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RESEARCH ARTICLE
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Impact of Climate Change on the Emergence of Plant Pathogens in Tomato Plants

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ABSTRACT

Climate change poses an escalating challenge to agricultural systems worldwide, significantly impacting both input availability and crop yields. As global temperatures rise and weather patterns become more erratic, the spread of plant diseases is intensifying, thereby threatening global food security. This study aimed to evaluate the effects of climate change on pathogen emergence, severity, and tomato crop production. The experimental design included four treatments: a control group, an increased temperature scenario (2-3°C above ambient), elevated CO_2 concentration (300 ppm), and a combination of increased temperature and CO_2 levels. These treatments were implemented in a controlled environment to regulate the experimental conditions precisely. The collected results were entered and analyzed using the R software. Descriptive statistics, ANOVA, and regression analysis were used to reach the results. The increase in temperature increased the pathogens by 40% after 16 weeks, while under CO_2 treatment, the pathogens increased by 30% compared to the control treatment. The mix treatment of temperature and CO_2 increased the pathogens by 70% compared to the control treatment. Disease severity increased to 2, 4, and 6 levels under the temperature, CO_2, and mix treatments. Regression analysis revealed significant correlations between elevated temperature and CO_2 concentrations and the severity of tomato diseases. Tomato production per plant dropped by 60%, 70%, and 30% under temperature, CO_2, and mix treatment. The study recommended the need for innovative agricultural practices to face the increased risk of plant production under climate change conditions.

Keywords: Climate change, Plant pathogens, Tomato, Carbon dioxide, Temperature

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INTRODUCTION

Climate change (CC) presents a significant new challenge to agricultural activities by impacting plant production and global food security (Lidon, 2018; Chapagai et al., 2023). The increase in global temperatures highly affects the patterns of precipitation and increases the CO_2 concentration which altered the environmental conditions that highly affected the cropping patterns in different areas of the world. Sbeiti et al. (2023) reported that, in addition to its impact on climate, CC also influences the dynamics of plant-pathogen interactions. The increase in temperature and CO_2 concentration leads to aggressive strains of soil-borne pathogens. Kaur et al. (2023) reported that the CC affected the host plant resistance with less tolerability of the plants for the new conditions. Sign et al. (2023) further noted that disease incidence and severity increased as the dynamics of plant-pathogen interactions complications increased due to CCs producing new pathogen strains and changed the pathogen distributions. Kaur et al. (2023, 2024) revealed that the development of effective disease management strategies is reliance on the deep understanding of the complications resulted from the CC conditions.

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Tomato (*Solanum lycopersicum*) is an economic crop planted in different parts of the world. This plant production threatened by different types of fungi, bacterial and virus diseases which leave high impact on its productivity and quality (Zhou et al., 2019). The CC affect the virulency and the distribution of plant diseases through affecting the pathogen life cycles. Singh et al. (2019) and (2023) reported that the capabilities of plant's defense and resistance is affected by the raise of CO_2 and temperatures. The increase of temperatures as a direct result of climate change affects the pathogen dynamics and diseases distribution (Zafar et al., 2022). Both microbial and vector-borne pathogens are affected pathogen dynamics across the ecosystem resulted from the increase of atmosphere temperatures. Realizing the mechanisms of the effect of high temperatures will facilitate the control of pathogen behavior and spread. Eliette et al. (2024) reported that increasing soil temperatures affect soil microorganisms by altering attack success and impacting microbial diversity and resistance to invasion. The fluctuation of temperatures impacts the pathogen's life cycles through its rushing leading to more frequent and severe outbreaks. Delgado-Baquerizo et al. (2020) discussed the increase of temperatures will increase the soil-borne fungal pathogens globally with prevalence increase under the CC scenarios.

Laine (2023) showed that tomato growth optimal temperature ranges from 25oC to 30oC, so that any deviations increase its susceptibility to diseases. Che et al. (2023) reported that the prefoliation of pathogens is encouraged under high temperatures and wet conditions that diversly affect the productivity. Late blight that produced by *Phytophthora infestans* leading to earlier and severe disease growth is increased by elevated temperatures (Laine, 2023). Du et al. (2020) explored that temperature increase reduce the gene's effectiveness leading to low plant disease resistance. The high temperature results in decreasing the tomatoes' resistance to root-knot nematodes. These findings highlight the potential for increased temperature to exacerbate disease pressures on tomato crops.

Elevated atmospheric CO_2 is a dominant feature of the CC, producing multifaceted effects on plant health with varied outcomes depending on the specific context. Wang et al. (2023) revealed that enhanced CO_2 can mitigate the adverse effects of heavy metals on vegetative growth by increasing antioxidant enzyme activities and reducing the accumulation of toxic metals in the upper parts of the plant. Sun et al. (2023) reported that eCO_2 increase the plant biomass, chlorophyll content, and antioxidants responses that improve its drought tolerance and decreasing oxidative stress. Plant physiology is affected by high concentrations CO_2 producing plant higher resistivity for diseases (Mourouzidou et al., 2023). In tomatoes, the high CO_2 concentrations have a direct effect on the plant's defense against pathogens which increase the incidence of diseases including *Tomato spotted wilt virus*.

