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Optimizing Late Blight Management in Ecuadorian Tomato Crops through Potassium Phosphite and Integrated Fungicide Strategies

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Abstract: A Late blight is a devastating plant disease affecting solanaceous crops, and fungicides play a crucial role in its management. Nevertheless, the extensive use of fungicides has alowed to the development of fungicide-resistant strains of the causal agent, *Phytophthora infestans*. Phosphites, a group of innocuous products, have been shown to have direct and indirect results on the development of oomycetes, including *P. infestans*. This study evaluated the efficacy of different methods, including fungicide rotation and the fungicide mixture with potassium phosphite, in controlling late blight in tomato. Tomato plants were transplanted in the field and subjected to nine different treatments, including various combinations of fungicide rotation, potassium phosphite application, chlorine dioxide, and ozonized water. **The** results showed that the use of fungicide rotation combined with potassium phosphite applications, at both 7-day and 14-day intervals, significantly reduced the intensity of late blight and increased tomato productivity. The application of phosphites and fungicides with different modes of action, such as Benalaxyl-M, Dimethomorph, Fluazinam, and Propamocarb, was found to be an effective alternative for late blight control in Solanaceae crops. These findings suggest that the integration of fungicide rotation and phosphite application can be a valuable strategy for managing late blight in tomato and other solanaceous crops, potentially reducing the selection pressure for fungicide-resistant *P. infestans* strains. To enhance the efficacy and sustainability of these treatments, further research should focus on determining the optimal timing and application rates.

Keywords: control; oomycetes; Potassium Phosphite; Benalaxyl-M; Dimethomorph; Fluazinam; Propamocarb; Solanaceous

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1. Introduction

Tomato production, particularly for the fresh market, relies heavily on fungicide applications to combat fungal diseases [1]. Among these diseases, late blight, caused by the oomycete *Phytophthora infestans* Mont. De Bary, poses a significant threat to tomato yields worldwide. Controlling this devastating disease accounts for an estimated 20% of total tomato production costs [2,3]. The pathogen's ability to complete its life cycle within a mere 3 to 4 days, coupled with its rapid inoculum accumulation under favorable conditions (temperatures between 20-22°C, high relative humidity, and abundant rainfall), necessitates frequent applications of both protective and curative fungicides to curtail disease development [4–6]. This reliance on chemical control is further exacerbated by the limited availability of commercially viable tomato cultivars exhibiting durable resistance to *P. infestans*.

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Consequently, tomato growers often resort to intensive fungicide spray programs, with the average number of applications per growing season ranging from 7 to 20, contingent upon prevailing weather patterns, disease pressure, and specific crop management practices [7]. However, this heavy reliance on fungicides has unintended consequences. The excessive and often indiscriminate use of these chemical agents exerts significant selection pressure on *P. infestans* populations, accelerating the evolution and spread of fungicide resistance [4,5]. This underscores the urgent need for sustainable late blight management strategies that minimize reliance on synthetic fungicides while effectively controlling the disease.

Fungicide resistance in plant pathogens presents a persistent and evolving challenge in agriculture. The propensity for developing resistance varies among pathogen classes, influenced by a complex interplay of biological factors. These factors, often acting synergistically, contribute to an elevated risk of resistance emergence [8]. Key biological attributes associated with heightened resistance risk include a rapid life cycle, prolific sporulation capacity, and efficient long-distance spore dispersal mechanisms. These traits enable pathogens to undergo rapid population growth and spread, accelerating the selection for and dissemination of resistant genotypes within pathogen populations [9–11].

Implementing a strategic fungicide rotation program, characterized by the rotation of fungicides with distinct modes of action, stands as a cornerstone strategy for mitigating the development of fungicide resistance in oomycete populations. This approach aims to disrupt the selection pressure exerted by continuous exposure to a single fungicide, thereby hindering the proliferation of resistant genotypes. By diversifying the fungicides employed, a rotation strategy effectively reduces the likelihood of pathogens developing resistance to multiple fungicide classes simultaneously [9,11].

