

Multifactorial Stressors: Linking *Fusarium* Infection, Heavy Metals, and Salinity to Physiological Dysfunction in Tomato *Solanum lycopersicum* L.

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Abstract

Tomato (*Solanum lycopersicum* L.) is a globally strategic crop, vital for food security and agricultural economies, yet its productivity is increasingly threatened by biotic and abiotic stresses. This study investigates the combined effects of *Fusarium oxysporum* f. sp. *lycopersici* (FOL), heavy metals (cadmium, cobalt, chromium and lead), and salinity on biochemical and growth parameters of the Yassamen tomato variety. Results revealed that FOL infection alone significantly reduced chlorophyll content (3.68 to 2.96 mg.g⁻¹) and total soluble carbohydrates (2.51 to 1.95 mg.g⁻¹), while elevating oxidative stress markers: hydrogen peroxide (H₂O₂, 0.18 to 0.58 μmol.g⁻¹) and malondialdehyde (MDA, 0.13 to 0.44 nmol.g⁻¹). Synergistic interactions exacerbated stress responses, with lead and high salinity (12 dS.m⁻¹) causing the most severe declines in chlorophyll (1.61 and 1.41 mg.g⁻¹, respectively) and carbohydrates (1.40 and 1.32 mg.g⁻¹). Proline accumulation peaked under combined stresses (2.20 μmol.g⁻¹ with FOL + 12 dS.m⁻¹), suggesting a partial compensatory mechanism. Growth parameters were severely inhibited: plant height decreased by 36.8% under FOL, plummeting further to 68% with FOL + 12 dS.m⁻¹, while root dry weight dropped by 63% under FOL + chromium. These findings underscore the compounded damage caused by FOL, heavy metals, and salinity, linked to oxidative membrane damage, photosynthetic impairment, and resource diversion to stress mitigation. To safeguard tomato productivity in stress-prone regions, integrated strategies such as developing stress-tolerant cultivars, optimizing soil remediation, and managing pathogen load are urgently recommended.

Keywords: *Fusarium oxysporum* f. sp. *lycopersici*, Oxidative stress, Heavy metal, Salinity stress, Tomato

I. Introduction

Tomato plants *Solanum lycopersicum* L., belonging to the Solanaceae family, are a strategic crop of global and Iraqi importance, playing a pivotal role in enhancing food and economic security through their contribution to nutrition and the agricultural value chain (Natali et al., 2025). According to FAO statistics (FAOSTAT, 2025), the global cultivated area of tomatoes is approximately 5 million hectares, with an annual production of 186.8 million tons, contributing around \$1.4 billion to the global economy. In Iraq, the total cultivated area of tomatoes reached 86,942 dunams, with a total production of 534,821 tons in 2023, as reported by the Central Statistical Organization (<https://www.cosit.gov.iq/ar/>).

Tomato production faces multiple challenges, most notably biotic factors such as pathogens (fungal, bacterial and viral), insect pests, nematodes, and weeds, alongside abiotic factors like salinity, heavy metal contamination, temperature extremes, and ozone effects, all of which threaten plant growth and productivity (Shi et al., 2025; Mustafa et al., 2025). Among fungal diseases, vascular wilt disease, caused by *Fusarium oxysporum* f.sp. *lycopersici* (FOL), stands out as a major global threat, leading to significant crop losses (Haque et al., 2023; Muhorakeye et al., 2024).

On the abiotic front, soil and water salinity pose a global challenge, affecting one billion hectares of land (20% of global land area), resulting in the loss of 900 million hectares of arable land (Velmurugan et al., 2020; Gabash et al., 2024). Salinity disrupts seed germination, inhibits growth, and damages cellular structures by increasing the accumulation of reactive oxygen species (ROS), leading to lipid peroxidation, protein denaturation, and nucleic acid damage (El Ghazali, 2020). This issue is exacerbated in Iraq's Basrah Governorate due to saltwater intrusion, which elevates soil salinity and negatively impacts agricultural productivity (Suhim et al., 2023; Al-Arabi et al., 2020).

