SURVIVAL, VEGETATIVE DEVELOPMENT, AND REPRODUCTIVE RESPONSE OF TOMATO PLANTS UNDER INTEGRATED AGROECOLOGICAL MANAGEMENT STRATEGIES IN OPEN-FIELD AND GREENHOUSE CONDITIONS

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RESUMO

O tomateiro (*Solanum lycopersicum* L.) é uma cultura de elevada importância agrícola, cujo desempenho em sistemas agroecológicos depende da interação entre estratégias de manejo e condições ambientais. O presente estudo teve como objetivo avaliar o crescimento vegetativo, o teor relativo de clorofila e o desempenho reprodutivo do tomateiro submetido a diferentes estratégias de manejo agroecológico, conduzidas em campo aberto e em ambiente protegido (estufa). O experimento foi realizado em delineamento em blocos casualizados, com cinco tratamentos: controle, *Trichoderma asperellum*, silício, enxofre e protocolo integrado, e cinco repetições em cada ambiente de cultivo. Foram avaliados altura das plantas, espessura do caule, índice SPAD, florescimento, frutificação e observações qualitativas de colheita. Os resultados indicaram que o protocolo integrado promoveu maior vigor vegetativo, maiores teores de clorofila e melhor desempenho reprodutivo em ambos os sistemas de cultivo. O cultivo em campo aberto favoreceu o crescimento vegetativo, enquanto a estufa apresentou limitações microclimáticas, embora com melhor qualidade dos frutos colhidos. Conclui-se que estratégias integradas de manejo agroecológico contribuem para maior estabilidade fisiológica e reprodutiva do tomateiro, sendo sua eficiência condicionada ao ambiente de cultivo.

Palavras-chave: Agroecologia; bioinsumos; índice SPAD; manejo integrado; tomateiro.

ABSTRACT

Tomato (*Solanum lycopersicum L.)* is a crop of major agricultural importance whose performance in agroecological systems depends on the interaction between management strategies and environmental conditions. This study aimed to evaluate the vegetative growth, relative chlorophyll content, and reproductive performance of tomato plants subjected to different agroecological management strategies under both open-field and protected cultivation (greenhouse) conditions. The experiment was conducted using a randomized complete block design with five treatments: control, *Trichoderma asperellum*, silicon, sulfur, and an integrated management protocol, with five replicates in each cultivation environment. Plant height, stem diameter, SPAD index, flowering, fruit set, and qualitative harvest observations were assessed. The results indicated that the integrated management protocol promoted greater vegetative vigor, higher chlorophyll content, and improved reproductive performance in both cultivation systems. Open-field cultivation favored vegetative growth, whereas greenhouse conditions presented certain microclimatic limitations, although they resulted in better fruit quality at harvest. It can be concluded that integrated agroecological management strategies contribute to greater physiological and reproductive stability in tomato plants, with their effectiveness being influenced by the cultivation environment.

Keywords: Agroecological management; bioinputs; SPAD index; integrated management; tomato.

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INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is one of the most economically important vegetable crops worldwide, being cultivated under diverse environmental conditions and production systems. However, tomato cultivation is frequently associated with intensive use of synthetic fertilizers and pesticides due to the crop's high susceptibility to pests and diseases, which contributes to environmental degradation and compromises the sustainability of agricultural systems. The excessive dependence on agrochemicals has been associated with ecological imbalance, biodiversity loss, and risks to human health, reinforcing the need for alternative management strategies based on sustainable agricultural principles (Pimentel, 2005).

In this context, agroecology has emerged as an approach focused on reducing external inputs and promoting ecological interactions within agroecosystems. Agroecological systems emphasize biodiversity, nutrient cycling, biological regulation, and the integration between soil, plants, microorganisms, and environmental conditions, aiming to improve system resilience and long-term sustainability (Altieri & Nicholls, 2020a; Gliessman, 2015). Within this perspective, Integrated Pest Management (IPM) plays a central role by combining biological, cultural, and ecological control strategies to maintain pest populations below economic damage thresholds while minimizing environmental impacts.

