

Integrated management strategies for *Septoria* leaf spot in fresh tomatoes, focusing on low pesticide contamination risk

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Abstract

Studies on fresh-market tomato crops in the state of Goiás, Brazil, are still scarce, especially regarding the validation of production technologies. This study aimed to evaluate strategies for the application of plant protection products to control *Septoria* leaf spot in tomato plants with a low risk of pesticide contamination in fruits. Two field trials were conducted under natural infection conditions. Apical meristem pruning was performed, and nine treatments were evaluated: untreated control; weekly application of chemical fungicides; weekly application of chemical fungicides with a switch to biological fungicides at the beginning of harvest; application of chemical fungicides based on a disease forecasting system; application of chemical fungicides based on a forecasting system with a switch to biological fungicides at the beginning of harvest; application of biological fungicide at the recommended rate; application of biological fungicide at double the recommended rate; weekly application of copper hydroxide; and weekly application of copper hydroxide with a switch to biological fungicides at the beginning of harvest. *Septoria* leaf spot severity was evaluated based on natural infection, and total yield was estimated by fruit class. Data were subjected to analysis of variance, and means were compared using *Tukey's* test at the 5% probability level. The weekly application of chemical fungicides showed the highest efficiency compared to applications based on the forecasting system and the use of biological products.

Keywords: *Solanum lycopersicum* L., pesticide residues, biological control, *Septoria* leaf spot, fungicides.

Estratégias de manejo integrado da Septoríose em tomates de mesa com foco no baixo risco de contaminação por agrotóxicos

Resumo

Estudos com tomate de mesa no estado de Goiás, Brasil, ainda são escassos, especialmente no que se refere à validação de tecnologias de produção. Este estudo teve como objetivo avaliar estratégias de aplicação de produtos fitossanitários para o controle da mancha-de-septória em plantas de tomate, com baixo risco de contaminação dos frutos por resíduos de pesticidas. Foram conduzidos dois experimentos de campo sob condições de infecção natural. Realizou-se a poda do meristema apical, e foram avaliados nove tratamentos: testemunha sem aplicação; aplicação semanal de fungicidas químicos; aplicação semanal de fungicidas químicos com substituição por fungicidas biológicos no início da colheita; aplicação de fungicidas químicos com base em um sistema de previsão da doença; aplicação de fungicidas químicos com base em um sistema de previsão da doença com substituição por fungicidas biológicos no início da colheita; aplicação de fungicida biológico na dose recomendada; aplicação de fungicida biológico em dose dupla da recomendada; aplicação semanal de hidróxido de cobre; e aplicação semanal de hidróxido de cobre com substituição por fungicidas biológicos no início da colheita. A severidade da mancha-de-septória foi avaliada com base na infecção natural, e a

produtividade total foi estimada por classes de frutos. Os dados foram submetidos à análise de variância, e as médias foram comparadas pelo teste de Tukey a 5% de probabilidade. A aplicação semanal de fungicidas químicos apresentou a maior eficiência em comparação com as aplicações baseadas no sistema de previsão da doença e com o uso de produtos biológicos.

Palavras-chave: *Solanum lycopersicum* L., resíduos de pesticidas, controle biológico, mancha-de-septória, fungicidas.

1. Introduction

Tomato (*Solanum lycopersicum* L.) production has great economic and social importance in global agribusiness, particularly in Brazil, and it is one of the most widely cultivated and consumed vegetable crops worldwide due to its nutritional value, broad industrial applications, and high added value. Global tomato production has increased in recent decades, driven by the growing demand for processed products and fresh consumption, making this crop strategic for several producing countries (Derbe et al., 2024; Pandey et al., 2024). Brazil ranked fourth in global tomato production between 2006 and 2013, with an approximate production of 4.2 million tons, behind China, the United States, and Turkey.

