reduced availability of essential nutrients, particularly phosphorus and iron, together with impaired root activity, cell division, and elongation (Sharma *et al.,* 2025).

Photosynthetic performance was also adversely affected, as chlorophyll a, chlorophyll b, total chlorophyll (Moradi *et al.,* 2026), and carotenoid contents decreased under alkaline conditions. Reduced pigment stability may result from oxidative damage to chloroplast structures and disruption of chlorophyll biosynthesis (Wang *et al.,* 2026). The concurrent increase in electrolyte leakage from 25.09% to 44.32% provides further evidence of membrane injury and loss of cellular integrity. These responses indicate that alkaline stress induces oxidative and structural disturbances that collectively limit carbon assimilation and plant development.

Antioxidant enzyme activities increased under stress, with SOD, CAT, and POD showing higher activities than the control, suggesting activation of the plant's protective defense system (Ali *et al.,* 2022). Nevertheless, this

endogenous response was insufficient to prevent physiological damage. Water relations were similarly disrupted, with RWC decreasing from 86.76% to 75.74% and both water and osmotic potentials becoming more negative (Amir *et al.,* 2025). Reduced tissue hydration can restrict stomatal functioning, photosynthesis, nutrient transport, and metabolic activity, further aggravating growth inhibition (Qiao *et al.,* 2025).

CFE application substantially alleviated several adverse effects of alkalinity. Moderate concentrations, particularly 2–3%, generally produced greater improvements in growth, water status, biomass, and yield, whereas 1% showed notable stimulation of antioxidant enzymes. The beneficial effects of CFE may be attributed to its phytochemical constituents, including eugenol, flavonoids, phenolic acids and tannins, which can contribute to ROS scavenging, antioxidant defense, membrane protection and improved physiological stability. Enhanced root development and water relations may additionally facilitate nutrient acquisition and sustain photosynthetic activity (Bhattacharya *et al.,* 2025). Improved source–sink relationships could explain the recovery of yield, with 3% CFE increasing production to 1549.82 g plant^{-1} compared with 1243.99 g plant^{-1} under untreated alkaline stress.

Overall, 3% CFE appeared to provide the most consistent mitigation across growth, biochemical, physiological, and yield attributes. These findings highlight CFE as a promising natural bio-stimulant for improving tomato resilience to alkaline stress (Mien *et al.,* 2026). Further field-scale studies should evaluate application timing, repeated treatments, soil interactions, and long-term effects to establish its practical potential for sustainable crop production.

CONCLUSION

The present study demonstrates that alkaline stress substantially restricts tomato growth, physiological functioning, and productivity by disrupting water relations, photosynthetic pigments, membrane integrity, antioxidant balance, and biomass accumulation. Application of clove fruit extract (CFE) effectively alleviated these adverse effects and improved plant performance under alkaline conditions. The beneficial response was evident through enhanced vegetative growth and biomass production, greater retention of chlorophyll and carotenoids, reduced electrolyte leakage, improved relative water content and osmotic regulation, and strengthened SOD, CAT, and POD activities. These physiological and biochemical improvements were ultimately reflected in better fruit development and yield recovery under stress.

Among the tested concentrations, 2% and 3% CFE produced the most consistent improvements, with 3% CFE showing the strongest overall performance across growth, physiological, biochemical, and yield-related attributes. The protective effects are likely associated with the antioxidant and growth-regulating properties of CFE phytochemicals, particularly eugenol, flavonoids, phenolic compounds, and tannins, which may enhance ROS detoxification, preserve cellular structures, and support nutrient and water acquisition.

Thus, CFE represents a promising plant-derived bio-stimulant for improving tomato tolerance to alkaline stress and reducing productivity losses in alkaline soils. However, field-scale validation, optimization of application timing and dosage, phytochemical characterization, and assessment of long-term soil–plant interactions are necessary to establish its practical efficacy and safety for sustainable crop production.

Limitations of the Study

The experiment was conducted under controlled conditions using a single tomato genotype; therefore, the results may not fully represent field conditions or responses of other cultivars.

The individual phytochemical components and molecular mechanisms responsible for the protective effects of CFE were not investigated. Further studies should identify the active compounds and clarify their roles in antioxidant

defense, hormonal regulation, and alkaline-stress tolerance.

Conflict of Interest

The authors hereby declare that they have no conflict of interest.

Generative AI statement

This study used Generative AI tools in data reorganization. We confirm that all AI-assisted processes were critically reviewed by the author's to ensure the integrity and reliability of the results. The final decisions and interpretations presented in this article were solely made by the author's.