Additionally, heavy metal pollution (e.g., lead, cadmium, cobalt, chromium) in agricultural soils presents severe risks to plant growth, human health, and ecosystems (Sharafi and Salehi, 2025). These metals accumulate in plant tissues, resist degradation, and transfer readily through the food chain (Hanif et al., 2025). Recent studies in Iraq have reported alarmingly high concentrations of these metals in Basrah's soils, exceeding global permissible limits. For instance, lead and cadmium levels reached 270 mg/kg and 9 mg/kg, respectively, compared to European standards of 100 mg/kg (lead) and 3 mg/kg (cadmium) (Al-Jabary et al., 2016; Madhi et al., 2021).

Given the scarcity of studies on the interaction between biotic and abiotic factors and the critical threat posed by *Fusarium* wilt, this study aims to analyse the morphological and biochemical responses of tomato plants to FOL infection under varying levels of salinity and heavy metal contamination.

II. . Materials and Methods

The applied experiment was conducted in a plastic greenhouse at the Date Palm Research Center, University of Basrah, to investigate the interactions between the pathogenic fungus *Fusarium oxysporum* f.sp. *lycopersici* (FOL), which causes vascular wilt disease, and selected levels of heavy metals and salinity based on field survey results of tomato farms in Basrah Governorate. The Yassamen variety was chosen for its sensitivity to the pathogen and the contamination levels under study. The experiment proceeded as follows:

2.1 Soil Preparation and Sterilization

Agricultural soil was collected from a tomato farm in Al-Zubair District, mixed with peat moss, and sterilized using formalin.

2.2 Preparation of *F. oxysporum* f.sp. *lycopersici* Inoculum

The fungal inoculum was prepared by culturing the pathogen on millet (*Panicum miliaceum* L.) seeds according to Mustafa et al. (2021). Sterilized soil was distributed into 1 kg plastic pots after mixing with the fungal inoculum (1% w/w) (Jones et al., 1984). The pots were watered and left for 72 hours to allow fungal growth. Tomato seedlings were then transplanted into the pots (five replicates per treatment, three seedlings per pot). Control treatments received sterilized millet seeds only.

2.3 Seedling Preparation

Two-week-old tomato seedlings (variety Yassamen) were obtained by sowing seeds in polystyrene seedling trays. Seeds were sterilized with 10% sodium hypochlorite, rinsed three times with distilled water, and placed in sterilized peat moss (three seeds per cell). Seedlings were watered with distilled water as needed and later transplanted into 1

kg plastic pots containing the prepared soil (inoculated with FOL), except for three control pots without fungal inoculation.

2.4 Experimental Treatments

Treatments (Table 1) included irrigation with heavy metal solutions (cadmium, cobalt, chromium and lead) and saline solutions (4, 8, 12 dS/m NaCl), prepared based on field survey results. Heavy metal solutions were prepared using chemical compounds listed in Table 2. Control and FOL-infected treatments were irrigated with distilled water only (Razak et al., 2024).

2.5 Applied Experiment

Treatments (Table 1) were applied to Yassamen tomato seedlings in the greenhouse. Plants were irrigated with heavy metal or saline solutions, while controls (non-infected) and FOL-infected plants received distilled water. Treatments continued for 60 days, after which the following parameters were measured.

Table 1. Applied treatments details for FOL interactions with heavy metals and salinity levels.

Treatments	Details
Control	Control
FOL	Pathogen FOL
FOL+ Cd	16 mg.kg-1
FOL+ Co	135 mg.kg-1
FOL+ Cr	298 mg.kg-1
FOL+ Pb	228 mg.kg-1
FOL+ SA ₁	Salinity 4 ds.m ⁻¹
FOL+ SA ₂	Salinity 8 ds.m ⁻¹
FOL+ SA ₃	Salinity 12 ds.m ⁻¹

Table 2. Heavy metals concentrations and their materials.

Heavy Metals	Concentration Mg.kg ⁻¹	Materials	Company	Country
Cd	16	CdCl ₂ .H ₂ O	Loba Chemie pvt Ltd.	India
Co	135	Cl ₂ Co.6H ₂ O	Atom scientific	UK
Cr	298	CrCl ₃ .6H ₂ O	Titan Biotch Ltd.	India
Pb	228	Pb(NO ₃) ₂	Loba Chemie pvt ltd	India

2.5.1 Total Chlorophyll Content

Total chlorophyll was estimated using Arnon's method (1949). Fresh leaf tissue (200 mg) was ground in 8 mL of 80% acetone using a pre-chilled ceramic mortar. The homogenate was centrifuged at 3000 rpm (Eppendorf 5804 R, Germany). Absorbance was measured at 663 and 645 nm using a UV-1100D spectrophotometer (EMCLAB GmbH, Germany). Total chlorophyll (mg/g fresh weight) was calculated using the formula:

$$\text{Total Chlorophyll} = (20.2 \times \text{OD}_{645} + 8.02 \times \text{OD}_{663}) \times \text{Extract Volume} / \text{S. W.}$$

Which S.W is sample weight.