Despite technological advances in crop management and production systems, tomato plants remain highly susceptible to several diseases, especially fungal foliar diseases, which can cause severe defoliation, yield reduction, and decreased fruit quality. Among these diseases, *Septoria* leaf spot, caused by the fungus *Septoria lycopersici* Spegazzini, stands out as one of the most important foliar diseases affecting tomato crops in regions with warm and humid climates. The disease can occur at all stages of plant development and is favored by high relative humidity, moderate temperatures, prolonged leaf wetness, and the lack of commercial cultivars or hybrids with satisfactory levels of resistance to major fungal diseases (Neri et al., 2019; Pandey et al., 2024).

The control of *Septoria* leaf spot is mainly achieved through the use of chemical fungicides, including compounds from the triazole, strobilurin, benzimidazole, dithiocarbamate groups, and copper-based fungicides applied as foliar sprays. However, the frequent use of chemical fungicide formulations may lead to the development of pathogen resistance to major antifungal molecules, in addition to increasing production costs and the risks of environmental and food contamination. Recent studies have demonstrated that isolates of *S. lycopersici* already show variability in sensitivity to fungicides widely used in Brazil, reinforcing the need for new disease management strategies (Costa et al., 2025).

Another major problem associated with the intensive use of pesticides in tomato production is the presence of residues in fruits. Tomatoes are among the vegetables with the highest frequency of pesticide residues due to the large number of applications required during the crop cycle. Studies on pesticide residues in food in Brazil show that a large percentage of fruit and vegetable samples contain detectable residues, and some exceed the maximum residue limits or contain products not authorized for the crop (Jardim; Caldas, 2024).

Furthermore, recent review studies indicate that the consumption of fruits and vegetables contaminated with pesticide residues may pose risks to human health, including chronic effects and exposure to multiple pesticide residues simultaneously, which has encouraged the development of more sustainable production systems with reduced use of chemical pesticides (Andrade et al., 2023). In addition, several pesticides can bioaccumulate in the food chain and affect vital biological systems of living organisms, persisting in the environment for several years. Tomato fruits are classified as a high-risk group associated with exposure to these chemical compounds (Cardoso et al., 2010; Ishaq et al., 2020).

In this context, the use of integrated disease management strategies, including biological control agents, fungicides with lower environmental impact, and disease forecasting systems, has become a promising alternative to reduce the number of fungicide applications and, consequently, decrease pesticide residues in fruits while maintaining crop productivity and plant health. Therefore, the objective of this study was to evaluate strategies for the application of plant protection products for the control of *Septoria* leaf spot in tomato plants with a low risk of pesticide contamination in fruits.

2. Materials and Methods

2.1 Experimental site and area characterization

The study was conducted at the experimental area of the Goiano Federal Institute – Morrinhos Campus (17.820700 W and 49.202901 S; 885 m above sea level) during 2019. The soil of the experimental area was

classified as a Dystroferic Red-Yellow Oxisol according to the Brazilian Soil Classification System (EMBRAPA, 2013). Two experiments were conducted during different growing seasons. The first experiment was established during the dry season (autumn/winter), with seedling transplanting on April 18, 2019. The second experiment was conducted at the beginning of the rainy season (spring/summer), with transplanting on September 25, 2019.

2.2 Plant material and crop management

The tomato hybrid Totale was used in the study. This hybrid is characterized by elongated fruits with intense red coloration, short internodes, and high resistance to several pathogens, including *Verticillium albo-atrum*, *Verticillium dahliae*, *Fusarium oxysporum* f. sp. *lycopersici* (races 1, 2, and 3), Tomato mosaic virus (ToMV), *Alternaria alternata* f. sp. *lycopersici*, *Stemphylium solani*, and Tomato spotted wilt virus (TSWV). It also exhibits intermediate resistance to *Meloidogyne arenaria*, *M. incognita*, *M. javanica*, and Tomato yellow leaf curl virus (TYLCV).

In both experiments, seedlings with two to three true leaves were obtained from a commercial nursery and transplanted into 1.2-m-wide beds covered with double-sided gray plastic mulch. Plants were arranged in double rows with a spacing of 0.7×0.7 m. Plants were trained using plastic twine and maintained with two stems through regular sucker removal. After the sixth fruit cluster, apical pruning was performed.

