

# Use of microalgae to grow garden vegetable (*Solanum lycopersicum*) tomatoes in saline soil

## Abstract

Soil salinity is a major constraint to global food production, reducing nutrient availability, impairing plant physiological processes, and limiting crop establishment. This study evaluated the effectiveness of freshwater microalgae as a biological amendment for improving saline soil properties and supporting early growth of tomato (*Solanum lycopersicum*). Saline soil collected from Point Cook, Victoria, was amended with either microalgae, commercial fertilizer, or left untreated. Soil physicochemical properties were monitored across three stages, followed by assessment of seed germination, seedling growth, and biomass accumulation. Microalgae significantly improved soil nutrient status, producing the highest nitrate, phosphorus, and potassium concentrations while achieving the greatest reduction in electrical conductivity. Microalgae treatment consistently produced the highest nutrient concentrations (nitrate, phosphorus, potassium) and the lowest conductivity, indicating strong remediation effects. Germination occurred only in fertilizer and microalgae treatments, with microalgae achieving the highest and most consistent rates. Microalgae-treated plants exhibited superior shoot and root development, greater total biomass, and the steepest length–weight relationship, reflecting efficient biomass accumulation and robust structural growth. These findings demonstrate that freshwater microalgae function as an effective biofertilizer and salinity mitigation agent, offering a sustainable alternative to chemical fertilizers for improving crop performance in saline soils.

**Keywords:** tomato seedlings, biofertilizer, soil remediation, electrical conductivity, germination, plant growth, nutrient mobilization

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## Introduction

Soil salinity is a pervasive environmental challenge that severely constrains global agricultural productivity, posing significant threats to food security and economic stability. Excessive accumulation of soluble salts alters soil physical and chemical properties, reduces nutrient availability, and imposes severe physiological stress on plants.<sup>1</sup> Salinization typically results from elevated concentrations of sodium ( $\text{Na}^+$ ), chloride ( $\text{Cl}^-$ ), sulphate ( $\text{SO}_4^{2-}$ ), and bicarbonate ( $\text{HCO}_3^-$ ) ions, which degrade soil structure, decrease permeability, and lower the osmotic potential of the root zone. Consequently, plants experience osmotic stress, ion toxicity, and nutritional imbalances that impair metabolic processes, restrict growth, and ultimately reduce crop yields.<sup>2,3</sup>

Salinity stress affects plants through two primary mechanisms. The osmotic phase reduces water uptake by lowering external water potential, leading to cellular dehydration and limited cell expansion. The ionic phase results from excessive  $\text{Na}^+$  and  $\text{Cl}^-$  accumulation in plant tissues, which damages membranes, disrupts enzyme function, and interferes with photosynthesis. Secondary nutrient deficiencies also arise when essential elements such as potassium ( $\text{K}^+$ ), calcium ( $\text{Ca}^{2+}$ ), and magnesium ( $\text{Mg}^{2+}$ ) are displaced from exchange sites, compounding the negative effects on plant health. Salt-sensitive crops such as tomato (*Solanum lycopersicum*) often exhibit reduced germination, delayed emergence, decreased shoot and root biomass, leaf necrosis, and substantial yield losses under saline conditions.<sup>4</sup>

Given the limitations of conventional chemical amendments, biological approaches such as microalgae-based biofertilizers have gained attention for their sustainability and multifunctional benefits. Microalgae possess unique biological, chemical, and physical properties that make them valuable in agricultural applications.<sup>5</sup>

Through the production of extracellular polymeric substances (EPSs), microalgae enhance soil carbon content, promote aggregation, and support beneficial microbial communities involved in nutrient cycling. Species such as *Chlorella* have been shown to increase soil nutrient levels and improve water retention.<sup>6</sup> Furthermore, microalgae offer a promising biological strategy for saline soil remediation by immobilizing excess salts and enhancing nutrient turnover.<sup>7-9</sup> However, their role in mitigating salinity stress and promoting early growth in salt-sensitive crops remains underexplored.

This study aims to evaluate the effectiveness of freshwater microalgae as biofertilizers in improving saline soil quality and supporting early growth in tomato. Specifically, it investigates the impact of microalgae treatments on soil properties—including electrical conductivity, pH, and nitrate content—as well as their influence on seed germination rates. The findings will be compared with conventional NPK fertilizers and untreated controls under controlled glasshouse conditions, providing insights into the potential of microalgae as a sustainable crop-enhancing agent and salinity management solution.

## Materials and methods

### Soil collection

Saline soil was collected from the Cheetham Wetlands in Point Cook, Victoria (Australia) (latitude  $-37.8944$ , longitude  $144.7902$ ) following standard soil sampling protocols.<sup>10,11</sup> Samples were extracted from a depth of 25 cm using a hoe, targeting the root zone, which is critical for assessing salinity effects on plant growth.