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REFERENCES

Ahmed, R.M., Abdullah, R.A., Majeed, A.K., ALAhmed, L.H., Hasan, A.F., 2025. The Effect of Clove Oil on the Expression of Xly Gene in Tomato Infected with *Fusarium oxysporum*. Agric. Sci. Digest., 45(spl): 91-97.

Al-Hakami, I.A., El-Shaibany, A., Al-Mahbashi, H., Humaid, A., Raweh, S., Elaasser, M.M., 2022. Phytochemical Screening, Antimicrobial, Antioxidant and Anticancer Activities of Yemeni *Croton socatranus*. Int. J. Nanotechnol. Allied Sci., 6(1): 1-13.

Ali, Q., Sami, A., Haider, M.Z., Ashfaq, M., Javed, M.A., 2024. Antioxidant production promotes defense mechanism and different gene expression level in Zea mays under abiotic stress. Sci. Rep., 14(1): 7114.

Amir, R., Jahan, S., Zafar, M., Naeem, M.B., Usman, S., Shah, A.A., et al. 2025. Organic amendments optimize Triticum aestivum var Zincol-16 performance under water stress through enhancement in physio biochemical traits, secondary metabolites and yield. Sci. Rep., 15(1):, 17995.

Arshad, I., Khan, Z.A., Shah, N.H., 2019. Effect of Hoagland and Arnon Nutrient Solution on the Growth and Yield of Mango (*Mangifera indica L.*) by Using Stem Injection Technique. Int. J. Altern. Fuels. Energy., 3(2): 25-30.

Azzam, C.R., Rady, M.M., Al-Taweel, S.K., Khaled, K.A.M., Mostafa, S.S.M., 2026. Biostimulants in modern agriculture: a comprehensive review of microbial and non-microbial categories, mechanisms, and sustainability implications. J. Plant Nutr., 49(9): 1642-1663.

Berhe, M., You, J., Dossa, K., Li, D., Zhou, R., Zhang, Y., Wang, L., 2024. Examining chlorophyll extraction methods in sesame genotypes: Uncovering leaf coloration effects and anatomy variations. Plants, 13(12): 1589.

Bhattacharya, S., Gupta, N., Dutta, A., Bonomo, M.G., Milella, L., Sarker, S.D., Nahar, L., 2025. Mitigating ROS signalling pathway-mediated defence mechanism: a novel approach to counteract bacterial resistance using natural antioxidant-based antibiotics. Phytochem. Rev., 1-33.

Daud, M., Qiao, H., Xu, S., Hui, X., Adil, M., Lu, Y., 2025. Understanding abiotic stress in alfalfa: physiological and molecular perspectives on salinity, drought, and heavy metal toxicity. Front. Plant Sci., 16: 1627599.

Desoky, E.S.M., Mahmood, M., Feng, D., Ahmed, A.F., Al Masoudi, L.M., Alahmari,

A.S., et al. 2025. Synergistic effects of clove fruit extract and nano-silicon to enhance drought resilience and productivity of soybean through improved plant defense mechanisms. BMC Plant Biol., 25(1): 236.

Di Sario, L., Boeri, P., Matus, J.T., Pizzio, G.A., 2025. Plant biostimulants to enhance abiotic stress resilience in crops. Int. J. Mol. Sci., 26(3): 1129.

Fu, J., Li, L., Xing, M., Xie, W., Zhu, C., Yang, K., et al. 2026. Physiological and molecular processes of plant tolerance to bicarbonate- induced alkaline stress. Stress Biol., 6(1): 53.

Hamoda, A., El-Mehy, A.A., Dabbour, M., Arab, Z.E., 2026. Effect of faba bean-garlic intercropping on low-molecular-weight organic acids, yield components, and profitability under different spatial arrangements. Sci. Rep., 16(1): 13888.

Hussain, S., Mahmood, M.H., Akber, A.R., Iqbal, M.S., 2026. Alkaline and acidic soils pose problems for nutrient availability: Mitigation strategies. In Sustainable soil chemistry and plant nutrition (pp. 115-136). Elsevier.

Iqbal, M.N, Ashraf, A., 2019. Trichoderma: a Potential Biocontrol Agent for Soilborne Fungal Pathogens. Int. J. Mol. Microbiol., 2(1): 22-24.

Islam, W., Awais, M., Noman, A., Wu, Z., 2016. Success of Bio Products against Bacterial Leaf Blight Disease of Rice caused by *Xanthomonas oryzae pv. oryzae*. PSM Microbiol., 01(2): 50-55.