2.3 Fertilization and irrigation

Fertilization was carried out according to soil fertility analysis recommendations. At planting, $1,000 \text{ kg ha}^{-1}$ of a 4-30-16 NPK fertilizer formulation was applied. Topdress fertilization was supplied via fertigation using monoammonium phosphate (MAP), potassium chloride, ammonium sulfate, and calcium nitrate. Irrigation was performed using a drip irrigation system, with irrigation depths adjusted according to crop requirements.

2.4 Experimental design

The experiment was arranged in a randomized complete block design (RCBD), with nine treatments and four replications. Each experimental plot consisted of a 5-m-long bed containing 14 plants. Between blocks, an additional bed was planted with two rows of maize to serve as a physical barrier and minimize spray drift among treatments.

2.5 Septoria leaf spot management and favorable conditions for disease development

To promote the development of *Septoria* leaf spot, sprinkler lines were installed along both sides of the experimental area, parallel to the first and last blocks. The system was operated three times per week for 30 min, creating favorable environmental conditions for disease establishment and development. Disease severity was assessed under natural infection conditions.

2.6 Fungicide treatments

Treatment applications began seven days after transplanting (DAT) using a CO_2 -pressurized backpack sprayer equipped with a spray boom containing four flat-fan nozzles spaced 0.5 m apart. A spray volume of 500 L ha^{-1} was used throughout the study.

The following treatments were evaluated:

Untreated control; Weekly application of chemical fungicides (calendar-based); Weekly application of chemical fungicides followed by replacement with biological fungicides at the beginning of harvest (calendar-based + biological); Application of chemical fungicides based on a disease forecasting system; Disease forecasting system followed by replacement with biological fungicides at the beginning of harvest; Biological fungicide applied at the recommended rate; Biological fungicide applied at twice the recommended rate; Weekly application of copper hydroxide;

Weekly application of copper hydroxide followed by replacement with biological fungicides at the beginning of harvest. Registered fungicides for *Septoria* leaf spot control in tomato were used, with toxicological classifications and pre-harvest intervals described in (Table 1). The fungicide application schedules for each

treatment are presented in (Table 2). In treatments involving the replacement of chemical or copper-based fungicides by biological fungicides, the transition occurred at 70 DAT, coinciding with the beginning of harvest. The biological fungicide was also evaluated as a standalone treatment at rates of 200 and 400 mL of commercial product per hectare.

Table 1. List of phytosanitary products used in the different treatments, including information on the recommended application rate, pre-harvest interval, and toxicological classification.

Active ingredient		Commercial product (Code)	Commercial product concentration (100 L of spray)	Pre-harvest interval (days)	Toxicological classification
Metiram	+	Cabrio Top [®] , BASF S.A. (MP)	200 g	7	4 – Slightly Toxic Product
Pyraclostrobin					
Fluxapyroxad	+	Orkestra [®] , BASF S.A. (FP)	35 mL	1	4 – Slightly Toxic Product
Pyraclostrobin					
Propineb		Antracol 700 WP [®] , Bayer Crop Science (Pr)	3000 g	7	5 – Unlikely to Cause Acute Damage Product
Metconazole		Caramba 90 [®] , BASF S.A. (Mt)	100 mL	7	5 – Unlikely to Cause Acute Damage Product
Chlorothalonil		Bravonil [®] , BASF S.A. (Cl)	200 mL	7	4 – Slightly Toxic Product
Copper hydroxide		Kocide [®] , DuPont (CuOH)	3000 g	No restrictions	4 – Slightly Toxic Product
<i>Bacillus subtilis</i> strain QST 713 (13.68)		Serenade [®] , Bayer Crop Science (Bsub)	200 e 400 mL	Not determined*	Not Classified

Note: *Pre-harvest interval not established due to the biological nature of the active ingredient. Source: Authors, 2026.

Table 2. Description of phytosanitary product applications according to days after transplanting (DAT) and the different treatments at the Goiano Federal Institute, Morrinhos Campus, Morrinhos, Goiás, Brazil.