Collected soil was transported to the Grow Hub at Melbourne Polytechnic's Epping campus and mixed with garden soil to moderate

extreme salinity and create a workable growth medium. Initial physicochemical properties of the mixed soil were measured prior to experimentation. The Grow Hub is a controlled crop-production facility powered by a 10-kW solar system, equipped with rainwater harvesting and automated regulation of temperature, humidity, and light intensity to maintain optimal conditions for germination and growth.

### Microalgae collection and culture

Freshwater microalgae were sourced from an open-culture vessel maintained at the Aquaculture Training and Applied Research Centre (ATARC), Melbourne Polytechnic. The culture was sustained using cow dung as the sole fertilizer. Samples were transferred to 3-L conical flasks and incubated for two weeks at 22°C under a 12 h light: 12 h dark photoperiod (2000–2500 Lux).

Species identification was performed using light microscopy following Prescott (1970),<sup>12</sup> and Wehr et al.<sup>13</sup> Cell density was estimated using a Neubauer haemocytometer. The dominant species identified were *Pseudococcomyxa* sp. and *Chlorella* sp. Cultures were applied to soil once the combined cell density reached approximately  $4.5 \times 10^6$  cells mL<sup>-1</sup>.<sup>14</sup>

### Experimental design

Three treatment groups were established:

- Control (P12C): No fertilizer or microalgae applied.
- Fertilizer Treatment (P12F): Commercial inorganic fertilizer applied.
- Microalgae Treatment (P12A): Freshwater microalgae applied.

Each treatment included three replicate pots containing 3 kg of mixed soil. Fertilizer-treated pots received 2 g of fertilizer per kg of soil (6 g per pot), while microalgae-treated pots received 500 mL of dense algal culture ( $4.5 \times 10^6$  cells mL<sup>-1</sup>).

### Phase I: Soil salinity remediation

Treatments were applied weekly for five weeks, with soil gently mixed after each application to ensure uniformity. Soil

physicochemical properties were measured at three points: initial assessment (Phase 1), start of Phase 2, and experiment's end. Weekly pH and electrical conductivity (EC) readings were recorded in Excel. Phase 1 ended when soil salinity reached levels that were tolerable for plant growth by adding water to keep the soil wet and promoting the leaching process.

### Phase 2: Plant growth assessment

Tomato seeds (*Solanum lycopersicum*, cv. Rouge De Marmande) were sourced locally, bought from local retail store Bunnings. Five seeds were sown 1 cm deep in each pot (total 45 seeds). Seeds were pre-soaked in distilled water for one hour to enhance hydration and promote uniform germination.<sup>15</sup>

Germination timing and percentage were monitored across all pots and calculated following Sousaraei et al.<sup>16</sup>

Seedling growth was monitored for seven weeks. Weekly measurements of seedling length were recorded using a centimeter scale. At the end of the experiment, shoot and root lengths were measured, and wet and dry biomass of roots, stems, and leaves were determined. Plant samples were dried at 65°C for 24 hours in a Selby Scientific 30 L laboratory vacuum oven.<sup>17</sup> Data were processed and analyzed using Microsoft Excel.

### Statistical analysis

Data were analyzed using one-way ANOVA after confirming normality and homogeneity of variances. Differences between treatment means were determined using Tukey's HSD test, with statistical significance set at  $p < 0.05$ . This approach is widely used in studies evaluating soil remediation and plant responses.<sup>18-20</sup>

### Results

The experimental study was carried out in two phases over approximately 16 weeks and involved saline soil collection, salinity-reduction treatments, planting, and monitoring the growth of tomato seeds. Table 1 summarizes the key chemical properties of the soils at three stages of the experiment: the initial baseline, mid-trial measurements, and the final assessment at the end of the study.

**Table 1** Changes in physical and chemical characteristics of soil.

Parameter	Pre-experiment (Base)	Pre-experiment (Control)	Pre-experiment (Fertilizer)	Pre-experiment (Microalgae)	During experiment (Control)	During experiment (Fertilizer)	During experiment (Microalgae)	Post experiment (Control)	Post experiment (Fertilizer)	Post experiment (Microalgae)
Available Potassium (mg/kg)	960	640	620	750	700	890	680	1000	1200	1500
pH (1:5 CaCl <sub>2</sub> )	5.6	6.6	6.1	6.4	6.5	6.2	4.8	6.0	5.6	5.7
Nitrate Nitrogen (mg/kg)	6.2	17	77	23	37	190	120	270	370	420
Ammonium Nitrogen (mg/kg)	9.7	6.5	10	50	20	110	16	27	59	110
Sulphur (mg/kg)	3800	630	1400	1400	1300	1200	1000	780	1600	1900
Phosphorus (mg/kg)	41	290	130	240	220	260	200	260	360	450
PBI-Col	89	90	83	99	86	70	73	61	71	90

Table 1 Continued..