Considering the above, for example, the phenylamides with Benalaxyl-M are products that are still used. They perform at specific sites of the pathogen, avoiding protein biosynthesis through interference with ribosomal RNA synthesis, which can be overcome by naturally resistant variants of the pathogen [12].

Dimethomorph, one of the fungicides released after to phenylamide resistance, is a cinnamic acid derivative with high specificity for certain members of the Peronosporaceae family, including *P. infestans*, this product affects cell wall synthesis in fungi. oomycetes specifically prevent the synthesis of cellulose synthase [13].

Propamocarb was first implemented in some markets for the control of oomycetes in 1978, since then it has been widely used for *Phytophthora* and *Pythium* of numerous crops. Specifically, it has been used successfully to control solanaceous late blight where some phenylamides have already generated resistance. The mode of action of propamocarb is to selectively interfere with oomycete membrane biosynthesis, although this has not been fully proven. Due to its lack of adverse effects on beneficial microorganisms such as mycorrhizae and *Trichoderma*, propamocarb has been considered a good component of integrated late blight management programs [14].

Fluazinam is a protectant fungicide belonging to the chemical group of 2,6-dinitroanilines. It has a broad spectrum of activity and is effective against a variety of pathogens, including *P. infestans*. It interrupts the energy production process of fungal cells through an uncoupling effect of oxidative phosphorylation. Its mechanism of action appears to be a simple protonophoric cycle involving protonation/deprotonation of the amino group [7].

The increasing demand for sustainable and environmentally sound agricultural practices, driven by both national and international market forces, has intensified the search for viable alternatives to conventional fungicides in managing plant diseases [15]. Among these alternatives, phosphorous acid salts, commonly known as phosphites, have emerged as promising candidates, particularly for combatting diseases caused by oomycete pathogens. Phosphites have demonstrated notable efficacy against economically significant oomycete genera, including *Phytophthora*, *Pythium,* and *Peronospora* [16–19].

The disease control mechanism of phosphites is multifaceted, encompassing both direct and indirect effects. Direct effects involve the inhibition of pathogen growth and development, effectively targeting the pathogen itself [17,18,20]. Conversely, indirect effects center around the activation of

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plant defense mechanisms, bolstering the host plant's natural ability to resist infection. This dual mode of action contributes to the efficacy of phosphites in disease management while potentially mitigating the risk of resistance development [16–18,21].

While fungicides have proven effective in controlling oomycetes like *P. infestans*, the causal agent of late blight, their long-term efficacy is threatened by the emergence of fungicide resistance. Several fungicides, including Benalaxyl-M, Dimethomorph, Propamocarb, and Fluazinam, along with the plant resistance inducer potassium phosphite, have demonstrated efficacy against *P. infestans*. However, research on the efficacy of these fungicides, particularly in combination and under Ecuadorian conditions, remains limited. This lack of locally relevant data underscores the need for integrated disease management strategies tailored to the specific challenges faced by tomato growers in Ecuador.

Therefore, this paper aims to present a comprehensive approach for managing late blight in tomatoes by integrating the use of potassium phosphite and strategic fungicide rotations, specifically within the context of Ecuadorian tomato production. This integrated strategy seeks to enhance disease control by leveraging multiple modes of action while minimizing the reliance on synthetic fungicides. By doing so, this approach aims to reduce the threat of fungicide resistance development and promote environmentally sound agricultural practices for sustainable tomato production in Ecuador.

2. Materials and Methods

2.1. Location

The study was carried out in the open field in the San Juan de Trigoloma Community in the locality of the Pallatanga canton belonging to the province of Chimborazo-Ecuador (geographical coordinates: 78° 57' west longitude and 01° 59' south latitude). The study site is located at an impressive altitude of 1,285 meters above sea level, experiencing a relatively temperate climate with a maximum annual temperature of 22°C and a minimum of 14°C. Precipitation at the site is abundant, reaching an annual total of 1,000 mm. Ecuadorian tomato crops in this zone are highly susceptible to late blight disease caused by *P. infestans*. Recent growing seasons have seen recurring outbreaks, with some cases resulting in complete crop losses within short timeframes.