Among the agroecological strategies currently adopted, microbiological bioinputs based on beneficial microorganisms have gained considerable attention. Fungi of the genus *Trichoderma* are widely recognized for their ability to promote plant growth, improve nutrient absorption, stimulate root development, and induce resistance against biotic and abiotic stresses. These microorganisms act as opportunistic symbionts in the rhizosphere, modulating plant physiological and metabolic responses and contributing to greater crop stability under adverse environmental conditions (Harman et al., 2004; Vurukonda et al., 2016).

Complementarily, alternative approaches such as homeopathic preparations have been incorporated into some agroecological systems as low-impact management tools. Although several studies report possible physiological responses associated with homeopathic treatments in plants, including effects on vegetative development and phytosanitary balance, the scientific literature still presents considerable inconsistencies regarding methodological standardization, reproducibility, and mechanistic understanding of these responses (Betti et al., 2013; Rossi et al., 2016). Therefore, the integration of homeopathic preparations with microbiological bioinputs should be interpreted cautiously and evaluated under controlled experimental conditions.

In addition to management practices, environmental conditions strongly influence tomato physiological performance and productive stability. Open-field and protected cultivation systems differ substantially in terms of temperature, relative humidity, air circulation, and moisture dynamics, factors directly associated with photosynthesis, transpiration, nutrient uptake, and reproductive development. Under protected cultivation, excessive humidity and thermal accumulation may negatively affect plant growth and favor physiological stress, reducing crop performance depending on management conditions.

Plant physiological responses to agroecological strategies can be evaluated through vegetative, reproductive, and physiological parameters. Among these indicators, the Relative Chlorophyll Index (SPAD) has been widely used as an indirect estimator of chlorophyll content, nitrogen status, and photosynthetic activity. Previous studies have demonstrated a strong relationship between SPAD values, plant nutritional balance, and physiological efficiency under different environmental and management conditions (Argenta et al., 2001).

Despite advances in the use of agroecological practices and microbiological bioinputs, studies evaluating the integrated effects of different management strategies under contrasting cultivation environments remain limited. Most available studies investigate these approaches separately, without considering the complexity of interactions among soil, microbiota, plant physiology, and environmental conditions. Therefore, integrated investigations conducted under realistic cultivation systems are essential to better understand the responses of tomato plants to agroecological management practices.

Within this context, the present study aimed to evaluate the survival, vegetative development, physiological performance, and reproductive response of tomato plants subjected to integrated agroecological management strategies under open-field and greenhouse cultivation conditions. The results contribute to improving the understanding of interactions between management practices and cultivation environments, supporting the development of more sustainable tomato production systems.

METHODOLOGY

Experimental area and cultivation conditions

The experiment was conducted at the experimental field of the Faculty of Animal Science and Food Engineering, University of São Paulo (USP–FZEA), located in Pirassununga, São Paulo State, Brazil (21°59' S, 47°25' W; altitude 634 m). According to the Köppen climate classification, the region presents a Cwa climate, characterized as tropical highland climate with hot and rainy summers and dry winters.

The experiment was carried out between October 2025 and January 2026 under two cultivation systems: open-field and protected environment (greenhouse). During the experimental period, temperature and relative humidity were monitored in both cultivation environments.

The soil of the experimental area was classified as Oxisol (Latossolo Vermelho-Amarelo), with medium to clayey texture and good drainage conditions. Prior to transplanting, soil preparation included plowing and harrowing operations. In both cultivation systems, agroecological management practices were adopted without the use of synthetic chemical pesticides.

Experimental design and treatments

The experiment was conducted using a randomized block design (RBD), with five treatments and five replications in each cultivation environment, totaling 25 experimental units per environment.

Each experimental unit consisted of two tomato plants spaced 0.5 m between plants and 1.2 m between rows. The treatments evaluated were:

T1: Control (without application of bioinputs or homeopathic preparations);

T2: Application of *Trichoderma asperellum*;

T3: Application of Silicea terra 6CH and 30CH;

T4: Application of Sulphur 6CH and 30CH;

T5: Integrated protocol combining *Trichoderma asperellum*, Silicea terra 6CH and 30CH, and Sulphur 6CH and 30CH.