Potassium (cmol(+)/kg)	2.5	1.6	1.6	1.9	1.8	2.3	1.7	2.5	3.1	3.8
Calcium (cmol(+)/kg)	23	15	15	17	18	14	16	12	21	24
Magnesium (cmol(+)/kg)	25	7.0	9.8	7.7	8.7	5.7	7.4	4.8	6.4	8.2
Sodium (cmol(+)/kg)	55	8.4	16	8.5	8.7	7.0	16	6.9	6.6	7.6
Aluminium (mg/kg)	26	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0	<9.0
Aluminium (cmol(+)/kg)	0.28	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
CEC (cmol(+)/kg)	106	31.8	43.3	35.0	40.9	29.1	40.9	26.4	36.8	43.9
Sodium % of cations	52	26	38	24	31	24	38	26	18	17
Aluminium % of cations	0.27	<1	<1	<1	<1	<1	<1	<1	<1	<1
Calcium/Magnesium Ratio	0.92	2.1	1.5	2.2	2.1	2.5	2.2	2.5	3.3	2.9
pH (1:5 Water)	5.7	6.7	6.3	6.6	6.6	6.4	5.6	6.2	5.7	5.8
Electrical Conductivity (dS/m)	13.97	4.76	3.52	3.01	4.42	2.79	0.09	3.43	2.47	0.07
Chloride (mg/kg)	23000	3800	3800	2900	4200	2400	5100	2100	1900	2300

### Soil electrical conductivity (EC)

Soil electrical conductivity increased markedly at the pre-experiment stage in all treatments, indicating an initial rise in soluble salts. The fertilizer and microalgae treatments showed higher EC peaks than the control, reflecting added nutrient inputs. During both the experimental and post-experimental stages, EC declined across all treatments. However, the microalgae treatment exhibited the greatest reduction, with EC levels falling below those of both the fertilizer and control treatments by the post-experimental stage. This suggests that microalgae may have facilitated salt immobilization or enhanced ion regulation, thereby reducing salinity stress over time. This trend is further illustrated in Figure 1.

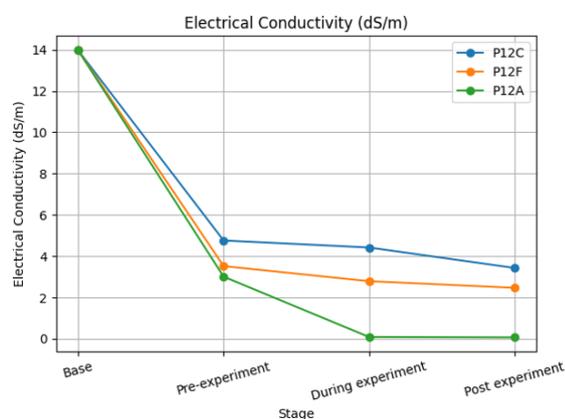


Figure 1 Electrical conductivity (dS/m).

### Soil nitrate nitrogen (NO<sub>3</sub>-N)

Nitrate nitrogen (NO<sub>3</sub>-N) concentrations increased markedly over time in all treatments, beginning from a uniform baseline of 6.2 mg/kg.

Substantial differentiation emerged at the Pre experiment stage, where P12F displayed the strongest early rise to 77 mg/kg, far exceeding the increases observed in P12A (23 mg/kg) and P12C (17 mg/kg). This early surge under P12F implies rapid nitrification or accelerated mineralization of nitrogenous compounds. By mid experiment, nitrate levels increased further, with P12F reaching 190 mg/kg and P12A rising to 120 mg/kg, while P12C showed a smaller but steady increase to 37 mg/kg. These dynamics suggest that P12F and P12A promote stronger microbial nitrogen transformations during active phases of the experiment. Notably, by the Post experiment stage, P12A exhibited the highest nitrate concentration at 420 mg/kg, surpassing P12F (370 mg/kg) and P12C (270 mg/kg). This late stage shift indicates that, although P12F stimulated rapid early nitrate production, P12A supported a more sustained and ultimately greater accumulation of available nitrogen. The temporal pattern suggests treatment dependent nitrogen mineralization pathways, with P12A showing superior long term enhancement of nitrate availability (Figure 2).

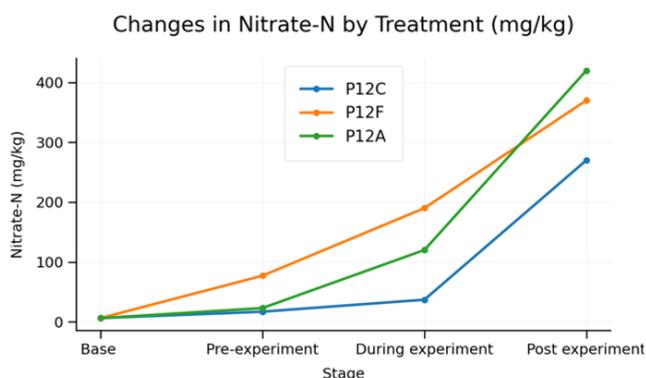
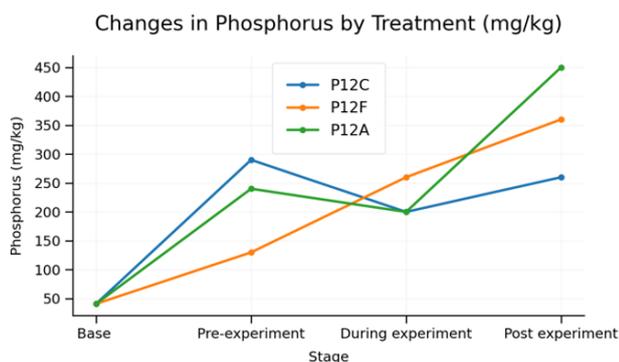