2.5.2 Total Soluble Carbohydrates

Carbohydrates were quantified via the anthrone method (Watanabe, 2000). Fresh leaves (0.5 g) were homogenized in 80% ethanol, centrifuged at 5000 rpm for 10 minutes, and 1 mL of supernatant was mixed with 3 mL anthrone reagent (50 mg anthrone in 50 mL 95% H₂SO₄). Samples were boiled for 10 minutes, cooled, and absorbance measured at 620 nm. Glucose standards were used for calibration.

2.5.3 Proline Content

Proline was determined using Bates et al. (1973). Leaf tissue (0.5 g) was homogenized in 3% sulfosalicylic acid, centrifuged at 6000 rpm for 5 minutes, and 2 mL supernatant was mixed with 2 mL glacial acetic acid and 2 mL acid ninhydrin reagent (1.25 g ninhydrin in 30 mL glacial acetic acid + 20 mL phosphoric acid). Samples were boiled for 1 hour, cooled, and extracted with toluene. Absorbance was measured at 520 nm. Proline content (μmol/g fresh weight) was calculated as:

$$\text{Proline} = \frac{\mu\text{g proline} \times \text{Toluene volume}}{115.5 \times \text{Sample weight}}$$

Which 115.5 is the proline molecular weight.

2.5.4 Hydrogen Peroxide (H₂O₂) Content

H₂O₂ was quantified by homogenizing 0.5 g leaves in 0.1% trichloroacetic acid (TCA), centrifuging at 13,000 rpm for 15 minutes, and mixing 1 mL supernatant with 0.5 mL 10 mM potassium phosphate buffer (pH 7) and 1 mL 1 M KI. Absorbance was read at 390 nm (Sergiev et al., 1997).

2.5.5 Malondialdehyde (MDA) Content

MDA was measured using Heath and Packer (1968). Leaf tissue (0.5 g) was homogenized in 0.1% TCA, centrifuged at 10,000 rpm for 5 minutes, and 1 mL supernatant was mixed with 4 mL 0.5% thiobarbituric acid (TBA) in 20% TCA. Samples were boiled for 30 minutes, cooled, and centrifuged at 10,000 rpm for 15 minutes. Absorbance was read at 532 and 600 nm. MDA content (μmol/g fresh weight) was calculated as:

$$\text{MDA} = \frac{\text{OD}_{532} - \text{OD}_{600} \times 100}{155}$$

Which 155 is the Extinction Coefficient for MDA.



2.5.6 Growth Parameters

- **Plant Height (cm):** Measured from soil surface to the shoot apex.
- **Leaf Area (cm²):** Determined using a scanner and ImageJ software (Aboukarima et al., 2017).
- **Dry Weight of Shoot and Root System:** Measured after drying at 70°C for 48 hours.

2.6 Statistical Analysis

The experiment followed a Completely Randomized Design (CRD). Data were analysed using one-way ANOVA (SPSS v24), with means compared via LSD test at $p \leq 0.05$.

III. Results

3-1 Impact of Interactions Between FOL Pathogen, Heavy Metals, and Salinity on Biochemical Traits of Tomato Plants

Table (3) summarizes the effects of interactions between *Fusarium oxysporum* f. sp. *lycopersici* (FOL), selected heavy metals, and salinity levels on the biochemical traits of the Yassamen tomato variety.

3-1-1 Total Chlorophyll Content

The control treatment showed a total chlorophyll content of 3.68 mg.g⁻¹ in tomato leaves, which decreased significantly to 2.96 mg.g⁻¹ under FOL infection. Combined interactions of FOL with heavy metals further reduced chlorophyll concentrations (Table 3). The lowest values were recorded for FOL + cadmium (2.20 mg.g⁻¹), FOL + cobalt (2.13 mg.g⁻¹), FOL + chromium (2.28 mg.g⁻¹), and FOL + lead (1.61 mg.g⁻¹). Lead exhibited the most pronounced negative effect compared to other metals.