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The experimental layout is presented in Figure 1.

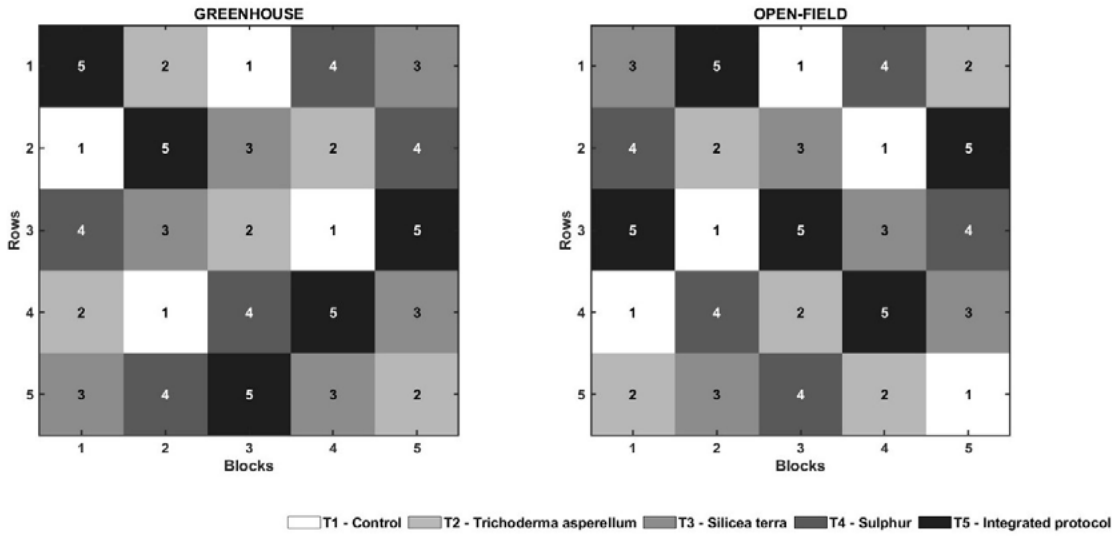

Figure 1. Experimental layout of the randomized block design (RBD) with five agroecological management treatments conducted under greenhouse and open-field conditions.

Note: T1 = Control; T2 = *Trichoderma asperellum*; T3 = Silicea terra; T4 = Sulphur; T5 = Integrated protocol.

Seedling production and crop management

Tomato seedlings were produced under protected conditions and transplanted to the experimental area on October 5, 2025. Prior to transplanting, cover crops consisting of *Crotalaria* spp. and *Pennisetum glaucum* were cultivated and later incorporated into the soil as green manure.

In each cultivation environment, seven planting rows were established, including two border rows and five central rows used for treatment application and evaluations.

Preparation and application of the microbiological bioinput

The microbiological bioinput used in treatments T2 and T5 was the commercial product Trichodermil® SC 1306 (Koppert do Brasil Holding S.A.), containing *Trichoderma asperellum* (strain ESALQ-1306) at a minimum concentration of 2.0×10^9 viable conidia mL^{-1}.

The spray solution was prepared immediately before application by diluting 10–15 mL of the commercial product in 10 L of water. Applications were performed by foliar spraying using a manual sprayer at 7, 21, and 35 days after transplanting (DAT), with 14-day intervals between applications.

Applications were carried out in the early morning or late afternoon to minimize evaporation losses and avoid periods of intense solar radiation.

Preparation and application of homeopathic treatments

The homeopathic preparations used in treatments T3, T4, and T5 were Silicea terra 6CH and 30CH and Sulphur 6CH and 30CH, obtained from a specialized compounding pharmacy and prepared according to the Hahnemannian centesimal dilution method.

Before application, the solutions were manually succussed using standardized vigorous shaking. For each application, 12 drops of the preparation were diluted in 500 mL of water and homogenized manually.

Applications were performed via foliar spraying using a manual sprayer at 7, 14, 21, 28, and 35–40 DAT, maintaining approximately 7-day intervals between applications.