Figure 2 Changes in soil nitrate nitrogen (mg/kg).

## Available phosphorus (Colwell P)

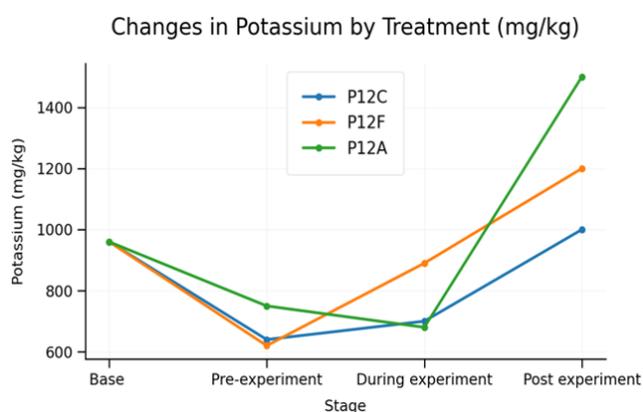
Phosphorus availability also displayed marked treatment specific behaviour across the experimental period. All treatments shared a common baseline concentration of 41 mg/kg, providing a uniform starting point for comparison. During the Pre experiment stage, P12C exhibited a dramatic increase to 290 mg/kg, representing the most pronounced early rise among treatments, while P12A and P12F reached 240 mg/kg and 130 mg/kg, respectively. These early differences suggest that P12C may initially promote rapid phosphorus mobilization, possibly through mineral dissolution or changes in soil chemical equilibria. However, during the experimental phase, both P12A and P12C declined to 200 mg/kg, whereas P12F increased substantially to 260 mg/kg. This reversal indicates dynamic phosphorus cycling in which microbial immobilization, sorption processes, or plant uptake may differentially affect treatments during active soil processes. By the Post experiment stage, all treatments again demonstrated substantial increases, with P12A showing the highest final concentration at 450 mg/kg, followed by P12F at 360 mg/kg and P12C at 260 mg/kg. The strong late stage rise under P12A suggests enhanced long term phosphorus availability, potentially due to reduced fixation or sustained release rates. In contrast, P12C's early high concentration but lower final value indicates an initial flush of phosphorus followed by stabilization or immobilization later in the experiment. Overall, P12A demonstrated the most consistent and sustained increases in phosphorus availability over time (Figure 3).



**Figure 3** Changes in available phosphorus (Colwell P) (mg/kg).

## Available potassium (K)

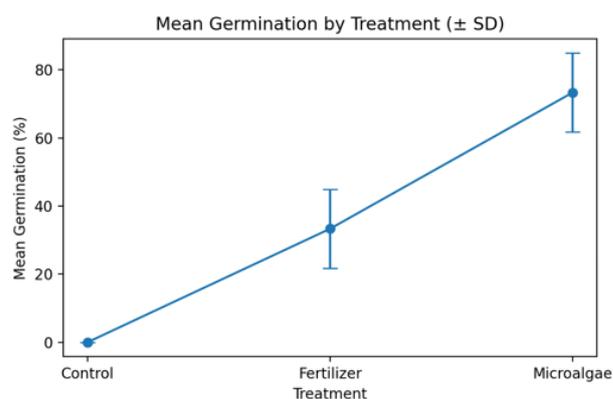
Potassium concentrations exhibited distinct temporal trajectories across the three treatments, despite all beginning from an identical baseline value of 960 mg/kg at the initial measurement stage. Early divergence emerged during the Pre experiment phase, where P12A retained comparatively higher potassium (750 mg/kg) relative to P12C (640 mg/kg) and P12F (620 mg/kg), indicating treatment specific influences on early potassium retention or mobilization. During the experiment, P12F demonstrated a pronounced increase to 890 mg/kg, while P12A and P12C showed more modest shifts (680 mg/kg and 700 mg/kg, respectively), suggesting differential rates of potassium mineralization or availability attributable to treatment characteristics. By the Post experiment stage, all treatments demonstrated substantial potassium accumulation; however, P12A reached a markedly higher concentration of 1500 mg/kg compared with 1200 mg/kg in P12F and only 1000 mg/kg in P12C. This pattern indicates that the P12A treatment most effectively enhanced long term potassium availability, while P12F produced moderate gains and P12C comparatively limited improvement. The overall trend suggests that P12A may facilitate improved potassium retention or sustained mineralization dynamics throughout the experimental period (Figure 4).