Salinity interactions with FOL also reduced chlorophyll content, while FOL + 4 dS.m⁻¹ salinity (2.93 mg.g⁻¹) showed no significant difference from FOL alone, higher salinity levels (8 and 12 dS.m⁻¹) caused significant declines to 2.15 mg.g⁻¹ and **1.41 mg.g⁻¹, respectively.

3-1-2 Total Soluble Carbohydrates

The control treatment had the highest soluble carbohydrate content (2.51 mg.g⁻¹), which dropped to 1.95 mg.g⁻¹ under FOL infection (Table 3). Interactions of FOL with cadmium (1.83 mg.g⁻¹) and chromium (1.73 mg.g⁻¹) caused non-significant reductions compared to FOL alone. However, FOL + lead (1.40 mg.g⁻¹) showed the most significant decline. Salinity at 12 dS.m⁻¹ combined with FOL further reduced carbohydrates to 1.32 mg.g⁻¹, the lowest value recorded.

3-1-3 Proline Content

FOL infection alone resulted in the lowest proline content (1.08 µmol.g⁻¹), which did not differ significantly from the control (1.20 µmol.g⁻¹). However, interactions with heavy metals increased proline levels: FOL + cadmium (1.30 µmol.g⁻¹), FOL + cobalt (1.53 µmol.g⁻¹), FOL + chromium (1.73 µmol.g⁻¹), and FOL + lead (1.75 µmol.g⁻¹). Chromium and lead had the most significant effects. Salinity interactions further elevated proline, with FOL + 12 dS.m⁻¹ reaching 2.20 µmol.g⁻¹, the highest value (Table 3).

3-1-4 Hydrogen Peroxide (H₂O₂) Content

H₂O₂ levels rose from 0.18 $\mu\text{mol.g}^{-1}$ in controls to 0.58 $\mu\text{mol.g}^{-1}$ under FOL infection. Combined FOL + heavy metal treatments further increased H₂O₂: cadmium (0.75 $\mu\text{mol.g}^{-1}$), cobalt (0.75 $\mu\text{mol.g}^{-1}$), chromium (0.81 $\mu\text{mol.g}^{-1}$), and lead (0.81 $\mu\text{mol.g}^{-1}$), with no significant differences between metals. Salinity at 12 dS.m⁻¹ + FOL caused the highest H₂O₂ accumulation (1.07 $\mu\text{mol.g}^{-1}$).

3-1-5 Malondialdehyde (MDA) Content

FOL infection increased MDA from 0.13 nmol.g⁻¹ (control) to 0.44 nmol.g⁻¹. Interactions with lead (0.85 nmol.g⁻¹) and chromium (0.75 nmol.g⁻¹) caused the highest MDA levels, while cadmium and cobalt showed lower effects (0.56 and 0.58 nmol.g⁻¹, respectively). Salinity at 12 dS.m⁻¹ + FOL resulted in 0.78 nmol.g⁻¹, comparable to lead's impact (Table 3).

Table 3. Interactions Between FOL Pathogen, Heavy Metals, and Salinity on Biochemical Traits of Tomato Plants

Treatments	Chlorophyll mg g ⁻¹	Carbohydrates mg g ⁻¹	Proline $\mu\text{M. g}^{-1}$	H ₂ O ₂ $\mu\text{M. g}^{-1}$	MDA nmole.g ⁻¹
Control	a3.86	a2.51	1.20fg	0.18e	0.13f
FOL	c2.96	cde1.95	1.08g	0.58c	0.44d
FOL+ Cd	d2.20	de1.83	1.30ef	0.75b	0.56c
FOL+ Co	d2.13	bcd2.03	1.53d	0.81b	0.58c
FOL+ Cr	d2.28	e1.73	1.73c	0.75b	0.75b
FOL+ Pb	e1.61	f1.40	1.75c	0.86b	0.85a
FOL+ SA ₁	c2.93	bc2.13	1.41de	0.48c	0.32e
FOL+ SA ₂	d2.15	cde1.90	1.95b	0.75b	0.51cd
FOL+ SA ₃	e1.41	f1.32	2.20a	1.07a	0.78ab
LSD (0.05)	0.23	0.22	0.14	0.10	0.09

3-2 Impact of Interactions on Growth Parameters

Table (4) summarizes the effects of FOL, heavy metals, and salinity on growth parameters of the Yassamen tomato variety.