Evaluated variables

Plant survival, vegetative development, physiological status, reproductive performance, and pest occurrence were evaluated throughout the crop cycle.

Vegetative development was assessed through plant height (cm) and stem diameter (mm), measured periodically during the experiment.

Physiological status was estimated using the Relative Chlorophyll Index (RCI/SPAD), measured with a ClorofiLOG® chlorophyll meter (Falker). Evaluations were conducted at 69, 82, and 97 DAT using fully expanded leaves collected from the middle third of the plants.

Reproductive performance was evaluated through the number of flowers and fruits per plant. Fruit yield was determined by total fruit mass harvested per experimental unit and expressed in grams per plot.

Phytosanitary evaluations consisted of periodic visual inspections for the occurrence of insect pests and symptoms compatible with *Tuta absoluta* infestation, including leaf galleries and fruit perforations.

Statistical analysis

Data were organized in electronic spreadsheets and analyzed separately for each cultivation environment.

Due to data distribution and sample imbalance caused by plant mortality, non-parametric statistical analysis was adopted. Plant height, stem diameter, relative chlorophyll index (RCI/SPAD), number of flowers, and number of fruits were analyzed using the Kruskal–Wallis test at a 5% significance level ($p < 0.05$).

When significant differences were detected, Dunn's post hoc test with Bonferroni adjustment was applied for multiple comparisons.

Plant survival was analyzed using the chi-square (χ^2) test, with Fisher's exact test applied when necessary.

All analyses were performed using MATLAB software.

RESULTS AND DISCUSSION

Plant survival under open-field and greenhouse conditions

Plant survival varied according to both cultivation environment and agroecological management strategy. From the total of 100 plants initially established, 59 plants survived until the end of the experimental period, corresponding to 64% survival under open-field conditions and 54% under greenhouse conditions.

Higher mortality observed in the greenhouse environment suggests that microclimatic conditions acted as an important limiting factor for tomato development. Excess moisture, reduced air circulation, and elevated temperatures likely compromised root system functioning and increased physiological stress throughout the crop cycle. In contrast, open-field conditions provided greater environmental balance, favoring plant establishment and persistence.

Microclimatic conditions differed substantially between cultivation environments throughout the experimental period. Greenhouse conditions showed consistently higher temperature and relative humidity values compared to open-field cultivation, particularly during the central phase of the crop cycle.

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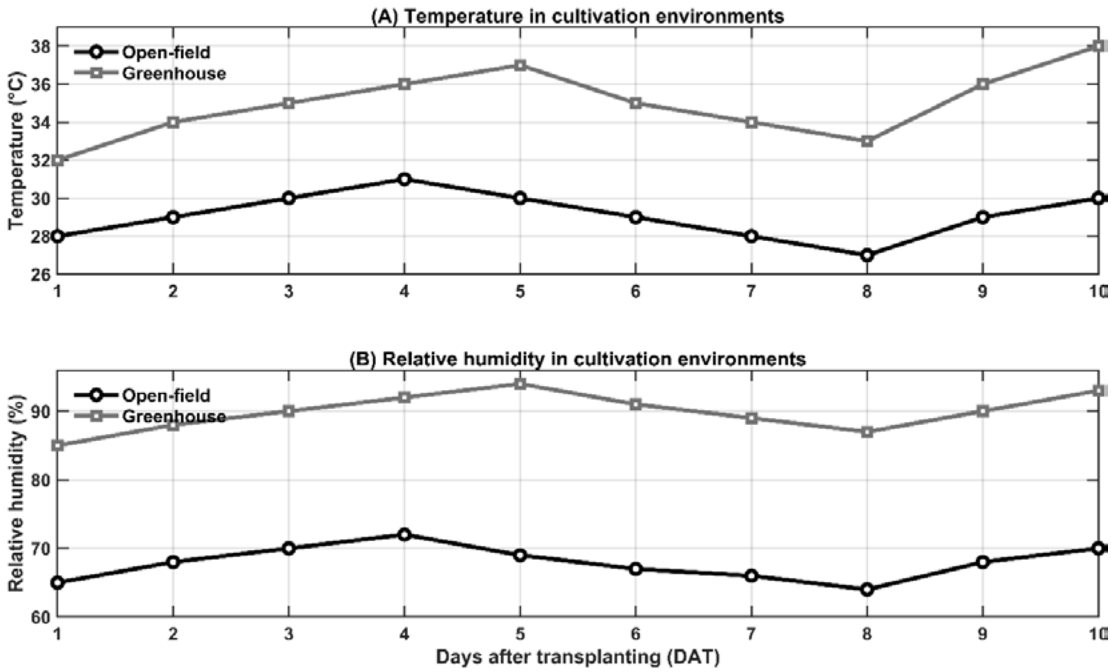