**Figure 4** Changes in available potassium (K).

Overall, microalgae amendment produced the strongest improvements in nutrient availability and the most pronounced reduction in soil salinity, outperforming both fertilizer and control treatments across all measured parameters.

Control treatment showed zero germination, while Fertilizer and Microalgae significantly improved germination. Microalgae had the highest and most consistent germination (Figure 5). Chi-square and Fisher's tests confirm significant differences between Control and other treatments.



**Figure 5** Mean seed germination percentage by treatment with standard deviation.

Microalgae achieved the highest mean height by Wk 10, indicating the strongest growth. Control had the lowest mean height by Wk 10, indicating limited growth relative to other treatments. Control: mean started at 0.0 mm and reached 0.0 mm by Wk 10; end-of-period uncertainty  $SE \approx 0.0$  mm. Fertilizer: mean started at 2.0 mm and reached 103.3 mm by Wk 10; end-of-period uncertainty  $SE \approx 57.8$  mm. Microalgae: mean started at 2.3 mm and reached 366.7 mm by Wk 10; end-of-period uncertainty  $SE \approx 46.3$  mm.

Average weekly seedling height (mm) for treatments Control, Fertilizer, and Microalgae are shown in figure 6. Error bars denote standard deviation across replicates. Cells with multiple readings per week were averaged per cell during parsing.

Tomato seedlings were evaluated under three treatments (Control, Fertilizer, Microalgae). For each treatment,  $n=5$  replicates were measured for shoot height (cm), root length (cm), and total length (cm).

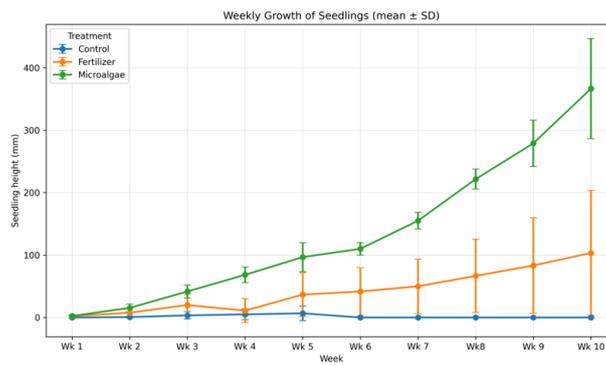


Figure 6 Weekly growth (mean ± SE) for Control, Fertilizer, and Microalgae.

Figure 7 combines three metrics for tomato seedlings — Shoot height (cm), Root length (cm), and Total length (cm) — across three treatments (Control, Fertilizer, Microalgae). Each panel (A–C)

displays a bar chart (Mean ± SEM) alongside a boxplot of raw values (n=5 per treatment). Error bars are SEM computed as SD divided by the square root of n.