The interaction of temperature increase and elevated CO_2 affect the pathogen dynamics which exposed to synergistic effects. Sunkad et al. (2023) found that the increase of temperatures to 30-35^{o}C increase the pathogens producing dry root rot and severe diseases, but it will be reduced if being exposed to elevated CO_2 conditions (550±25ppm) and the temperature increase by 2^{o}C. The combination of higher temperatures and elevated CO_2 can significantly increase the severity of different diseases such as the early blight (*Alternaria solani*) in tomatoes (Yang et al., 2020; Hu et al., 2023). Hu et al. (2023) found that elevated CO_2 and temperature significantly change the N-acylethanolamine (NAE) pathway in tomatoes, which is crucial for defense against pathogens like *Botrytis cinerea* and *Pseudomonas syringae pv.* tomato.

The interaction between temperature, CO_2 levels, and plant diseases is increasingly significant under different the CC scenarios. Research found that incidence and severity of palnt diseases will increase as the global temperatures increased from 0.9 to 0.5oC by 2100 (Sunkad et al. 2023) reported that the rise of global temperatures by 0.9 to 3.5 °C by 2100, will increase the incidence and severity of various plant diseases. Rice sheath blight which is caused by *Rhizoctonia solani*, demonstrated increased lesion lengths under elevated temperatures, although CO_2 alone did not significantly impact disease severity (Shen et al. 2023). Furthermore, temperature increases enhance virulence in soil-borne pathogens such as *Verticillium* spp., leading to greater susceptibility in host plants (Sbeiti et al. 2023). To control agricultural production and reach sustainable production effective disease management strategies needed (Kaur et al. 2023).

Different research in different regions investigated the effect of the CC on plant production and pathogens. In the Mediterranean region, the occurrence of bacterial diseases was affected by the change patterns of precipitation and temperatures such as *Xanthomonas perforans* (Cieschi et al. 2019). In USA, research approved the need of plant disease management practices to control plant diseases under different climatic changes. The high impact of the CC on plant production, the distribution of plant disease and immunity of plant diseases causes raised the need for deep investigation to understand the behavior of plant pathogens (PP) in different conditions. The reachability of high resilient crop varieties will facilitate the natural control of plant diseases and encourage the reachability of sustainable plant production that reserves environment and human health.

This study investigates the tomato PP behavior under different temperatures and CO_2 levels. It focuses on the distribution of these pathogens and the severity of infections across different environmental conditions. By simulating changes in temperature and CO_2 concentration, the study aims to elucidate the impacts of the CC on pathogen spread, incidence, severity, and crop yield. Understanding these dynamics is crucial for developing effective strategies to mitigate the CC-related risks to food security.

The findings of this research are expected to provide valued understandings of the the CC effect on pathogen dynamics and inform the development of adaptive agricultural practices. Addressing the challenges will be essential for ensuring the sustainability and productivity of tomato crops and other essential agricultural systems (Fischbach et al., 2022; Mills et al., 2023). This experiment aims to study the effect of controlled climate conditions related to temperature, humidity, and CO_2 levels on the emergence of pathogens and crop production of tomatoes.

MATERIALS & METHODS

Objectives

This research investigates the effect of temperature and CO_2 concentration on tomato crop pathogens and production. The experiment was conducted in Al Karak governorate in Jordan, about 150 km south of the capital Amman. The experiment was conducted in the period Feb 2024 to May 2024. The recorded temperature through the experiment ranged from the minimum temperature of 14^{o}C to maximum temperatures reached 35^{o}C.

Treatments and Design

To investigate the effect of the CC on tomato production and diseases, four treatments were used in this experiment to cover the parameters that attributed with the CC. The control (C) which used the common climate conditions without any interference was used to compare with the other CC treatments. The second treatment is the temperature (T) treatment, 2-3^{O}C over the control treatment was applied (Hassan & Hashim, 2020). The CO_2 (CO) concentration which was fixed to 300ppm (Chen et al., 2024), and the last treatment was the mix (TCO) between the temperature and the CO_2 concentration to measure the interaction effect on PP. The treatments were distributed using a randomized complete block design (RCBD) with three replicates. The chambers were used for the treatments under temperature, CO_2 concentration, and a mix of both treatments. Thermometer sensors were used to ensure the temperature degrees within the chambers and CO_2 sensors were used to control the concentrations (Fig. 1).

Implementation

The climate-controlled chamber growth was used and supplied with temperature and CO_2 control sets. The temperature, humidity, and CO_2 levels were monitored throughout the experiment. The tomato plants with PP (*Fusarium oxysporum*) were used (Zhou et al., 2019). The pathogens' addition was equal among the different treatments.