2.2. Design of the Experiment

The study employed a randomized complete block design, encompassing nine treatments replicated across four blocks. The experimental layout spanned a 264 m^2 area, subdivided into 36 experimental plots, each measuring 6.4 m2 and containing 20 tomato plants. To minimize potential edge effects, a 1-meter buffer zone separated adjacent plots. Table 1 provides a detailed overview of the treatments evaluated and their respective application frequencies.

Table 1. Description of treatments in this study.

Treatments	Description	Frequency
T1	Rotation (Benalaxyl-M+Chlorothalonil (FANTIC STAR ® PM - ISAGRO; Wettable powder 50 $g.kg^{-1}$ of Benalaxyl-M and $g.kg^{-1}$ of Chlorothalonil at a dose of 2.5 $g.L^{-1}$) – Dimethomorph (FORUM ® PM - BASF; Wettable powder 500 $g.kg^{-1}$ in a dose of 3 $g.L^{-1}$)- Fluazinam (ALTIMA® SC– SYNGENTA; Concentrated Suspension 500 $g.L^{-1}$ in a dose of 2.5 $mL.L^{-1}$ – Propamocarb (PROTON ® SC -SOLAGRO; Concentrated Suspension 722 $g.L^{-1}$ in doses of 2.5 $mL.L^{-1}$)).	7 days

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T2	Rotation + Potassium phosphite (AGRIFOS ® SL – ISAGRO; Liquid suspension 45.8% of monopotassium and dipotassium phosphite in doses s of 2.5 mL.L^{-1}).	7 days
T3	Rotation	14 days
T4	Rotation + Potassium phosphite (AGRIFOS ® SL – ISAGRO; Liquid suspension 45.8% monopotassium and dipotassium phosphite in doses of 2.5 mL.L^{-1})	14 days
T5	Chlorine Dioxide (CLODOS ® SL-AGROACTIVO; Liquid suspension 2500 ppm of ClO_2).	7 days
T6	Chlorine Dioxide.	14 days
T7	Ozonated water (OZOAGRO® SL-OZOAGRO; Liquid suspension 20 g.L^{-1} in doses of 50 mL.L^{-1}).	7 days
T8	Ozonated water.	14 days
T9	Control (treatment without application of any product)	

2.3. Tomato Crop Management

The field experiments were conducted in the year 2021 using the 'Revolution' tomato hybrid (Milano-indeterminate type tomato, Sakata, Bragança Paulista, Sao Paulo, Brazil). Seeds were sown in 128-cell plastic trays filled with Berger BM2® substrate (250 grams/cell). Seedlings were transplanted at 28 days old, spaced 0.80 meters apart within rows and with 0.40 meters between rows. Prior to transplanting, the field was prepared, and soil fertility was amended to meet crop nutritional requirements using diammonium phosphate (N18-P46-K0), potassium chloride (N0-P0-K60), potassium nitrate (N13.5-P0-K46), and ammonium nitrate (N34-P0-K0). Throughout the study, tomato plants received irrigation based on crop water demands.

2.4. Application of the Different Treatments

The study leveraged natural disease pressure within the field, as the site provided conducive environmental conditions for late blight development, characterized by relative humidity consistently exceeding 80%, temperatures surpassing 24°C, and ample rainfall. Treatments were applied foliarly to tomato plants using a 20-liter backpack sprayer (Jacto, 20 L) fitted with a conical nozzle, commencing 15 days post-transplantation. Treatment regimens consisted of either 12 applications at 7-day intervals or 6 applications at 14-day intervals, depending on the specific treatment.

2.5. Variables Evaluated

To analyze the effect of the different treatments, variables related to the intensity of the late blight disease (Percentage of incidence and severity of *P. infestans*, area under the disease progress curve for incidence (AUDPCi) and area under the disease progress curve for severity (AUDPCs)) and variables related to tomato productivity (number of flowers and fruits and yield (kg/plant) were studied.