DAT	Control	Calendar-based	Calendar-based + Biological	Forecast-based System (Trial 1/ Trial 2)	Forecast + Biological (Trial 1/ Trial 2)	Biological (200 Lp.c./100 L)	Biological (400 Lp.c./100 L)	Copper	Copper + Biological
7	-	Cl+FP	Cl+FP	-	-	Bsub 200	Bsub 400	CuOH	CuOH
14	-	MP	MP	-	-	Bsub 200	Bsub 400	CuOH	CuOH
21	-	FP+Pr	FP+Pr	FP+Pr	FP+Pr	Bsub 200	Bsub 400	CuOH	CuOH
28	-	MP	MP	MP	MP	Bsub 200	Bsub 400	CuOH	CuOH
35	-	FP+Pr	FP+Pr	FP+Pr	FP+Pr	Bsub 200	Bsub 400	CuOH	CuOH
42	-	Cl+Mt	Cl+Mt	Cl+Mt / Cl+Mt	Cl+Mt / Cl+Mt	Bsub 200	Bsub 400	CuOH	CuOH
49	-	FP+Cl	FP+Cl			Bsub 200	Bsub 400	CuOH	CuOH
56	-	Cl+Mt	Cl+Mt	Cl+Mt	Cl+Mt	Bsub 200	Bsub 400	CuOH	CuOH
63	-	Pr	Pr	Pr / Pr	Pr / Pr	Bsub 200	Bsub 400	CuOH	CuOH
70	-	Cl+Mt	Bsub 200			Bsub 200	Bsub 400	CuOH	Bsub 200
77	-	Pr	Bsub 200	Pr	Bsub 200	Bsub 200	Bsub 400	CuOH	Bsub 200
84	-	Cl+Mt	Bsub 200	Cl+Mt	Bsub 200	Bsub 200	Bsub 400	CuOH	Bsub 200
91	-	Pr	Bsub 200	Pr	Bsub 200	Bsub 200	Bsub 400	CuOH	Bsub 200

Note: MP = Metiram + Pyraclostrobin, Cabrio Top®, BASF S.A., 200 g/100 L; FP = Fluxapyroxad + Pyraclostrobin, Orkestra®, BASF S.A., 5 mL/100 L; Pr = Propineb, Antracol 700 WP®, Bayer Crop Science, 300 g/100 L; Mt = Metconazole, Caramba 90®, BASF S.A., 100 mL/100 L; Cl = Chlorothalonil, Bravonil®, BASF S.A., 200 mL/100 L; CuOH = Copper hydroxide, Kocide®, DuPont, 300 g/100 L; Bsub = *Bacillus subtilis* strain QST 713, Serenade®, Bayer Crop Science, 200 and 400 mL/100 L. Source: Authors, 2026.

2.7 Disease and yield assessments

Septoria leaf spot severity was assessed periodically as the percentage of diseased leaf area using the diagrammatic scale proposed by Boff et al. (1991). Based on disease severity assessments collected throughout the epidemic, the Area Under the Disease Progress Curve (AUDPC) was calculated. Fruits were harvested as they reached commercial maturity (colored fruits). The final harvests were performed on April 18 and December 29, 2019, for Experiments 1 and 2, respectively. At the end of the crop cycle, total yield and yield by fruit size class were determined. Fruit classes were defined according to transverse diameter as follows:

Class 1: 55–65 mm, and Class 2: 45–55 mm.

2.8 Statistical analysis

Data were subjected to analysis of variance (ANOVA). Whenever treatment effects were significant ($P < 0.05$), means were compared using Tukey's test at the 5% probability level. The statistical analyses were performed using the SISVAR software package (Ferreira, 2019).

3. Results

3.1 *Septoria* leaf spot progress

Symptoms of *Septoria* leaf spot were observed in both experiments under natural infection conditions. Disease symptoms appeared earlier during the autumn/winter season (Figure 1A) than during the spring/summer season (Figure 1B). In the autumn/winter trial, significant differences among treatments were detected in all disease assessments ($P < 0.0001$). From 40 DAT onwards, weekly fungicide applications and weekly copper hydroxide

applications consistently resulted in the lowest disease severity values compared with the untreated control.