Figure 2. Microclimatic conditions recorded during the experimental period under open-field and greenhouse cultivation systems. (A) Mean temperature observed throughout the crop cycle. (B) Relative humidity recorded during the experimental period. DAT = days after transplanting.

Among the evaluated treatments, the integrated protocol (T5) showed the highest survival rate (80%), followed by the treatment with *T. asperellum* (T2), which presented 65% survival. The lowest survival rate was observed in the Silicea terra treatment (T3), with 40% survival. These results indicate that treatments involving microbiological bioinputs contributed to greater plant stability throughout the experimental period.

The association analysis using the chi-square test indicated a relationship between treatment and plant survival, reinforcing the influence of agroecological management strategies on tomato persistence under both cultivation systems.

Vegetative development of tomato plants

Vegetative development, evaluated through plant height and stem diameter, differed among treatments and cultivation systems (Figure 3). Overall, plants cultivated under open-field conditions showed greater vegetative growth compared to greenhouse-grown plants.

In open-field cultivation, treatments involving integrated management strategies promoted progressive increases in plant height and stem diameter, particularly the integrated protocol (T5), which consistently presented the highest mean values. Treatments T2 (*Trichoderma asperellum*) and T4 (*Sulphur*) also showed superior vegetative performance relative to the control treatment.

Under greenhouse conditions, vegetative growth was generally reduced for all treatments, indicating that environmental limitations negatively affected plant development. Nevertheless, the integrated protocol maintained superior performance compared to the remaining treatments, suggesting that combined agroecological strategies partially mitigated the adverse effects of the protected environment.

The greater stem diameter observed in treatments T2 and T5 suggests improved structural development and greater capacity

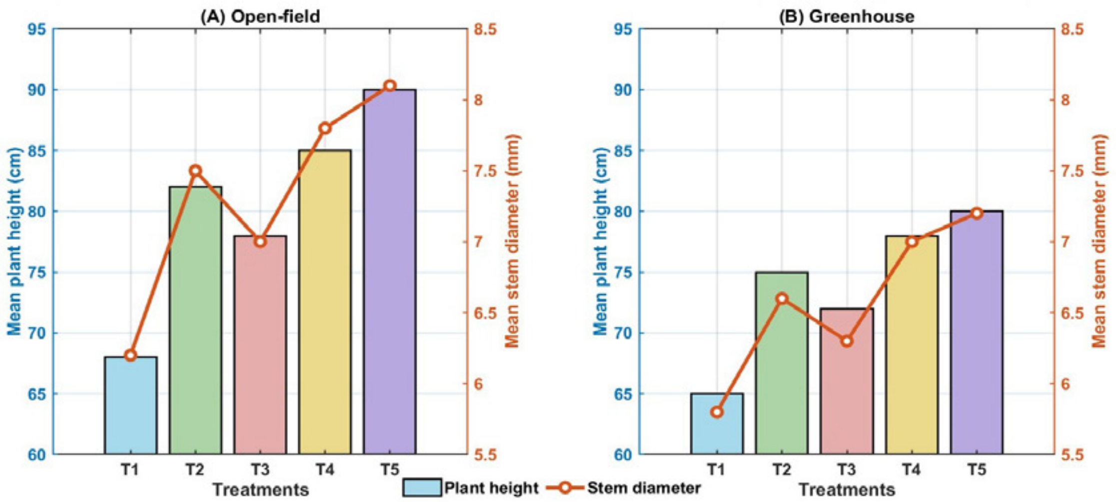

Figure 3. Mean plant height and stem diameter of tomato plants cultivated under open-field and greenhouse conditions subjected to different agroecological management strategies. Colored bars represent mean plant height (cm), while the line represents mean stem diameter (mm). Treatments: T1 = Control; T2 = *Trichoderma asperellum*; T3 = Silicea terra; T4 = Sulphur; T5 = Integrated protocol.