2.5.1. Incidence of P. infestans

The percentage of incidence of *P. infestans* was obtained using the following equation:

$$\% \, Incidence = \frac{\# \, of \, plants \, with \, symptoms \, of \, P. infestans}{\# \, of \, total \, plants \, / \, treatment} \, x \, 100$$

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For each evaluated plot, the percentage of incidence was determined by evaluating the status of the plants every 48 h.

2.5.2. Severity of P. infestans

The severity percentage of *P. infestans* was obtained using the descriptive severity grade scale proposed by Cuesta et al.,(2015), which proposes nine levels of damage (level 1: 0% - where no disease symptoms are observed; level 2: 0.1% - a few plants are observed in the plot with late blight; level 3: 1% - 10 spots of blight per plant; level 4: 5% - approximately 50 spots of blight per plant, more than one spot per leaflet; level 5: 25% - almost every leaflet infected, but plants maintain normal shape, every plot appears green although plants are affected; level 6: 50% - every plant is affected, with 50% of the leaf area destroyed, the plot appears green with brown spaces; level 7: 75% of the leaf area destroyed, the plot shows a predominantly brown color; level 8: only a few leaves are visible on the plants, but stems remain green and level 9:100% - all dead leaves, plant stems dead or drying up). For each evaluated plot, the percentage of severity was determined by evaluating the status of the plants using the scale every 48h.

2.5.3. AUDPCi and AUDPCs

To determine the area under the disease progress curve for incidence (AUDPCi) and area under the disease progress curve for severity (AUDPCs), the accumulated data of the incidence and severity of *P. infestans* of each one of the treatments were used and it was calculated by means of the trapezoidal integration method [23] using the following formula:

$$AUDPC = \sum_{i=1}^{n} \left[\frac{Yi + n1 + Yi}{2}\right] [Xi + 1 - Xi]$$

In which Yi=*P.infestans* severity or incidence (per unit) at the ith observation, Xi= time (days) at the ith observation, and n=total number of observations.

2.5.4. Evaluation of Tomato Production Variables

The number of flowers and fruits per plant and the yield per plant in kg were evaluated: In the case of the number of flowers and fruits per plant, these variables were determined 60 days after transplanting the tomatoes. In the case of the yield per plant, the production of four weeks from 120 days after the transplant was considered. To obtain the weight of the fruit, an electronic scale (Camry, Model EK9450) was used.

2.6. Statistical Analysis

The variables incidence, severity, AUDPCi, AUDPCs, number of flowers and fruits and yield in kg/plant were evaluated using analysis of variance and their means were compared with Tukey's test at 5%. The normality and heterogeneity of the variances of the data obtained were verified using the Shapiro-Wilk's and Bartlett's test. The RStudio Team program was used to perform the analyzes.

3. Results

The analysis of variance for the percentage of incidence and AUDPCi of *P. infestans* evaluated in the tomato plots treated with the different treatments, showed that there was no effect of the treatments ($P > 0.05$) or of the frequencies ($P > 0.05$) of application on these variables (Table 2). On the other hand, this changed in relation to the variables final severity and AUDPCs of *P. infestans* determined in the different treatments, since the analysis of variance indicated that there was an effect of the different treatments ($P = 0.0001$) and the frequency of application ($P=0.0032$) on these variables (Table 2).

Table 2. Variables associated with the intensity of late blight disease (*P. infestans*) in tomato plants where the different treatments under study were applied. Different letters in the values obtained indicate significant differences according to Tukey's test (α =0.05). CV%: Coefficient of variation.