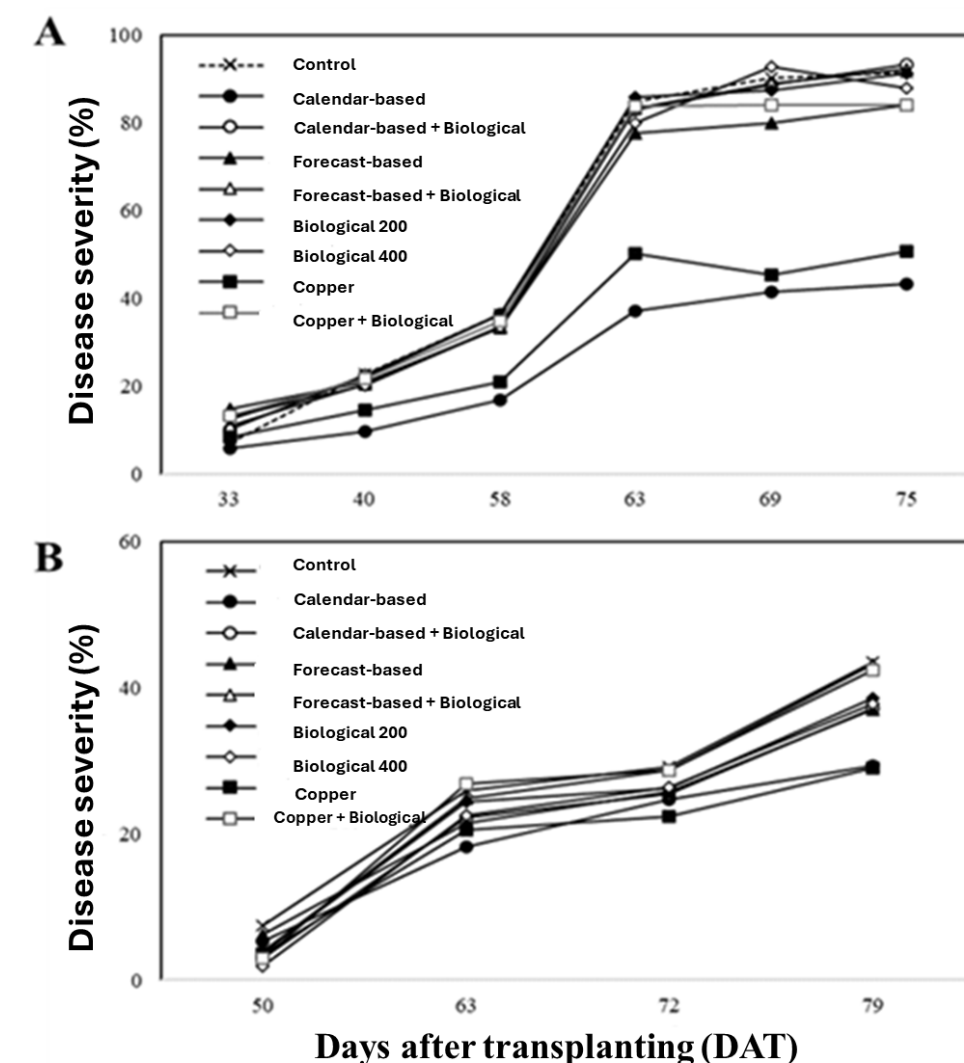


Figure 1. *Septoria* disease progress curves observed in the autumn/winter (A) and spring/summer (B) trials under the different phytosanitary management strategies. Source: Authors, 2026.

The same trend was observed in the spring/summer trial. Based on final disease severity and AUDPC values, the weekly fungicide schedule and copper hydroxide treatments provided the greatest reduction in disease development in both growing seasons (Table 3).

Table 3. Final disease severity and area under the disease progress curve (AUDPC) values observed in the two trials as affected by the different treatments.