Data collection

Two types of reading were recorded. The plant disease records included the number of infected plants under each treatment weekly, and the disease severity records based on lesion size and wilting. The rate of pathogen spread was measured under each treatment. Plant vegetative characteristics were measured under each treatment including the plant height and production.

Statistical analysis

Descriptive statistics describe the criteria of infection and vegetative growth. Using R software, the RCBD ANOVA tested the statistical differences among the treatments. The regression analysis evaluated the relationship between the treatments and pathogen virulence.

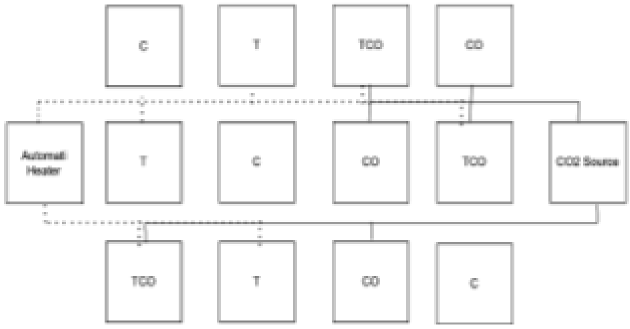

Fig. 1: Experiment design for the control (C), temperature (T), CO_2 (CO), and mix treatment (TCO).

RESULTS

Under C treatment the disease incidence was minimal, with only 10% of the tomato plants showing mild symptoms of infection by the end of the experiment, while under T treatment, the results showed that the incidence of disease increased significantly, with 40% of the plants exhibiting symptoms. The onset of symptoms occurred earlier compared to the C treatment, indicating a potential acceleration of pathogen activity due to higher temperatures, while under CO treatment, the elevated CO_2 group showed a moderate increase in disease incidence, with 30% of the plants infected. Symptoms appeared slightly later than in the increased temperature group but were more severe, suggesting that elevated CO_2 levels might enhance pathogen virulence (Fig. 1).

Under the TCO treatment, the highest incidence occurred, with 70% of the plants showing severe symptoms. Disease onset was rapid, and the pathogen spread more aggressively, suggesting a synergistic effect of increased temperature and CO_2 levels on pathogen virulence. The statistical analysis showed that the results were statistically significant ($P<0.001$) (Fig. 2).

Concerning the disease severity showed that under the C treatment, the severity remained low throughout the experiment, with small lesions and mild wilting observed in the few infected plants. Under T treatment, the severity increased significantly, with larger lesions, extensive wilting, and stunted growth in the infected plants. The average lesion size was 3-4 times larger than in the C treatment. Under CO treatment, the severity was higher than in the control group but lower than in the increased temperature group. Lesions were more numerous but smaller, and wilting was moderate (Fig. 3).

Under the TCO treatment, the highest severity was observed, characterized by extensive tissue necrosis, severe wilting, and substantial plant mortality. Both lesion size and number were significantly elevated, leading to near-total plant collapse in several instances. Statistical analysis confirmed these findings with significant results ($P<0.001$) (Fig. 3).

Under the TCO treatment, the highest severity was observed, characterized by extensive tissue necrosis, severe wilting, and substantial plant mortality. Both lesion size and number were significantly elevated, leading to near-total plant collapse in several instances. Statistical analysis confirmed these findings with significant results ($P<0.001$) (Fig. 3).

Concerning the pathogen spread, under the C treatment, the results showed that the pathogen spread was limited, with infection localized to a small area of the plant. There was minimal inter-plant spread. Under the T treatment, the pathogen spread more rapidly both within and between plants. The average rate of spread was 2-3 times higher than in the control group, with multiple plants infected from a single inoculation point (Fig. 4).

Under CO treatment, the pathogen spread was moderate, with noticeable movement within individual plants and occasional spread to neighboring plants, while under TCO, the rate of pathogen spread was the highest, with rapid colonization of entire plants and significant cross-plant infection. The spread was 4-5 times faster than in the control group. The results showed statistically significant results ($P<0.01$) (Fig. 4).

Under the TCO treatment, plant mortality reached 50% by the end of the experiment. The lowest mortality rate was observed under the C treatment. The TCO and CO treatments exhibited intermediate levels of plant mortality relative to the TCO treatment (Fig. 5). Statistical analysis indicated that these results were significant ($P<0.01$).

Crop Yield

The crop yield results indicated that the highest yield was recorded under the C treatment (100%), followed by the CO treatment (70%) and the T treatment (60%). The lowest yield was observed under the TCO treatment (30%) (Table 1).