Kafashzade, Z., Nabavi Kalat, S.M., Abbasi, M. R., Souhani Darban, A.R., 2024. Effect of deficit irrigation on Relative Water Content (RWC), Proline concentration, antioxidant enzymes content, chlorophyll concentration and forage yield of five clover species. Iranian J. Soil Water Res., 55(7): 1185-1197.

Majeed, A., Muhammad, Z., Islam, S., Ullah, Z., Ullah, R., 2017. Cyanobacterial Application as Bio-fertilizers in Rice Fields: Role in Growth Promotion and Crop Productivity. PSM Microbiol., 2(2): 47-50.

Mien, P.T., Ngoc Trieu, B.T., Minh Huyen, N.T., Minh-Thu, P., 2026. Isolation and Characterization of Sea Grape-Associated Bacterial Strains with Potential Plant Growth-Promoting Properties. Egyptian J. Aquatic Biol. Fish., 30(3): 877-894.

Mokria, M., Gebrekirstos, A., Said, H., Hadgu, K., Hagazi, N., Dubale, W., Bräuning, A., 2022. Fruit weight and yield estimation models for five avocado cultivars in Ethiopia. Environ. Res. Commun., 4(7): 075013.

Moradi, M., Roosta, H.R., Nasrabadi, H.N., Shamsabadi, V., 2026. The melatonin improves the growth indices, photosynthetic performance, and essential oil content of Thymus daenensis L. under salt stress. BMC Plant Biol., 26(1): 505.

Qiao, M., Hong, C., Jiao, Y., Hou, S., Gao, H., 2024. Impacts of drought on photosynthesis in major food crops and the related mechanisms of plant responses to drought. Plants, 13(13): 1808.

Rao, M.J., Duan, M., Zhou, C., Jiao, J., Cheng, P., Yang, L., et al. 2025. Antioxidant defense system in plants: reactive oxygen species production, signaling, and scavenging during abiotic stress-induced oxidative damage. Hortic., 11(5): 477.

Saleem, A., Anwar, S., Nawaz, T., Fahad, S., Saud, S., Ur Rahman, T., Nawaz, T., 2025. Securing a sustainable future: the climate change threat to agriculture, food security, and sustainable development goals. J. Umm Al-Qura Uni. Appl. Sci., 11(3): 595-611.

Sediqui, N., Amin, M.W., Dawlatzai, N., Gulab, G., Poyesh, D.S., Terada, N., et al. 2024. Elucidation of shoot and root growth, physiological responses, and quality traits of tomato (*Solanum lycopersicon* L.) exposed to elevated calcium carbonate concentrations. Horticult., 10(6): 573.

Sharma, N., Manhas, A., VijaiSelvaraj, K.S., Bajpai, A.B., Rather, G.A., Kumar, M., 2025. Regulation of essential plant nutrients and beneficial elements for growth and development of vegetable crops. In Growth Regulation and Quality Improvement of Vegetable Crops: Physiological and Molecular Features (pp. 71-95). Singapore: Springer Nature Singapore.

Shi, Y., Chu, H., He, R., Ma, W., Liang, Q., Li, Z., et al. 2026. Harnessing rhizosphere microbes: the synergistic roles of PGPR and AMF in sustainable tomato production under stress. Front. Microbiol., 17: 1746930.

Sun, Q., Miao, C., Hanel, M., Borthwick, A. G., Duan, Q., Ji, D., Li, H., 2019. Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. Environ. Int., 128: 125-136.

Tariq, H., Alhudhaibi, A.M., Abdallah, E.M., 2025. *Syzygium aromaticum* (clove buds) as a natural antibacterial agent: a promising alternative to combat multidrug-resistant bacteria. Front. Microbiol., 16: 1674590.

Wang, Y., Xu, T., Ji, J., Li, H., Chen, F., Hu, X., et al. 2026. Chlorophyll and Carotenoid Degradation in Pepper (*Capsicum* spp.): Pathways, Mechanisms, and Postharvest Implications. Food Rev. Int., 1-21.

Yu, G., Zheng, W., Sun, J., Zhang, Q., 2025. Salt-alkali-tolerant rice: Physiological and biochemical regulatory mechanisms, research progress, and future applications. Adv. Resour. Res., 5(3): 1735-1756.

Yuan, X., Li, S., Chen, J., Yu, H., Yang, T., Wang, C., 2024. Impacts of global climate change on agricultural production: a comprehensive review. Agron., 14(7): 1360.