Treatments	Autumn/Winter		Spring/Summer	
	Final disease severity (%)	AUDPC	Final disease severity (%)	AUDPC
Control	91.6 A ¹	2046.8 A	43.4 A	636.5 A
Calendar-based	43.3 D	935.0 D	29.3 C	471.7 C
Calendar-based + Biological	93.4 A	2036.6 AB	37.1 B	525.5 B
Forecast-based	84.2 B	1885.6 B	37.0 B	542.2 B
Forecast-based + Biological	92.4 A	1986.4 AB	43.3 A	599.5 A
Biological 200	91.4 A	2039.2 AB	38.5 B	561.1 B
Biological 400	88.1 AB	1983.2 AB	37.7 B	530.9 B
Copper	50.7 C	1165.9 C	28.9 C	465.9 C
Copper + Biological	84.19 B	1966.02 AB	42.5 A	609.6 A
<i>p</i> -value	<0.0001	<0.0001	<0.0001	<0.0001
Coefficient of variation (%)	5.63	5.94	4.54	4.78

Note: ¹ Means followed by the same letter do not differ significantly according to the Least Significant Difference (LSD) test ($p \leq 0.05$). AUDPC (Area Under the Disease Progress Curve. Source: Authors, 2026.

3.2 Fruit yield during the autumn/winter season

Significant treatment effects were observed for total yield, Class 1 fruit yield, and rotten fruit production (Table 4). The weekly fungicide program resulted in the highest total yield (34.5 kg plot⁻¹), followed by copper hydroxide (30.2 kg plot⁻¹) and the biological fungicide applied at 400 mL ha⁻¹ (30.5 kg plot⁻¹). For Class 1 fruits, the highest yield was obtained with the weekly fungicide schedule, followed by copper hydroxide applications. Copper hydroxide also resulted in the lowest incidence of rotten fruits among all treatments.

Table 4. Mean tomato fruit yield (kg⁻¹) per plot as affected by the different treatments in the autumn/winter trial.

Treatments	Total	Class 1	Class 2	Rotten fruits
Control	26.5 C	9.34 C	14.95	4.8 AB
Calendar-based	34.5 A	16.6 A	14.80	3.1 C
Calendar-based + Biological	28.2 BC	9.1 C	15.37	3.7 ABC
Forecast-based	29.4 BC	9.5 C	15.80	4.1 ABC
Forecast-based + Biological	29.8 BC	10.4 C	15.86	3.6 BC
Biological 200	28.8 BC	10.5 BC	15.29	2.9 C
Biological 400	30.5 B	9.7 C	15.53	5.2 A
Copper	30.2 B	13.2 B	14.42	2.6 C
Copper + Biological	27.5 BC	9.9 C	14.48	3.1 C
<i>p</i> -value	0.0080	0.0002	0.8776	0.0415
Coefficient of variation (%)	8.21	17.69	10.47	30.07

Note: ¹ Means followed by the same letter do not differ significantly according to the Least Significant Difference (LSD) test ($P \leq 0.05$). Source: Authors, 2026.

3.3 Fruit yield during the spring/summer season

The performance of treatments was similar to that observed in the autumn/winter experiment. Weekly fungicide applications and copper hydroxide were the only treatments that significantly increased total fruit yield

compared with the untreated control (Table 5). Regarding Class 1 fruits, the same treatments provided the highest yields. The greatest amount of rotten fruit was observed in the weekly fungicide treatment, whereas copper hydroxide treatments resulted in minimal fruit rot incidence.

Table 5. Mean tomato fruit yield (kg⁻¹) from 14 plants as affected by the different treatments in the spring/summer trial.

Treatments	Total	Class 1	Class 2	Rotten fruits
Control	14.0 C	0.7 C	11.56	1.8 B
Calendar-based	23.3 A	4.8 A	13.05	5.5 A
Calendar-based + Biological	16.7 BC	1.4 BC	12.79	2.5 AB
Forecast-based	12.9 C	0.9 BC	12.01	0.02 B
Forecast-based + Biological	14.5 C	0.7 C	13.68	0.2 B
Biological 200	14.4 C	2.1 BC	10.62	1.8 B
Biological 400	15.0 C	0.7 C	14.33	0.0 B
Copper	22.2 AB	3.1 AB	18.98	0.03 B
Copper + Biological	15.9 C	0.47	15.49	0.0 B
<i>p</i> -value	0.0123	0.0113	0.1065	0.0500
Coefficient of variation (%)	24.77	97.43	26.52	185.58

Note: ¹ Means followed by the same letter do not differ significantly according to the Least Significant Difference (LSD) test ($p \leq 0.05$). Source: Authors, 2026.