for water and nutrient transport, factors directly associated with plant physiological performance and productive potential.

Relative chlorophyll content (SPAD index)

The relative chlorophyll content, estimated by the SPAD index, varied among treatments and cultivation environments. Under open-field conditions, treatments T4 (Sulphur) and T5 (integrated protocol) exhibited higher median SPAD values and lower variability compared to the control treatment, indicating greater physiological stability.

The control treatment showed greater dispersion and lower minimum SPAD values, suggesting increased sensitivity to environmental variations and lower nutritional and physiological balance.

Under greenhouse conditions, SPAD values exhibited greater variability overall. However, the integrated protocol again showed the highest chlorophyll content values, indicating that combined management strategies contributed to maintaining photosynthetic activity even under less favorable environmental conditions.

The maintenance of higher SPAD values in treatments involving microbiological bioinputs may be associated with improved nutrient availability and enhanced physiological regulation promoted by *T. asperellum*, as reported in previous studies.

Flowering and fruiting performance

The reproductive performance of tomato plants was strongly influenced by both management strategy and cultivation environment (Figure 4).

Under open-field conditions, treatments involving integrated management practices showed greater flower emission and higher fruit production. The integrated protocol (T5) presented the highest mean number of fruits per plant, followed by treatments T4 and T2. The control treatment showed the lowest reproductive performance.

Under greenhouse conditions, flowering and fruiting were reduced for most treatments, reflecting the negative influence of excess moisture and microclimatic stress on reproductive development. Despite these limitations, treatment T5 maintained superior reproductive continuity compared to the remaining treatments.

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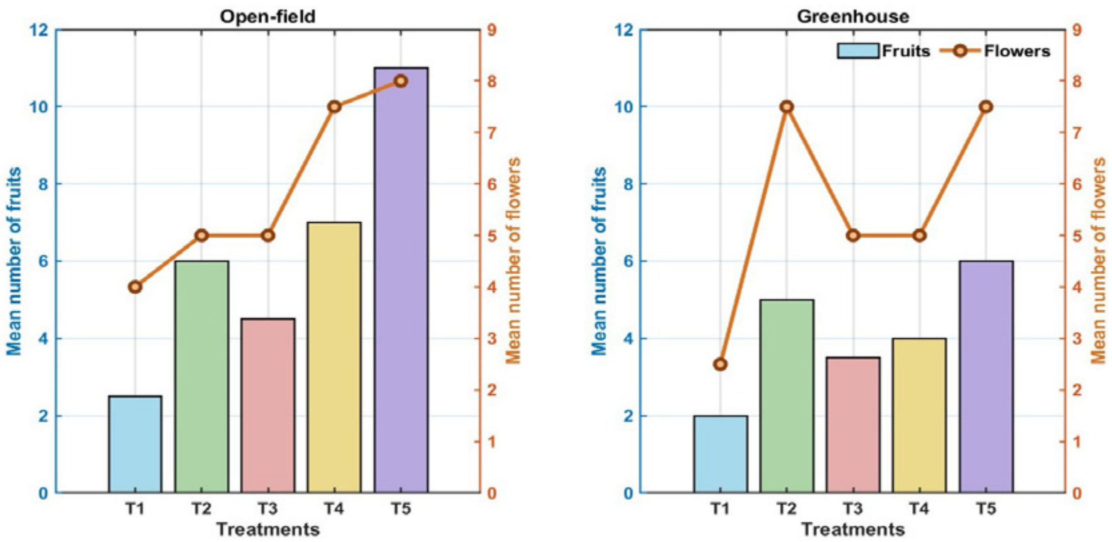
Figure 4. Mean number of fruits and flowers of tomato plants cultivated under open-field and greenhouse conditions subjected to different agroecological management strategies. Bars represent the mean number of fruits, while the line represents the mean number of flowers per plant.