3-2-1 Plant Height

FOL infection reduced plant height from 22.90 cm (control) to 14.48 cm. Lead + FOL caused the most severe reduction (8.56 cm), while cadmium, cobalt, and chromium + FOL resulted in non-significant declines (13.25, 12.73, and 11.15 cm, respectively). Salinity at 12 dS.m⁻¹ + FOL further reduced height to 7.33 cm.

3-2-2 Leaf Area

Leaf area decreased from 7.06 cm² (control) to 4.43 cm² under FOL. Lead + FOL caused the most significant reduction (3.25 cm²), followed by cadmium (3.80 cm²), cobalt (3.56 cm²), and chromium (3.71 cm²). Salinity at 12 dS.m⁻¹ + FOL reduced leaf area to 3.13 cm², the lowest value recorded.

3-2-3 Dry Weight of Shoot

Shoot dry weight dropped from 76.66 mg (control) to 49.33 mg under FOL. Heavy metal interactions further reduced weights: cadmium (37.00 mg), cobalt (31.66 mg), chromium (37.00 mg), and lead (37.66 mg). Salinity at 12 dS.m⁻¹ + FOL caused the lowest shoot weight (33.66 mg).

3-2-4 Dry Weight of Root

Root dry weight decreased from 9.00 mg (control) to 5.66 mg under FOL. Lead + FOL (3.66 mg) and chromium + FOL (3.33 mg) showed the most severe reductions. Salinity at 12 dS.m⁻¹ + FOL resulted in the lowest root weight (3.33 mg).

Table 4. Interactions Between FOL Pathogen, Heavy Metals, and Salinity on Growth Parameters of Tomato Plants

Treatments	Plant Height cm	Leaf area cm ²	Dry weight of Shoot system mg	Dry weight of Root system/ mg
Control	22.90a	7.06a	76.66a	9.00a
FOL	14.48cd	4.43c	49.33c	5.66b
FOL+ Cd	13.25cd	3.80de	37.00d	4.66bcd
FOL+ Co	12.73de	3.56ef	31.66d	4.33cde
FOL+ Cr	11.15e	3.71ef	37.00d	3.33e
FOL+ Pb	8.56f	3.25gh	37.66d	3.66de
FOL+ SA ₁	14.98c	4.03d	40.33d	4.66bcd
FOL+ SA ₂	12.81de	3.43 fg	36.33d	4.33cde
FOL+ SA ₃	7.33f	3.13h	33.66d	3.33e
LSD (0.05)	1.66	0.28	7.80	1.07

IV. Discussion

The findings of the current study demonstrated that infection by the pathogenic fungus *Fusarium oxysporum* f. sp. *lycopersici* (FOL), which causes vascular wilt disease, significantly reduced leaf chlorophyll content, total soluble carbohydrates, and growth parameters (plant height, leaf area, shoot and root dry weight) in tomato plants compared to the control. This may be attributed to the severe oxidative stress induced by FOL infection due to the accumulation of reactive oxygen species (ROS) such as hydrogen peroxide (H₂O₂) and reactive compounds like malondialdehyde (MDA) (Feng et al., 2023). The current study confirmed this, showing that FOL infection increased H₂O₂ and MDA levels by approximately 3.22-fold and 3.38-fold, respectively, compared to the control. Singh et al. (2017) noted that FOL produces toxins like fusaric acid, which trigger ROS accumulation, leading to membrane damage and reduced photosynthetic pigments in tomato leaves.

Cellular membrane damage is a critical consequence of pathogen infection, including FOL. High ROS levels oxidize membrane lipids (lipid peroxidation), compromising membrane integrity and permeability. This disrupts ion homeostasis (e.g., Mg^{2+} , Ca^{2+} , K^{+} leakage), impairs water and nutrient transport, destabilizes cytoplasmic components, and inhibits vital processes like photosynthesis and respiration (Sikandar et al., 2025). The accumulation of MDA in plant cells is a precise biomarker of membrane damage under biotic and abiotic stresses (Abdelaziz et al., 2024).

The decline in carbohydrate content in FOL-infected leaves can be explained by multiple interconnected mechanisms:

1. Reduced photosynthetic efficiency due to leaf tissue damage and chloroplast membrane degradation.
2. ROS-induced oxidation of biomolecules, diverting carbohydrate resources to defence pathways instead of growth.
3. Disruption of metabolic pathways critical for sugar synthesis and storage (Anjum et al., 2024).