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	Treatments	Incidence	Severity	AUDPCi [1]	AUDPCs[2]
1	Rotation every 7 days	100.00 a	12.41 c	3770.25 a	192.63 c
2	Rotation + potassium phosphite every 7 days	100.00 a	6.65 c	3679.50 a	103.20 c
3	Rotation every 14 days	100.00 a	50.86 b	3729.00 a	788.53 b
4	Rotation + potassium phosphite every 14 days	100.00 a	56.15 b	3737.25 a	870.55 b
5	Chlorine dioxide every 7 days	100.00 a	61.91 b	3993.00 a	959.93 b
6	Chlorine dioxide every 14 days	100.00 a	82.25 a	3,885.75 a	1282.85 a
7	Ozonated water every 7 days	100.00 a	60.53 b	3,770.00 a	938.43 b
8	Ozonated water every 14 days	100.00 a	52.17 b	3,918.75 a	808.88 b
9	Control (Without application of any treatment)	100.00 a	96.66 to	3,993.00 a	1498.48 a
Average		100.00	53.29	3806.91	827.00
CV %		0	12.77	4.76	12.96

[1]AUDPCi: area under the disease progress curve for incidence. [2]AUDPCs: area under the disease progress curve for severity.

The treatment with the lowest final severity and AUDPCs reached was where the proposed rotation of fungicides plus potassium phosphite was applied with an application period of 7 days (T2) with severity values of 6.65% and 103.20 AUDPCs, reducing the final severity by 90.01% and the AUDPCs by 93.11% in relation to the control treatment, where the highest values of severity and AUDPCs were observed, reaching values of 96.66% and 1498.48, respectively (Table 2).

It is worth mentioning that in this study alternative products such as ozonated water and chlorine dioxide were tested to observe the effect of these products commonly used as biocides, however, no reduction in the intensity of damage was observed in plants treated with these products with in relation to the plants used as control and in relation to the rotation proposals of fungicides with and without potassium phosphite, in the two application frequencies (7 and 14 days) (Table 2).

In relation to the productive variables of the tomato (Table 3), it was evidenced that there was an effect of the treatments and frequency of application (7 and 14 days) on the variables number of flowers (*P = 0.0001* for the treatments and *P = 0.0004* for the frequency), number of fruits (*P= 0.0001* for the treatments and *P = 0.002* for the frequency) and yield (*P = 0.0001* for the treatments and *P = 0.0002* for the frequency). The treatment in which rotation plus potassium phosphite (T2) was used obtained the highest value in the variables number of flowers (36), number of fruits (41.65) and yield (6.38 kg/plant). while the lowest values of number of flowers (8.25), number of fruits (7.10) and yield (1 kg/plant) were obtained for the control treatment in which no treatment was applied, the increase percentage of this treatment was 538% in yield in relation to the control treatment (Table 3).

Table 3. Variables associated with the productivity of tomato plants where the different treatments under study were applied. Different letters in the values obtained indicate significant differences according to Tukey's test (α =0.05). CV%: Coefficient of variation.

	Treatments	Number of flowers	Number of fruits	Yield (kg/plant)
1	Rotation every 7 days	26.25 b	34.70 b	5.28 b

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2	Rotation + potassium phosphite every 7 days	36.00 a	41.65 a	6.38 a
3	Rotation every 14 days	21.00 bcd	24.05 c	3.85 c
4	Rotation + potassium phosphite every 14 days	24.50 bc	27.75 c	5.00 b
5	Chlorine dioxide every 7 days	24bc	24.40 c	3.98 c
6	Chlorine dioxide every 14 days	14.75 of	15.90 d	2.54 d
7	Ozonated water every 7 days	22.75 bc	22.20 c	3.76 c
8	Water ozonated every 14 days	17.75 cd	22.45 c	2.55 d
9	Witness (Without application of any treatment)	8.25 e	7.10 e	1.00 e
Average		24.65	24.46	3.40
CV%		7.87	5.29	11.41

Remarkably, both the fungicide rotation program without phosphite applied every 7 days (T1) and the rotation program supplemented with potassium phosphite applied every 14 days (T4) achieved substantial yields, reaching 5.28 kg/plant and 5 kg/plant, respectively. (Table 3). The frequency of pesticide applications is increasing in many agricultural systems, particularly in open-field crops where climatic conditions are becoming more favorable for pest and disease development. This study demonstrated that the addition of potassium phosphite to a fungicide program for managing late blight in tomatoes helped to reduce the required frequency of fungicide applications. This reduction in fungicide use contributed to a substantial increase in yields, minimizing yield losses by up to 500%. These findings suggest that potassium phosphite can play a valuable role in not only increasing tomato production but also promoting more environmentally sound management of late blight by reducing the overall number of fungicide applications required per crop cycle.