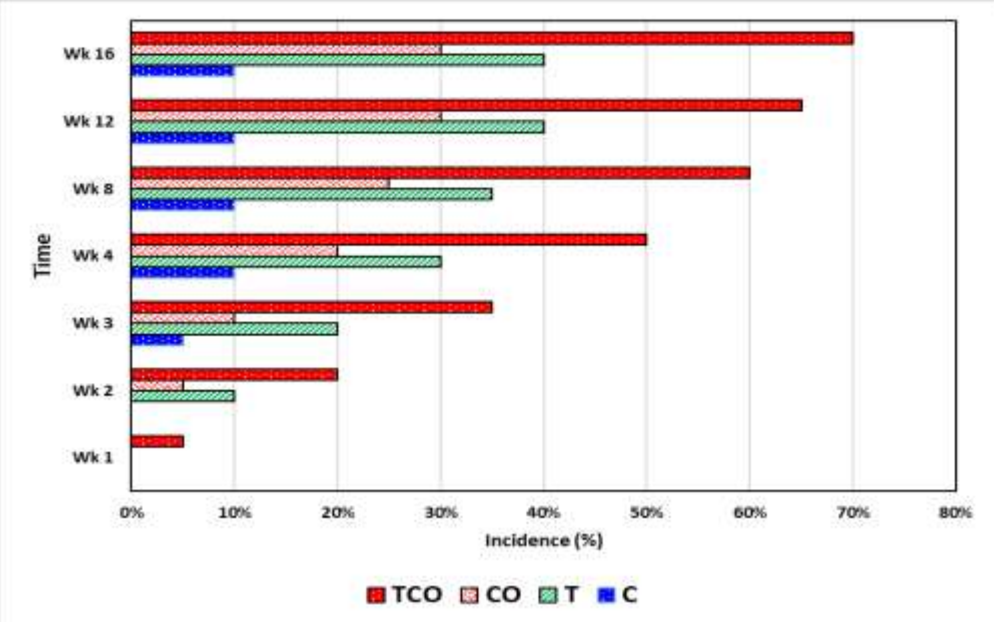

Fig. 2: The effect of control (C), temperature (T), CO_2 (CO), and mixed treatment (TCO) on disease incidence (%) per week (wk).

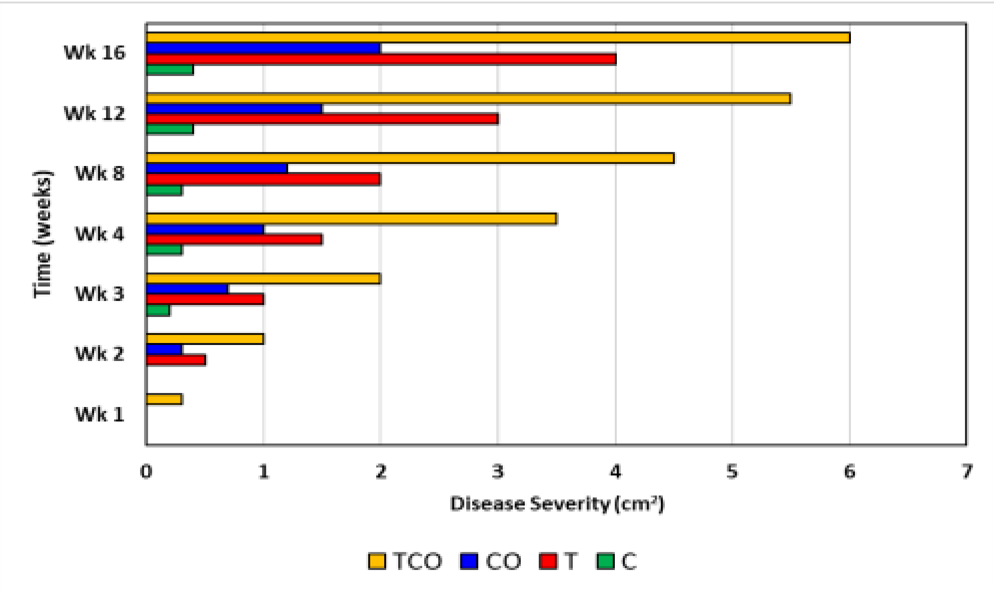

Fig. 3: The effect of control (C), temperature (T), CO_2 (CO), and mixed treatment (TCO) on disease severity (Average Lesion Size in cm^2) per week (wk).