4. Discussion

The occurrence of *Septoria* leaf spot in both growing seasons confirms the high susceptibility of tomato crops to *Septoria lycopersici* under favorable environmental conditions (Ávila et al., 2020). The earlier onset of symptoms during the autumn/winter season was likely associated with rainfall events occurring shortly after transplanting, which may have promoted spore dispersal and infection establishment. Environmental factors such as leaf wetness duration, relative humidity, and temperature are recognized as the primary drivers of *Septoria* epidemics, frequently resulting in severe defoliation and significant yield reductions when disease management is inadequate (Pandey et al., 2024; Reis et al., 2006). In addition, recent studies emphasize that climate variability and short-term extreme rainfall events can intensify early epidemic establishment, especially in susceptible cultivars, accelerating disease progress and reducing the window for effective control (Gu et al., 2025).

The superior performance of the weekly fungicide program demonstrates the importance of maintaining continuous protection of the foliage throughout the crop cycle. Lower disease severity and reduced AUDPC values were directly associated with increased fruit yield, indicating that preservation of healthy leaf area is essential for sustaining photosynthetic activity and assimilate production. Similar relationships between disease suppression, maintenance of canopy integrity, and increased productivity have been reported for tomato crops under field conditions (Borba et al., 2017; Baldicera et al., 2020). More recent evidence also reinforces that protective spray schedules remain highly effective in high-pressure disease environments, particularly when pathogen inoculum is continuously present (Alizadeh-Moghaddam et al., 2024).

The disease forecasting strategy evaluated in the present study did not provide satisfactory suppression of *Septoria* leaf spot (Ávila et al., 2020; Beyer et al., 2022). Although forecasting systems have been successfully adopted in several pathosystems to reduce fungicide applications, their efficiency is highly dependent on local climatic conditions, pathogen pressure, and cultivar susceptibility. Therefore, the threshold adopted in this study may not have been sufficiently restrictive to prevent disease development. Similar limitations have been reported in forecasting systems developed for tomato diseases when environmental conditions differed from those used during model calibration (Becker, 2019; Pandey et al., 2024). Recent advancements in machine learning-based forecasting models suggest improved accuracy, but field validation under tropical conditions remains limited (Kumari; Nagar, 2026).

The biological fungicide based on *Bacillus subtilis* exhibited limited efficacy when applied alone, regardless of the dose used. Biological products have become increasingly important as components of sustainable disease management programs (Santos et al., 2022); however, their field performance is frequently influenced by environmental conditions, pathogen pressure, formulation stability, and persistence on leaf surfaces. Several studies have demonstrated that *Bacillus*-based products generally provide partial disease suppression and are often more effective when integrated with conventional fungicides rather than used as standalone treatments (Abdel-Rahman et al., 2015; Feliciano-Rivera; Karačić et al., 2024; Vincelli, 2023). Recent research also highlights that strain selection and formulation improvements (e.g., encapsulation and adjuvants) may significantly enhance field efficacy (Ali et al., 2025).

An important finding of this study was the performance of copper hydroxide. In both growing seasons, copper applications resulted in disease control levels comparable to those obtained with conventional fungicide programs while maintaining fruit yields significantly higher than those observed in the untreated control. Similar results have been reported in studies evaluating copper-based fungicides for the management of foliar diseases in tomato, where copper compounds consistently provided effective protection against pathogen infection due to their multisite mode of action (Feliciano-Rivera; Vincelli, 2023; Baldicera et al., 2020). More recent studies continue to support copper's stability under variable environmental conditions, particularly in integrated spray programs (Singh et al., 2025).