4. Discussion

A Late blight, caused by the oomycete pathogen *Phytophthora infestans*, is a devastating disease affecting tomato crops worldwide. The strong negative correlations observed between late blight severity (Spearman's rho = - 0.74, $P<0.01$) and incidence (Spearman's rho = - 0.58, $P<0.01$) with tomato yield underscore the significant impact of uncontrolled late blight on crop productivity. This highlights the critical need for effective management strategies, including the continual evaluation of novel approaches, to combat this rapidly developing and potentially devastating disease [2,4]. Effective management strategies are crucial to ensure sustainable and profitable crop production. Fungicide rotations have emerged as a key component in mitigating the risk of fungicide resistance development in *P. infestans* populations. The high reproductive potential and rapid spread of this pathogen can quickly overwhelm control measures, making it essential to employ diverse management tactics [24]. Specifically, studies have shown that rotating between fungicides with different modes of action can effectively delay the emergence of resistance [25]. This is because different fungicides exert distinct selection pressures on the pathogen population, reducing the likelihood of a single resistance mechanism conferring protection across all compounds [10].

This study investigated the efficacy of a strategically designed fungicide rotation program for managing oomycete diseases in tomato crops. The program incorporated four distinct fungicides, each with a unique mode of action: benalaxyl, fluazinam, dimethomorph, and propamocarb. This rotational approach aimed to minimize the risk of fungicide resistance development while providing broad-spectrum control against *P. infestans*. The fungicide rotation strategy proposed demonstrated significant efficacy in managing late blight, both as a standalone treatment and when integrated with

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potassium phosphite [16,19]. Notably, a seven-day application frequency for both the rotation and the combined treatment consistently yielded the most favorable results in disease suppression (Table 2).

While fungicide rotations are a valuable strategy, the search for alternative control agents continues to be an important area of research. One approach that has been explored is the use of ozonated water and chlorine dioxide as potential disinfecting agents against plant pathogens [26]. However, the observed ineffectiveness of these alternatives in this study (Table 2) for late blight management warrants further investigation. It is crucial to understand the specific experimental conditions, application methods, and target pathogens that may have influenced the outcomes. For instance, studies have shown that the efficacy of ozonated water and chlorine dioxide can vary depending on factors such as concentration, exposure time, and the specific pathogen being targeted [27].

This study represents a pioneering effort in exploring the combined use of potassium phosphite and fungicide rotation as an effective strategy for controlling *P. infestans* in tomato crops. The findings contribute to the ongoing efforts to develop sustainable and integrated approaches to managing plant diseases, reducing the reliance on chemical pesticides, and promoting the use of alternative, nature-friendly solutions. Previous research has demonstrated the efficacy of phosphites in mitigating the severity of *P. infestans* infections in Solanaceae crops [21]. The beneficial effects of phosphites extend beyond *P. infestans* to other oomycete pathogens across various host plants. Studies have explored the application of phosphites both as standalone treatments and in integrated approaches, notably in combination with fungicides, such as phenylamides, to enhance disease control [16].

Various studies related to the effect of phosphites, and in particular potassium phosphite, have increased in recent years mainly due to the double mode of action that these products have, a direct and indirect action on pathogens and in particular oomycetes [16,19]. The direct action of phosphite-based products has already been studied through the incorporation of these compounds in culture media, revealing the effect on the pathogen *Pythium* sp. [17,21], demonstrating the ability of these compounds in inhibiting the growth of hyphae and mycelium. Indirectly, potassium phosphite is considered as an inducer of systemic acquired resistance (SAR), which is a natural mechanism of plants for defense against attack by phytopathogenic microorganisms [19].