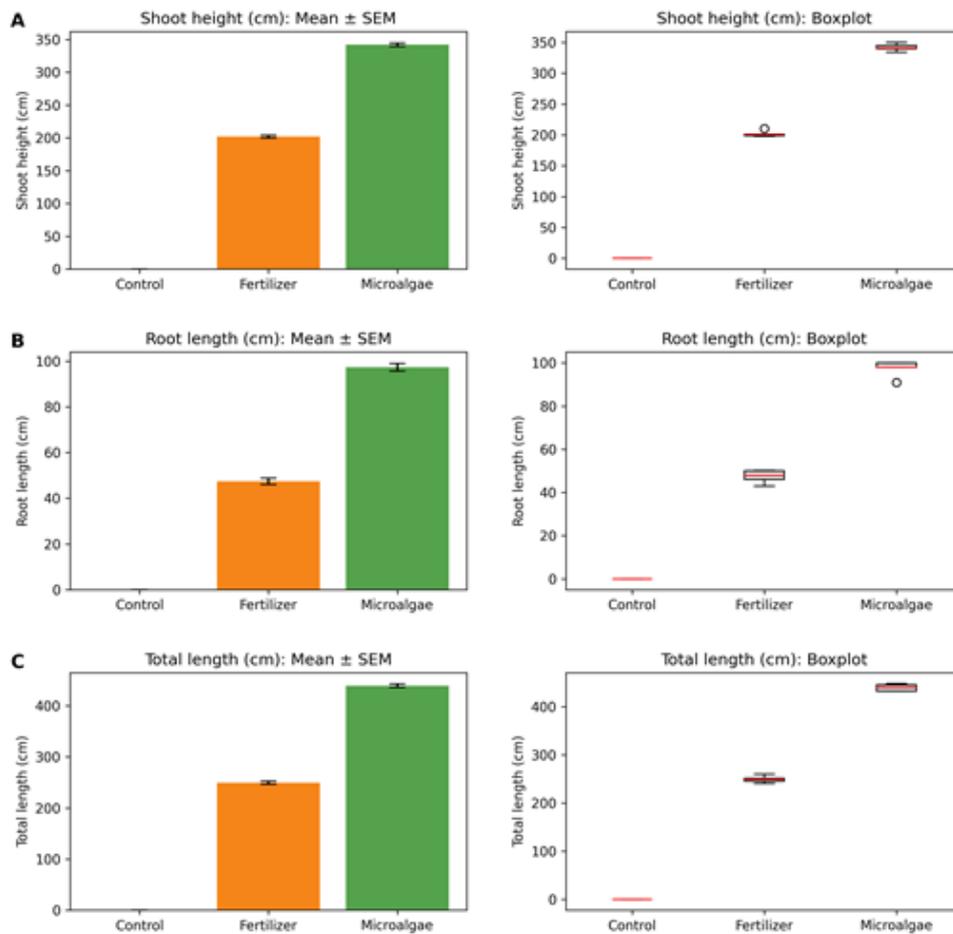
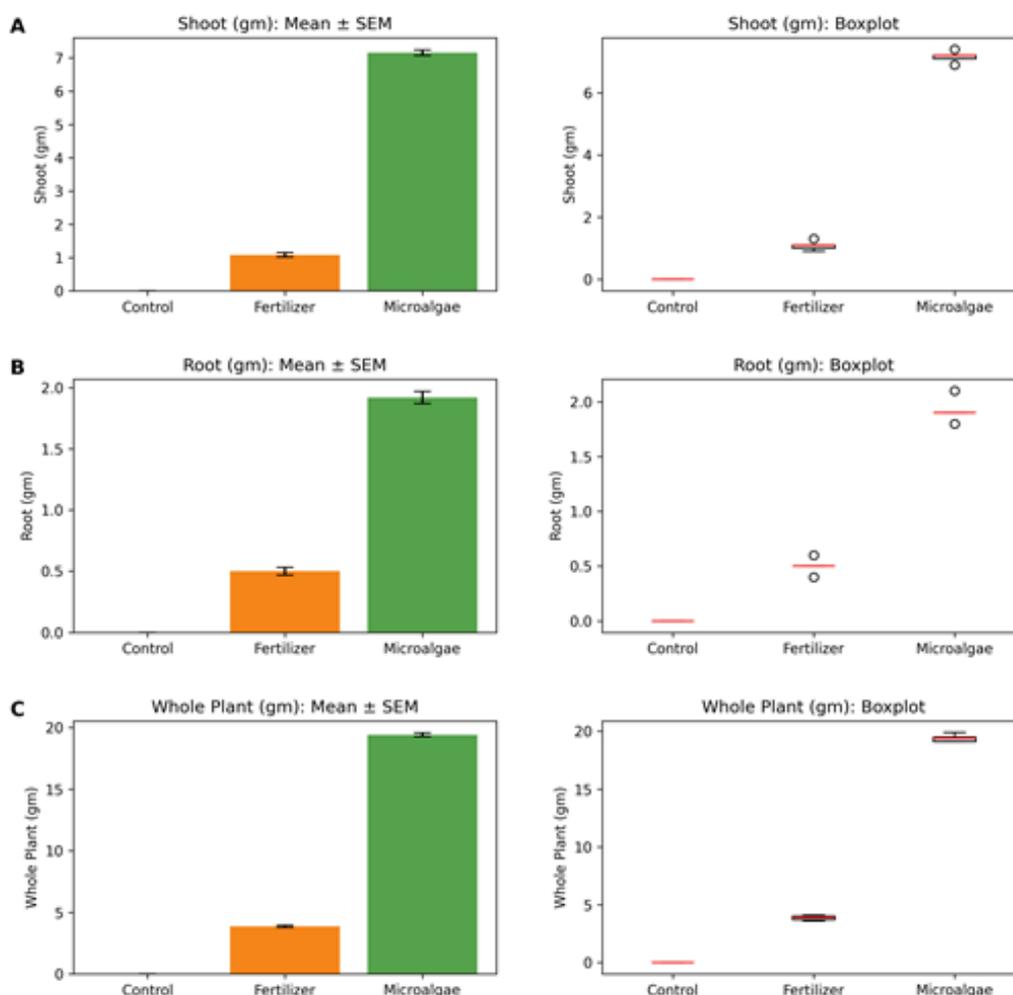


Figure 7 Panels A–C: For each metric, mean ± SEM bar (left) and boxplot (right) across Control, Fertilizer, and Microalgae treatments.

Figure 8 combines three fresh-weight metrics for tomato seedlings — Shoot (gm), Root (gm), and Whole Plant (gm) — across three treatments (Control, Fertilizer, Microalgae). Each panel (A–C)

displays a bar chart (Mean  $\pm$  SEM) alongside a boxplot of raw values (n=5 per treatment). Error bars are SEM computed as SD divided by the square root of n.