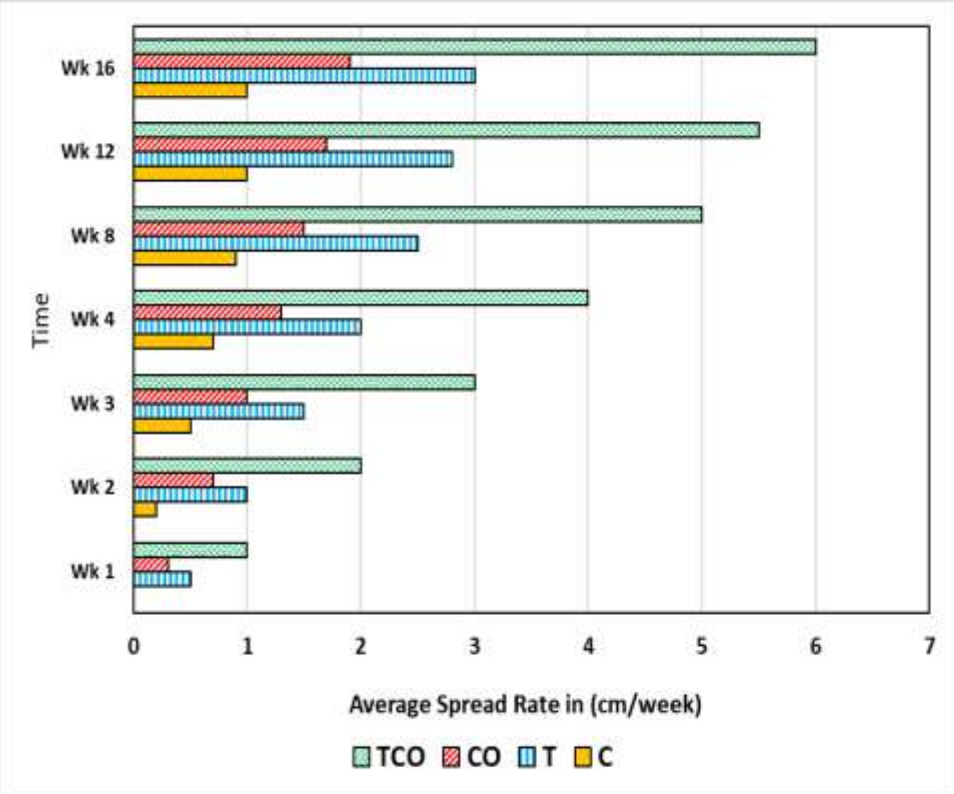

Fig. 4: The effect of control (C), temperature (T), CO_2 (CO), and mix treatment (TCO) on pathogens spread (Average Spread Rate in cm/week) per week (wk).

Regression Analysis for the Pathogen Virulence (PV)

The regression coefficient of T was 0.85 ($p<0.001$) indicating that the increase of T by 1°C will increase the PV by 85% reflecting the T as a strong predictor of disease severity in tomato crops. The model regression coefficient is 0.76 explaining that 76% of the variance in PV is explained by T (equation 1).

PV = 0.85 T (R^2 = 0.76)..(1)

The regression coefficient of CO was 0.45 ($p<0.001$) indicating that the increase of CO by 100ppm will increase the PV by 45% reflecting the CO as a predictor of disease severity in tomato crops with a less degree than T. The model regression coefficient is 0.58 explaining that 58% of the variance in PV is explained by CO (equation 2).

PV = 0.45 CO (R^2 = 0.58) ....(2)

The regression coefficient of T was 0.75 ($p<0.01$), the regression coefficient of CO was 0.38 ($p<0.05$), and the TCO regression coefficient was 0.22 ($p<0.01$) indicating that both T, CO, and TCO contributed to PV in tomatoes. The model regression coefficient is 0.82 explaining that 82% of the variance in PV is explained by T and CO (equation 2).

PV = 0.75 T+0.38 CO+TCO (R^2=0.82) ....(3)

Table 1: The effect of control (C), temperature (T), CO_2 (CO), and mix treatment (TCO) on tomato crop yield (kg per plant) per week (wk)

Treatment	Wk 4	Wk 8	Wk 12	Wk 16	Final Yield (%) Compared to Control
C	0.5	1.2	2.0	3.0	100
T	0.4	0.9	1.5	1.8	60
CO	0.3	0.8	1.3	1.5	70
TCO	0.2	0.6	1.0	0.9	30

P value: 0.001

DISCUSSION

The experiment's results highlight the significant influence of the CC-related factors on the emergence and virulence of PP in tomato crops. The T, CO, and TCO not only heightened the incidence and severity of plant diseases but also accelerated pathogen spread and increased plant mortality, ultimately reducing crop yield.

The disease incidence data revealed a clear trend: as environmental stressors intensified, the percentage of infected plants rose sharply. In C, disease occurrence was minimal, indicating that under current average climate conditions, the tomato plants maintain a relatively robust defense against the selected pathogen. However, under T when exposed to temperature, the incidence rate quadrupled, suggesting that higher temperatures may weaken plant defenses or create conditions more favorable for pathogen survival and reproduction. Similarly, CO also led to a marked increase in disease incidence, though to a lesser degree than temperature, pointing to the multifaceted nature of pathogen emergence under the CC. Zou et al. (2019) have shown that the elevated CO_2 concentration leads to the increase of plant disease incidence. Gilardi et al. (2016) have shown that CO_2 increased both the incidence and severity of plant diseases. Hu et al. (2023) justified the effect of T, CO, and TCO on tomato disease through the effect on the N-acylethanolamine pathway which is affected by the temperature and CO_2 increase that decreases the tomato defend against pathogens.