The observed growth inhibition in FOL-infected plants aligns with Ribeiro et al. (2022), who linked vascular system disruption to fungal colonization (e.g., hyphal plugs in xylem vessels) and mycotoxin secretion, which impede water transport. Anatomical studies by Aybeke (2017) confirmed severe degradation of vascular tissues, particularly xylem, in infected plants.

The significant reduction in shoot and root dry weight reflects impaired photosynthesis, energy diversion to defence mechanisms (Soliman et al., 2022), and compromised root efficiency in water and nutrient uptake (Sahu et al., 2024). These findings are consistent with Aybeke (2017), Ribeiro et al. (2022), and Sikandar et al. (2025), who reported similar declines in growth parameters, photosynthetic pigments, and carbohydrates in FOL-infected plants.

Contrary to previous studies (Abdelaziz et al., 2024; Sikandar et al., 2025), proline levels decreased in FOL-infected plants compared to controls. This discrepancy may stem from disrupted metabolic pathways (e.g., glutamate-proline synthesis via P5CS enzyme inhibition) under fungal stress. Additionally, energy deficits in infected plants may trigger proline degradation to fuel alternative respiratory pathways for ATP production (Pedrotti et al., 2018).

The interaction of FOL with heavy metals (cadmium, cobalt, chromium, lead) exacerbated damage in tomato plants. Lead exhibited the highest toxicity, significantly reducing growth parameters and biochemical traits. These results align with Kakaei et al. (2023), who reported that lead exposure (300 mg.kg^{-1}) reduced plant height, root length, and dry weight in tomatoes, alongside declines in proline and carbohydrates. Ur Rahman et al. (2024) attributed lead toxicity to disrupted photosynthesis, hormonal imbalance, and membrane damage. Anjum et al. (2025) further noted that high lead levels ($>300 \text{ mg.kg}^{-1}$) reduced stem and root length by 49.78 and 57.62%, respectively, while lowering chlorophyll and proline content.

Salinity at high levels (8 and 12 dS.m^{-1}) amplified FOL-induced stress, whereas 4 dS.m^{-1} showed no additive effect. Salinity triggers osmotic stress (reduced root water potential), toxic ion accumulation (Na^{+} , Cl^{-}), and ROS overproduction, which degrade chlorophyll, damage chloroplasts, and impair photosynthesis (Lungoci et al., 2022). Sora et al. (2024) found that salinity (5 dS.m^{-1}) reduced growth parameters (height, leaf area, dry weight) and nutrient uptake (sulfur, phosphorus, potassium) in tomatoes. Similarly, Sultana et al. (2025) reported that 100 mM NaCl decreased growth and essential minerals (K^{+} , Ca^{2+} , Mg^{2+}) while elevating proline, MDA, and H_2O_2 levels.

V. Conclusions

This study elucidates the compounded detrimental effects of *Fusarium oxysporum* f. sp. *lycopersici* (FOL), heavy metals, and salinity on biochemical and growth parameters of the Yassamen tomato variety. FOL infection alone significantly reduced chlorophyll content and total soluble carbohydrates, while elevating oxidative stress markers,

including hydrogen peroxide and malondialdehyd. These findings highlight FOL-induced oxidative damage, likely due to reactive oxygen species (ROS) accumulation and membrane lipid peroxidation, which impair photosynthesis and metabolic stability.

The interaction of FOL with heavy metals and salinity exacerbated stress responses. Lead emerged as the most toxic element, synergizing with FOL to drastically reduce chlorophyll and carbohydrates, while elevating MDA. Similarly, high salinity (12 dS.m⁻¹) combined with FOL caused severe declines in chlorophyll and carbohydrates, alongside the highest H₂O₂ and MDA levels. Proline accumulation under combined stresses (e.g., 2.20 µmol.g⁻¹ with FOL + 12 dS.m⁻¹ salinity) suggests a partial adaptive response, though insufficient to mitigate growth inhibition. Growth parameters were severely compromised: FOL reduced plant height, leaf area, and shoot/root dry weights. Lead and high salinity further suppressed growth.

These results underscore the vulnerability of tomato plants to combined biotic (FOL) and abiotic (heavy metals, salinity) stresses, which disrupt physiological and morphological functions. The study emphasizes the urgency of integrated agricultural strategies, such as developing stress-tolerant varieties and optimizing soil management.

VI. References

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