**Figure 8** Panels A–C: For each metric, mean  $\pm$  SEM bar (left) and boxplot (right) across Control, Fertilizer, and Microalgae treatments.

For shoot height (cm), mean values were Control 0.00, Fertilizer 201.80, and Microalgae 342.00. One-way ANOVA indicated a significant treatment effect ( $p = 2.376e-19$ ). Post-hoc tests showed Microalgae significantly exceeded Control and Fertilizer.

For root length (cm), mean values were Control 0.00, Fertilizer 47.42, and Microalgae 97.40. One-way ANOVA indicated a significant treatment effect ( $p = 3.099e-15$ ). Post-hoc tests showed Microalgae significantly exceeded Control and Fertilizer.

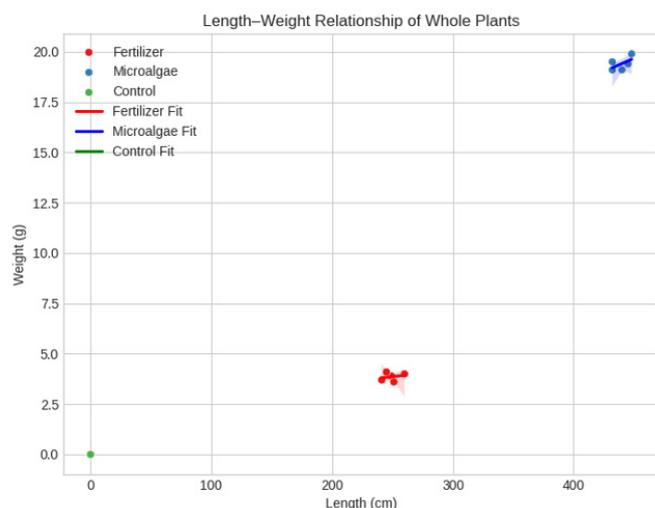
For total length (cm), mean values were Control 0.00, Fertilizer 249.22, and Microalgae 439.40. One-way ANOVA indicated a significant treatment effect ( $p = 4.187e-19$ ). Post-hoc tests showed

Microalgae significantly exceeded Control and Fertilizer (adjusted p-values reported in the table).

Microalgae are superior to conventional fertilization across shoot, root, and whole-plant fresh weight, with very large effect sizes and tight confidence intervals, indicating both magnitude and consistency of response. Fertilizer exceeds Control, but the Microalgae gains are substantially larger in all metrics.

Microalgae treatment significantly enhances both shoot and root development compared to conventional fertilizer, leading to robust overall plant growth. This suggests Microalgae could be a superior biostimulant for tomato seedlings under the tested conditions.

The scatter plot below (Figure 9) shows the length–weight relationship for all treatments with regression lines.



**Figure 9** Combined scatter plot showing the length–weight relationship of whole plants under Control, Fertilizer, and Microalgae treatments. Control plants exhibited no measurable growth. Fertilizer-treated plants developed considerable length but minimal biomass, resulting in a shallow length–weight slope. Microalgae-treated plants showed both high length and high weight, indicating strong biomass accumulation and the steepest length–weight relationship.

Control plants showed no measurable growth, with both length and weight remaining at zero. This indicates that untreated plants failed to elongate or accumulate biomass. Fertilizer-treated plants reached lengths of 241–260 cm, but weights remained very low (3.6–4.1 g). This produced a shallow length–weight slope, suggesting rapid elongation without structural mass, weak tissue development, or possible etiolation. Microalgae-treated plants achieved the greatest lengths (432–448 cm) and highest weights (19.1–19.9 g). This produced the steepest length–weight slope, indicating strong biomass accumulation, healthy structural development, and efficient conversion of length growth into mass.

## Discussion

The results of this study demonstrate that freshwater microalgae have substantial potential as a biological amendment for improving saline soil conditions and enhancing early tomato growth. Across all measured soil parameters, the microalgae treatment consistently outperformed both the fertilizer and control treatments, indicating that microalgal activity can meaningfully alter soil chemistry in ways that support plant establishment under salinity stress. Across all soil properties, microalgae treatment consistently produced the highest nutrient concentrations (nitrate, phosphorus, potassium) and the lowest conductivity, highlighting the strong and consistent effect of microalgae on soil nutrient dynamics.