The disease severity results further underscore the detrimental effects of the CC on plant health. The highest severity was observed under the TCO (6) followed by T (4) with less severity recorded under CO_2 (2) compared to the

C, demonstrating that not only does the CC promote the spread of pathogens, but it also enhances their virulence. Gilardi et al. (2016) reported that the increase in temperature will increase the incidence and severity of plant diseases. The TCO representing the combination of temperature and CO_2 showed the highest severity, with extensive tissue damage and rapid disease progression. This advocates a potential synergistic effect, where multiple the CC factors interact to exacerbate the impact on plant health. Jang et al. (2019) reported that the elevated temperature increases the bacterial sport severity. Kaur et al. (2023) reported that the interaction between temperature and CO_2 concentration increases the tomato's disease severity.

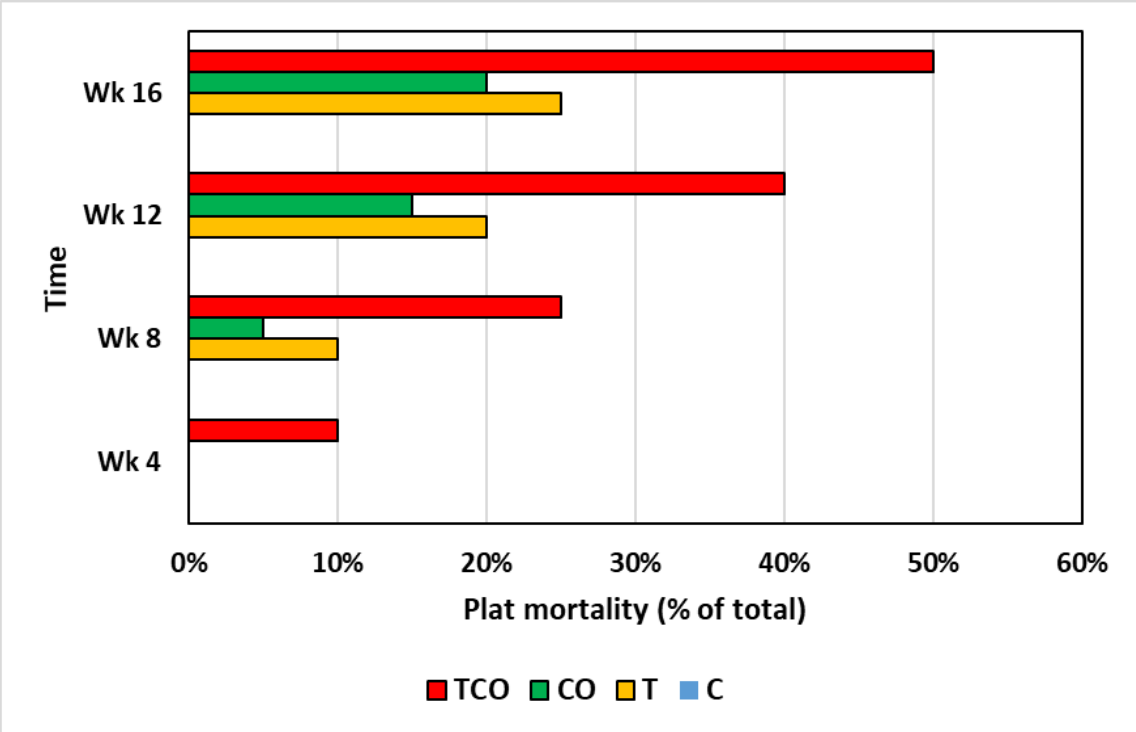

Fig. 5: The effect of control (C), temperature (T), CO_2 (CO), and mix treatment (TCO) on plant mortality (% of Dead Plants) per week (wk).

Under stress conditions, pathogen spread rates were higher mainly in the TCO treatment. The rapid colonization of entire plants and the spread of infection to close plants under this treatment highlight the potential for more widespread outbreaks under future climate scenarios. The high speed of infection among the plants decreases the efficiency of the traditional disease control methods, which call for more severe and frequent epidemics in crops like tomatoes.

Tomato plants mortality and crop yield were used to measure the CC effect on tomato plants. The experiment final results showed that the TCO treatment experienced the highest mortality rate (50%), with the highest productivity reduction (30%) compared to C treatment. Yang et al. (2023) reported that the elevated CO_2 and temperature decreased the plant production. Under T and CO treatments, the yield was reduced significantly reflecting the economic impact of climate-induced pathogen emergence on tomato production under the CC conditions. The reduction of yield was directly correlated with the increase of disease incidence and severity, reflecting that the CC could leave severely compromise food security by lowering the productivity of tomato. Sunkad et al. (2023) and Jang et al. (2019) revealed that the interaction between T and CO levels and the plant-pathogens is very important to understanding and managing tomato production under changing climatic conditions.

Conclusions and recommendations

Results reflected evidence of the CC effect on PP and so affecting tomato production. Higher disease incidence and greater severity accompanied with faster pathogens spread ad plant mortality were the causes of tomato production under TCO. The effect on tomato plants for the separate treatments of T and CO was less. The CC factors resulted in a substantial reduction in tomato productivity which reflects the implications for global food security.