Treatments: T1 = Control; T2 = *Trichoderma asperellum*; T3 = Silicea terra; T4 = Sulphur; T5 = Integrated protocol.

The relationship between vegetative vigor, chlorophyll stability, and reproductive performance suggests that treatments promoting better physiological balance also favored flower retention and fruit set.

Phytosanitary observations and occurrence of *Tuta absoluta*

Symptoms compatible with *T. absoluta* infestation were observed predominantly under open-field conditions, including leaf galleries and fruit perforations.

Treatments involving *T. asperellum* application, especially the integrated protocol (T5), showed lower incidence of pest damage compared to the control treatment. These observations suggest that microbiological bioinputs may have contributed to greater plant resistance and physiological robustness.

No significant pest occurrence was observed in the greenhouse environment during the experimental period.

Integrated interpretation of results

The results obtained in the present study demonstrate that tomato performance was strongly influenced by the interaction between cultivation environment and agroecological management strategies. Overall, plants cultivated under open-field conditions exhibited greater physiological stability, vegetative development, and reproductive performance compared to those grown under greenhouse conditions. The microclimatic differences observed between cultivation environments likely played a central role in plant responses throughout the experimental period, particularly due to the higher temperatures and relative humidity recorded under greenhouse conditions, which may have intensified abiotic stress and compromised survival, growth, and reproductive stability. Similar observations were reported by Wamser et al. (2007), Delazari (2018), and Marouelli et al. (2012), who demonstrated that protected cultivation systems may present thermal accumulation and humidity imbalances capable of negatively affecting transpiration, photosynthesis, water relations, and physiological regulation in tomato crops.

The lower survival observed under greenhouse conditions indicates that environmental limitations acted as important stress factors during the crop cycle. High temperature associated with excessive moisture likely impaired root aeration and increased metabolic stress in plants. According to Taiz et al. (2017), excess moisture reduces oxygen availability in the rhizosphere, compromising nutrient absorption and respiration processes essential for plant development. Similar observations were described by Delazari (2018) and Marouelli et al. (2012), who highlighted the importance of environmental and water management for maintaining physiological stability in tomato cultivation systems.

Among the evaluated treatments, the integrated protocol consistently showed the best overall performance across survival, vegetative development, chlorophyll maintenance, and reproductive response. Treatments involving *T. asperellum* also exhibited superior vegetative growth compared to the control treatment, particularly regarding plant height and stem diameter. These responses reinforce the beneficial role of microbiological bioinputs in promoting plant vigor and resilience under stress conditions. Harman et al. (2004) demonstrated that *Trichoderma* species stimulate root development, nutrient absorption, and hormonal signaling, contributing to greater tolerance to abiotic stress. Similarly, Vurukonda et al. (2016) reported that beneficial microorganisms improve nutrient uptake efficiency and regulate physiological mechanisms associated with plant defense and stress tolerance.

The greater stem diameter observed in treatments involving *T. asperellum* and the integrated protocol is particularly relevant because stem thickening is associated with improved structural support and greater efficiency in water and nutrient transport. According to Taiz et al. (2017), increased stem robustness reflects greater physiological functionality and contributes to improved tolerance to environmental fluctuations. In agroecological systems, where crops are frequently exposed to variable environmental conditions, structural vigor becomes an important component of productive stability.

The physiological responses observed through SPAD measurements further reinforce the beneficial effects of integrated agroecological management. Treatments T4 and T5 showed greater chlorophyll stability and higher SPAD values, particularly under open-field conditions, indicating improved physiological balance and maintenance of photosynthetic activity throughout the crop cycle. According to Argenta et al. (2001), SPAD values are strongly associated with leaf nitrogen concentration and photosynthetic efficiency, serving as reliable indicators of plant physiological status. The greater chlorophyll stability observed in the present study suggests that integrated management strategies promoted more efficient nutrient assimilation and metabolic regulation, even under conditions of environmental stress. Similar responses were described by Vurukonda et al. (2016), who reported enhanced physiological performance in plants associated with beneficial microorganisms.