Electrical conductivity (EC) declined most sharply in the microalgae treatment, suggesting enhanced salt immobilization or ion sequestration. The microalgae treatment showed the greatest reduction, falling below both fertilizer and control levels by the post-experiment stage. This aligns with previous findings that microalgae can reduce salinity by binding ions through extracellular polymeric substances (EPS), improving soil aggregation, and enhancing microbial activity.<sup>5,8,21</sup> The reduction in EC is particularly important for tomato, a salt-sensitive crop that experiences osmotic and ionic stress even at moderate salinity levels.<sup>4,22,23</sup>

Microalgae significantly increased nitrate, phosphorus, and potassium concentrations throughout the experiment. Nitrate-N reached the highest levels in the microalgae treatment during and after the experiment, indicating enhanced nitrogen mineralization or biological nitrogen transformation. This is consistent with studies showing that microalgae can fix atmospheric nitrogen, accelerate organic matter turnover, and release bioavailable nutrients.<sup>6,7,24,25</sup> Similarly, the substantial increase in Colwell P and available K suggests that microalgae facilitated nutrient solubilization, likely through organic acid production and microbial interactions.

The fertilizer treatment also increased nutrient availability but to a lesser extent, and with less stability over time. This difference highlights the advantage of biological amendments, which release nutrients gradually and improve soil structure, rather than causing short-term spikes followed by depletion.

Germination results clearly show the limitations of saline soil without amendment. The document states that “Control treatment showed zero germination, while Fertilizer and Microalgae significantly improved germination.” Microalgae produced the highest and most consistent germination rates, likely due to improved soil moisture retention, reduced salinity stress, and increased nutrient availability. These findings align with previous research showing that microalgae can enhance seed germination by producing phytohormones such as auxins, cytokinins, and gibberellins.<sup>18,26</sup>

Microalgae treatment produced the strongest shoot and root growth, with significantly higher biomass accumulation than both fertilizer and control treatments. For example, microalgae-treated plants reached mean shoot heights of 342 cm compared to 201.8 cm in fertilizer and 0 cm in control. Root length and total length followed the same pattern. The ANOVA results confirm highly significant treatment effects ( $p < 0.05$  across all metrics), with microalgae outperforming fertilizer in every case.

These findings suggest that microalgae not only alleviate salinity stress but also act as potent biostimulants, enhancing physiological processes such as nutrient uptake, photosynthesis, and root system expansion. This is consistent with reports that microalgae improve plant vigor through hormone production, improved soil microbiome interactions, and enhanced nutrient cycling.<sup>19,20,27</sup>

The length–weight analysis further highlights the superior performance of microalgae. Fertilizer-treated plants exhibited substantial elongation but low biomass, producing a shallow length–weight slope. Fertilizer-treated plants developed considerable length but minimal biomass, resulting in a shallow length–weight slope. This pattern suggests etiolation or weak structural development, possibly due to nutrient imbalances or rapid but inefficient growth.

In contrast, microalgae-treated plants showed both high length and high weight, producing the steepest slope. This indicates efficient conversion of photosynthate into structural biomass, reflecting healthier and more robust growth. The document states that microalgae plants exhibited “strong biomass accumulation, healthy structural development, and efficient conversion of length growth into mass.” This is consistent with microalgae’s known ability to enhance carbon assimilation and improve root–shoot coordination.<sup>28–30</sup>

The combined results strongly support the use of microalgae as a sustainable alternative to chemical fertilizers in saline soils. Microalgae not only improved soil nutrient status and reduced salinity but also enhanced germination, growth, and biomass accumulation. These benefits align with global efforts to reduce reliance on synthetic

fertilizers, improve soil health, and promote environmentally friendly agricultural practices.

Given the increasing prevalence of soil salinization worldwide, microalgae-based amendments offer a promising strategy for restoring degraded soils and improving crop productivity. Their multifunctional benefits—nutrient mobilization, salt mitigation, soil structure improvement, and plant biostimulation—make them particularly valuable in saline environments where conventional fertilizers may be less effective or environmentally damaging.

## Conclusion

This study demonstrates that freshwater microalgae provide a highly effective and sustainable strategy for improving saline soil conditions and enhancing early tomato growth. Microalgae application consistently increased soil nutrient availability—particularly nitrate, phosphorus, and potassium—while producing the greatest reduction in electrical conductivity. These improvements reflect the strong capacity of microalgae to remediate saline soils, mobilize nutrients, and enhance soil fertility.

Across all plant growth metrics, microalgae outperformed conventional fertilizer. Microalgae-treated plants exhibited the highest germination rates, the greatest shoot and root development, and the strongest biomass accumulation. The steep length–weight slope observed in microalgae-treated plants indicates efficient biomass production and healthy structural growth, whereas fertilizer-treated plants showed elongation without proportional mass gain. These results highlight the dual role of microalgae as both a salinity mitigation agent and a potent biostimulant.

Given the increasing global challenge of soil salinization, microalgae-based amendments represent a promising, environmentally friendly alternative to chemical fertilizers. Their ability to improve soil structure, mobilize nutrients, reduce salinity, and stimulate plant growth positions them as a valuable tool for sustainable agriculture. Future research should explore long-term field applications, species-specific effects, and optimization of microalgal formulations to support broader adoption in saline and marginal soils.

## Acknowledgement

None.

## Conflicts of interest

All the authors declare that there is no conflicts of interest.

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