The increased temperatures contributed to fasting disease progression and severe symptoms in the affected tomato plants, which reflects the impact of global temperatures rise on more aggressive outbreaks of plant diseases that overwhelm current agricultural practices and disease management strategies. The elevated CO_2 levels affect the tomato's disease prevalence although with fewer results compared to temperature. However, the TCO treatment created a synergistic effect producing severe outcomes. This reflects that multiple the CC factors double the challenges posed by PP in future agricultural systems.

In conclusion, the study reinforces the critical need for innovation in agricultural practices to face the challenges of the CC. As the global climate continues to change, developed strategies can mitigate the increased risk of plant diseases, safeguarding the sustainability and productivity of crops.

Future research

The results suggest that future agricultural research needs to investigate the scenarios that deal with these changing conditions, to find out the proper strategies that mitigate the enhanced virulence and spread of pathogens.

REFERENCES

Chapagai, P. P., Katel, O., & Penjor, P. (2023). Relationships Between Food Systems, Agricultural Practices, and Food Security Amidst Climate Change in Western Bhutan. *American Journal of Food Science and Technology*, *3*(1), 1–12. https://doi.org/10.54536/ajfst.v3i1.2295

Che, Z., Ren, L., & Wang, W. (2023). Diversity of Fungal Community in Rhizosphere Soil of Tomato with Different Diseases. *Journal of Progress in Engineering and Physical Science*, *2*(2), 96–103. https://doi.org/10.56397/jpeps.2023.06.12

Chen, Z., Wang, W., Forzieri, G., & Cescatti, A. (2024). Transition from positive to negative indirect CO2 effects on the vegetation carbon uptake. *Nature Communications*, *15*(1). https://doi.org/10.1038/s41467-024-45957-x

Cieschi, M. T., Polyakov, A. Y., Lebedev, V. A., Volkov, D. S., Pankratov, D. A., Veligzhanin, A. A., Perminova, I. V., & Lucena, J. J. (2019). Eco-friendly iron-humic nanofertilizers synthesis for the prevention of iron chlorosis in soybean (Glycine max) grown in calcareous soil. *Frontiers in Plant Science*, *10*(April), 1–17. https://doi.org/10.3389/fpls.2019. 00413

Delgado-Baquerizo, M., Guerra, C. A., Cano-Díaz, C., Egidi, E., Wang, J. T., Eisenhauer, N., Singh, B. K., & Maestre, F. T. (2020). The proportion of soil-borne pathogens increases with warming at the global scale. *Nature Climate Change*, *10*(6), 550–554. https://doi.org/10.1038/s41558-020-0759-3

Du, C., Jiang, J., Zhang, H., Zhao, T., Yang, H., Zhang, D., Zhao, Z., Xu, X., & Li, J. (2020). Transcriptomic profiling of Solanum peruvianum LA3858 revealed a Mi-3-mediated hypersensitive response to Meloidogyne incognita. *BMC Genomics*, *21*(1). https://doi.org/10.1186/s12864-020-6654-5

Egerer, M., Liere, H., Lucatero, A., & Philpott, S. M. (2020) Plant damage in urban agroecosystems varies with local and landscape factors. *Ecosphere, 11*, e0374. https://doi.org/10.1002/ecs2.3074

Eliette, A. S., Elodie, B., Arnaud, M., Tiffany, R., Aymé, S., & Pascal, P. (2024). Idiosyncratic invasion trajectories of human bacterial pathogens facing temperature disturbances in soil microbial communities. *Scientific Reports*, *14*(1). https://doi.org/10.1038/s41598-024-63284-5

Gilardi, G., Pugliese, M., Chitarra, W., Ramon, I., Gullino, M. L., & Garibaldi, A. (2016). Effect of Elevated Atmospheric CO2 and Temperature Increases on the Severity of Basil Downy Mildew Caused by Peronospora belbahrii Under Phytotron Conditions. *Journal of Phytopathology*, *164*(2), 114–121. https://doi.org/10.1111/jph.12437

Hassan, W. H., & Hashim, F. S. (2020). The effect of climate change on the maximum temperature in Southwest Iraq using HadCM3 and CanESM2 modelling. *SN Applied Sciences*, *2*(9). https://doi.org/10.1007/s42452-020-03302-z

Hu, Z., Shi, J., Feng, S., Wu, X., Shao, S., & Shi, K. (2023). Plant N-acylethanolamines play a crucial role in defense and its variation in response to elevated CO2 and temperature in tomato. *Horticulture Research*, *10*(1). https://doi.org/10.1093/hr/uhac242

Jang, J. O., Kim, B. H., Lee, J. B., Joa, J. H., & Koh, S. (2019). Evaluation of bacterial spot disease of Capsicum annuum L. In drought stress environment by high temperature. *Research in Plant Disease*, *25*(2), 62–70. https://doi.org/10.5423/RPD.2019.25.2.62