Phosphites cannot be converted into assimilable phosphorus within the plant, so they do not participate directly in biochemical pathways, with negative effects on plant metabolism being observed in some cases **[28].** However, there is much research that shows that phosphites in adequate doses can stimulate the plant to produce different biologically active metabolites; enhancing flowering, yield, fruit size, total soluble solids and anthocyanin concentration, and providing control of some pathogens; therefore, this makes phosphite to be considered a beneficial product for plants **[29].** In this study, a clear bio-stimulation effect was observed in the number of flowers and total yield, demonstrating that phosphites, in addition to having fungicidal properties, possess bio-stimulating properties in the case of tomato cultivation.

The utilization of phosphites to control *P. infestans* in Solanaceae crops stands as a pivotal practice in agriculture. *P. infestans*, commonly recognized as late blight, poses a severe threat, causing substantial losses in potato and tomato crops. Potassium phosphite, in particular, has emerged as an effective method due to its multifaceted action against this pathogen. Extensive studies have showcased its efficacy in reducing the impact of *P. infestans* and this study also contributes to that. Consequently, the judicious application of phosphites proves to be an invaluable tool in safeguarding Solanaceae crops, providing a multifaceted approach to combat the detrimental effects of *P. infestans* while fortifying the health and productivity of these vital crops [24].

The use of phosphites, particularly potassium phosphite, has become an important tool for managing *P. infestans* in Solanaceae crops like potatoes and tomatoes. Late blight, as the disease is commonly known, can devastate these crops, causing significant yield losses. Potassium phosphite's effectiveness stems from its multifaceted modes of action against the pathogen. Numerous studies, including the present research, have demonstrated its ability to significantly reduce the impact of late blight. The strategic integration of phosphites into disease management programs offers a valuable means of protecting Solanaceae crops. This approach not only combats the damaging effects of *P. infestans* but also contributes to the overall health and productivity of these economically important crops. The use of phosphites in the current study suggest that potassium phosphite can serve as a valuable tool for not only enhancing tomato production but also fostering more environmentally sustainable late blight management practices. By reducing the overall number of fungicide applications required throughout a crop cycle, potassium phosphite contributes to minimizing potential environmental impacts associated with conventional fungicide use.

As new molecules emerge in the agricultural market, continued research is crucial to evaluate their efficacy and sustainability in managing plant diseases. While exploring novel chemistries, it remains essential to prioritize integrated pest management strategies that incorporate diverse control methods. Genetic control, particularly the development of tomato cultivars with durable resistance to a broad spectrum of *P. infestans* variants, should be a cornerstone of long-term management strategies. In the meantime, however, leveraging the disease-suppressive properties of products like phosphites offers an effective and environmentally sound approach to manage late blight in susceptible cultivars. Integrating phosphite-based strategies can contribute significantly to sustainable pathogen control in tomato production, reducing reliance on conventional fungicides and promoting the long-term health of tomato ecosystems.

5. Conclusions

Late blight, caused by the devastating oomycete pathogen *Phytophthora infestans*, poses a persistent threat to tomato production worldwide. This destructive disease can decimate entire fields within a short timeframe, leading to significant economic losses for farmers and jeopardizing global food security. Traditional reliance on synthetic fungicides has proven unsustainable, often resulting in the development of resistant pathogen strains, negative environmental impacts, and potential risks to human health. This study highlights the efficacy of an integrated approach, combining the unique properties of potassium phosphite with a comprehensive fungicide rotation program, to achieve sustainable and effective late blight management in tomato crops. The findings of this study underscore the potential of integrating potassium phosphite with a comprehensive fungicide rotation program as a sustainable and effective strategy for managing late blight in tomato crops. This multifaceted approach not only combats disease but also enhances plant health, reduces reliance on synthetic fungicides, and minimizes environmental impact. The integration of potassium phosphite with a comprehensive fungicide rotation program presents a promising strategy for sustainable and effective management of *P. infestans* in tomato crops. This approach not only combats disease but also enhances plant health and productivity, contributing to a more resilient and environmentally sound agricultural system.

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