The reduced incidence of rotten fruits observed in copper-treated plots deserves particular attention. Besides its fungicidal activity, copper exhibits broad-spectrum antimicrobial properties that may contribute to the suppression of secondary pathogens associated with fruit decay (Lamichhane et al., 2018; Wang et al., 2025). This characteristic is particularly advantageous during harvest periods, when concerns regarding pesticide residues and food safety become more relevant. Moreover, the multisite mechanism of copper compounds is associated with a lower risk of resistance development compared with site-specific fungicides (Amorim et al., 2011; Feliciano-Rivera; Vincelli, 2023). Recent studies also suggest that copper may indirectly modulate phyllosphere microbial communities, reducing opportunistic post-harvest infections (Feng et al., 2023).

The poor performance observed after replacing conventional fungicides with biological products at the onset of harvest suggests that maintaining effective protection during the final stages of crop development is essential for adequate disease suppression. Recent studies have demonstrated that variability in pathogen sensitivity to fungicides, combined with favorable environmental conditions, may compromise disease control when less effective products are used during critical periods of crop development. Furthermore, populations of *S. lycopersici* with reduced sensitivity to certain fungicide groups have already been reported, reinforcing the need for integrated disease management strategies and fungicide resistance monitoring (Costa et al., 2025; Baldicera et al., 2020). Recent reports also highlight that late-season disease escape is a major driver of yield and quality losses in tomato production systems (Costa et al., 2025; Lopez et al., 2025; Pandey et al., 2024).

Overall, the results demonstrate that effective disease suppression was directly associated with yield preservation. Although conventional fungicide programs provided the highest levels of disease control, copper hydroxide emerged as a promising alternative due to its comparable efficacy, lower toxicological risk, multisite activity, and superior reduction in fruit rot incidence (Grzanka et al., 2024). Future studies should focus on optimizing the integration of biological products and disease forecasting systems into tomato disease management programs to reduce fungicide dependence while maintaining satisfactory levels of disease control and crop productivity (Hasanaliyeva et al., 2022; Shanmugam et al., 2024). In addition, recent advances in integrated pest management (IPM) frameworks emphasize combining chemical, biological, and predictive tools to enhance sustainability and delay resistance evolution (Meno et al., 2025; Panthee et al., 2024; Raghuvanshi et al., 2025; Wu; Liang, 2026).

A limitation of the present study is the absence of an economic evaluation of the proposed management strategies. Although the biological and agronomic effectiveness of the treatments was demonstrated, practical adoption by growers also depends on their economic feasibility. Parameters such as application cost, total management program cost, gross and net revenue, benefit–cost ratio (B:C), and return on investment were not recorded during the experiment, preventing a comprehensive economic assessment. Economic analyses have become increasingly important in crop protection studies because they provide essential information for decision-making and technology adoption under commercial production systems. Therefore, future studies should integrate agronomic performance with detailed economic indicators to identify the most profitable and sustainable management strategy for producers (Bayiyana et al., 2023).

5. Conclusions

Weekly fungicide applications provided the highest levels of *Septoria* leaf spot control and resulted in the greatest tomato yields across the evaluated growing seasons. These results demonstrate that calendar-based fungicide programs remain the most effective strategy for disease management under conditions favorable to disease development. Copper hydroxide applications achieved disease control levels comparable to those obtained with conventional fungicide programs, while also contributing to reduced fruit rot incidence. Considering its lower toxicological risk and broad availability, copper hydroxide represents a viable alternative for integrated disease management in tomato production systems.

Although the biological fungicide and disease forecasting-based strategies did not consistently match the performance of conventional fungicide programs under the conditions evaluated, their use remains promising within sustainable crop protection programs. Further studies are warranted to optimize the integration of biological products and forecasting systems, particularly regarding application timing, product combinations, and environmental conditions, aiming to reduce fungicide inputs while maintaining satisfactory disease control and crop productivity.

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7. Authors' Contributions

Francisco Rafael Santos Conceição: conceptualization, methodology, investigation, data curation, formal analysis, writing – original draft. *Abadia dos Reis Nascimento*: investigation, data collection, validation. *Miriam Fumiko Fujinawa*: methodology, formal analysis, writing – review & editing. *Nadson de Carvalho Pontes*: supervision, conceptualization, project administration, funding acquisition, resources, writing – review & editing.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

Not applicable.

10. References

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