Kaur, G., Singh, H., Maurya, S., Kumar, C., & Kumar, A. (2023). Current scenario of climate change and its impact on plant diseases. *Plant Science Today*, *10*(4), 163–171. https://doi.org/10.14719/pst.2479

Kaur, R., Kumar, S., Ali, S., Kumar, S., Ezing, U., Bana, R., Meena, S., Dass, A., & Singh, T. (2024). Impacts of climate change on crop-weed dynamics: Challenges and strategies for weed management in a changing climate. *Open Journal of Environmental Biology*, *9*(1), 015–021. https://doi.org/10.17352/ojeb.000042

Laine, A. L. (2023). Plant disease risk is modified by multiple global change drivers. *Current Biology*, *33*(11), R574–R583. https://doi.org/10.1016/j.cub.2023.03.075

Lidon, F. J. C. (2018). Climate change and food security. *Emirates Journal of Food and Agriculture*, *30*(6), 428. https://doi.org/10.4324/9781315272085-3

Mourouzidou, S., Ntinas, G. K., Tsaballa, A., & Monokrousos, N. (2023). Introducing the Power of Plant Growth Promoting Microorganisms in Soilless Systems: A Promising Alternative for Sustainable Agriculture. *Sustainability (Switzerland)*, *15*(7). https://doi.org/10.3390/su15075959

Sbeiti, A. A. L., Mazurier, M., Ben, C., Rickauer, M., & Gentzbittel, L. (2023). Temperature increase modifies susceptibility to Verticillium wilt in Medicago spp and may contribute to the emergence of more aggressive pathogenic strains. *Frontiers in Plant Science*, *14*. https://doi.org/10.3389/fpls.2023.1109154

Shen, M., Cai, C., Song, L., Qiu, J., Ma, C., Wang, D., Gu, X., Yang, X., Wei, W., Tao, Y., Zhang, J., Liu, G., & Zhu, C. (2023). Elevated CO2 and temperature under future climate change increase severity of rice sheath blight. *Frontiers in Plant Science*, *14*. https://doi.org/10.3389/fpls.2023.1115614

Singh, B. K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J. E., Liu, H., & Trivedi, P. (2023). Climate change impacts on plant pathogens, food security and paths forward. *Nature Reviews Microbiology*, *21*(10), 640–656. https://doi.org/10.1038/s41579-023-00900-7

Sun, Q., He, X., Wang, T., Qin, H., Yuan, X., Chen, Y., Bian, Z., & Li, Q. (2023). The Beneficial Roles of Elevated [CO2] on Exogenous ABA-Enhanced Drought Tolerance of Cucumber Seedlings. *Horticulturae*, *9*(4). https://doi.org/10.3390/horticulturae9040421

Sunkad, G., Dore, D., Patil, M., Joshi, R., & Kumar, M. (2023). Impact of temperature, moisture and CO2 on growth of pathogen and severity of emerging dry root rot disease of chickpea in Karnataka. *Journal of Agrometeorology*, *25*, 312–319. https://doi.org/10.54386/jam.v25i2.2125

Wang, X., Li, D., & Song, X. (2023). Elevated CO2 mitigates the effects of cadmium stress on vegetable growth and antioxidant systems. *Plant, Soil and Environment*, *69*(5), 202–209. https://doi.org/10.17221/125/2023-PSE

Yang, H., Beak, D. R., & Park, M. H. (2020). CO2 treatment and co-treatment with ClO2 improves quality of “Dotaerang” tomato during storage. *Korean Journal of Food Preservation*, *27*(7), 837–849. https://doi.org/10.11002/KJFP.2020.27.7.837

Yang, J., Feng, Y., Chi, T., Wen, Q., Liang, P., Wang, A., & Li, P. (2023). Mitigation of Elevated CO2 Concentration on Warming-Induced Changes in Wheat Is Limited under Extreme Temperature during the Grain Filling Period. *Agronomy*, *13*(5). https://doi.org/10.3390/agronomy13051379

Zafar, M. M., Mustafa, G., Shoukat, F., Idrees, A., Ali, A., Sharif, F., & Li, F. (2022). Heterologous expression of cry3Bb1 and cry3 genes for enhanced resistance against insect pests in cotton. *Scientific Reports*, *12*(1), 10878. https://doi.org/10.1038/s41598-022-13295-x

Zhou, Y., Van Leeuwen, S. K., Pieterse, C. M. J., Bakker, P. A. H. M., & Van Wees, S. C. M. (2019). Effect of atmospheric CO2 on plant defense against leaf and root pathogens of Arabidopsis. *European Journal of Plant Pathology*, *154*(1), 31–42. https://doi.org/10.1007/s10658-019-01706-1

Zou, Z., Liu, F., Chen, C., & Dilantha Fernando, W. G. (2019). Effect of elevated Co2 concentration on the disease severity of compatible and incompatible interactions of Brassica napus–leptosphaeria maculans pathosystem. *Plants*, *8*(11). https://doi.org/10.3390/plants8110484