The reproductive performance of tomato plants directly reflected the vegetative and physiological responses observed throughout the experiment. Under open-field conditions, treatments involving *T. asperellum*, sulphur, and especially the integrated protocol exhibited greater flower emission and fruit production compared to the control treatment. According to Taiz et al. (2017), reproductive success depends on the availability of assimilates and on the maintenance of physiological stability during the crop cycle. Therefore, the greater vegetative vigor and chlorophyll maintenance observed in integrated treatments likely contributed to improved flower retention and

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fruit set. Similar relationships between plant vigor and productive stability were reported by Venzon et al. (2021), who highlighted that balanced agroecological management enhances crop resilience and reduces susceptibility to environmental stress.

Although greenhouse conditions negatively affected plant survival and vegetative performance, fruits produced under protected cultivation exhibited superior visual quality, greater firmness, and lower incidence of rot symptoms. This result demonstrates that cultivation environment influences not only plant development but also postharvest quality characteristics. According to Fontes (1999), protected cultivation systems may improve fruit quality by reducing direct exposure to rainfall, environmental contamination, and excessive moisture on fruit surfaces, despite creating thermal challenges for plant development.

Phytosanitary observations also revealed important differences among treatments and cultivation systems. Symptoms associated with *T. absoluta* infestation were more evident under open-field conditions, particularly in the control treatment. Villas Bôas et al. (2009) described *T. absoluta* as one of the most economically important tomato pests in Latin America, capable of causing severe production losses and increasing production costs when management practices are inadequate. Krechemer (2014) further demonstrated that environmental conditions, especially temperature, directly influence the development, survival, and reproduction of *T. absoluta* populations, helping explain the variations in pest incidence observed between cultivation environments in the present study.

The lower incidence of severe pest symptoms observed in treatments involving *T. asperellum* and the integrated protocol suggests that these strategies may have contributed to improved plant resistance or tolerance to pest attack. Harman et al. (2004) reported that beneficial microorganisms can induce systemic resistance mechanisms and enhance plant responsiveness to biotic stress. Similarly, Altieri (2018) emphasized that agroecological systems characterized by greater biological balance tend to reduce pest outbreaks through ecological regulation processes. These findings reinforce the importance of combining biological inputs, environmental management, and ecological balance within sustainable tomato production systems.

The beneficial effects associated with microbiological bioinputs are also supported by recent studies on sustainable agriculture and bioinsumos. According to the MAPA bioinsumos guide (2025), biological products derived from microorganisms, plants, and natural compounds contribute to plant development, disease suppression, and environmental sustainability. According to Altieri (2018) and Altieri and Nicholls (2020a), agroecological management strategies contribute to improving soil quality, biodiversity conservation, and ecological stability while reducing dependence on external chemical inputs.

Overall, the present findings reinforce the systemic perspective proposed by agroecology, in which plant performance results from the interaction between soil, microbiota, environmental conditions, and management practices rather than from isolated interventions. The integration of microbiological bioinputs such as *T. asperellum* with complementary agroecological practices promoted greater physiological stability, vegetative vigor, reproductive performance, and phytosanitary balance in tomato cultivation. However, the effectiveness of these strategies remained strongly dependent on environmental conditions and the overall balance of the cultivation system.

CONCLUSION

Integrated agroecological management strategies significantly influenced tomato survival, vegetative development, physiological stability, and reproductive performance under both cultivation systems. Among the evaluated treatments, the integrated protocol combining *Trichoderma asperellum*, Silicea terra, and Sulphur consistently promoted superior plant performance.

Open-field cultivation provided more favorable environmental conditions for tomato development, while greenhouse conditions imposed important microclimatic limitations despite improving fruit visual quality. The results reinforce the importance of integrating microbiological bioinputs and ecological management practices to enhance crop resilience and sustainability in agroecological tomato production systems.

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