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Influence of a Greenhouse Adapted to the Ecuadorian Coastal Climate on Pest Dynamics in Tomato Crops

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Abstract

Integrated pest management (IPM) in tomato (*Solanum lycopersicum* L.) on the Ecuadorian coast represents a critical challenge, given that pest persistence has led producers to abandon the crop, generating significant losses. This study compared pest population fluctuations in greenhouse and open field conditions under realistic management conditions and free infestation, considering the influence of environmental factors and applications of biorational, semisynthetic, and synthetic pesticides. In open fields, infestations were high and sustained, exceeding treatment thresholds, while in greenhouses, levels were lower, attributable to the protection of the aphid netting. Product efficacy depended on the pest and the level of infestation: *Azadirachta indica*, *Bacillus thuringiensis*, and *Beauveria bassiana* were effective in low infestations; spinetoram and abamectin reached efficacies between 80 and 100% in moderate infestations; neonicotinoids had variable efficacy, ranging from 47.8% to 89.9%. Since the system determines the type of pest and the level of infestation, monitoring becomes a key tool for timely decision-making. The findings show that the greenhouse limits the entry of the main pest, *Prodiplosis longifila*. While it does not prevent the presence of smaller pests, such as thrips and white mites, the combination of physical barriers and low-toxicity pesticides significantly reduces populations, minimizing the number of applications and the use of more toxic insecticides. The proposed strategy provides solid evidence for the effective implementation of a greenhouse to reduce pest pressure and promote IPM in protected coastal systems in Ecuador.

Keywords: treatment thresholds; protected agriculture; resilience; sampling methods; integrated pest management

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1. Introduction

The tomato (*Solanum lycopersicum* L.) is one of the most consumed fruits in the world [1]. By 2022, global tomato production reached 254 million tons, placing it among the most produced fruit and vegetable crops worldwide, without surpassing more important food crops such as the potato, whose annual production exceeds 330 million tons [2,3]. It is a plant native to Central and South America, from Mexico to Peru and the southern United States [4]. It has a high content of vitamins A, B and C, potassium, iron and phosphorus, in addition to being a source of lycopene [5]. It also contains beta-carotene, which acts as an

antioxidant against harmful free radicals in the body [6]. Production in Ecuador's coastal region faces significant challenges due to constant pest and disease pressure, which has caused considerable yield losses and led to intensive pesticide use [7]. This is exacerbated by prolonged periods of drought, which cause population displacement [8]. The largest decrease in cultivated areas in Guayas was recorded in 2004, at 1792 hectares. This figure has since drastically decreased to just 39 hectares in 2020, with a slight recovery to 169 hectares in 2022. As of 2024, no data is recorded on cultivated areas in the province, which is considered alarming for the region [9].

Being a commercial crop of large areas, it is not free from phytosanitary problems that can reduce its productivity. Worldwide, 100 species of insect pests have been identified that reduce the quality and quantity of production and/or are vectors of important diseases [10]. In Ecuador the main insect pests that cause losses in yields and increase production costs are: *Prodiplosis longifila* Gagné, 1986 (Diptera: Cecidomyiidae), *Spodoptera sunia* Guenée, 1852 (Lepidoptera: Noctuidae), *Tuta absoluta* Meyrick, 1917 (Lepidoptera: Gelechiidae) and *Bemisia tabaci* Gennadius, 1889 (Hemiptera: Aleyrodidae) [11].

P. longifila is the most economically important pest in the crop, since its larval stages cause damage that limits its production and profitability, reaching losses of up to 100% in yield [12]. Furthermore, the severity of this pest is such that it leads farmers to abandon the crop, because the dry season is the most favorable on the coast and the short biological cycles favor rapid recolonization [13].

Likewise, Rasouli et al. [14] mentions that *T. absoluta* is a pest that causes significant damage to tomatoes and other solanaceae crops, and its control is based on conventional insecticides that cause a reduction in economic benefits due to the high costs of the insecticides, destruction of natural enemy populations, and the development of resistance. In Europe, it is known as the South American tomato moth due to its invasive pest condition, reported for the first time in Europe in the province of Castellón (Spain), rapidly spreading through Mediterranean countries [15]. In addition, it has been shown that chemical control has limited efficacy against this insect, even with insecticides that have different modes of action [16,17].

On the other hand, Ebratt et al. [18] mention that thrips are among the most important pests of tomato crops, since, in addition to the direct damage they cause to the plant, they are transmitters of important viral diseases. Likewise, they mention that in Colombia, the most abundant species in tomato crops belong to the Thripidae family, such as: *Frankliniella occidentalis* Pergande, 1895; *Thrips palmi* Karny, 1925; and *Thrips tabaci* Lindeman, 1889 [19]. According to the European and Mediterranean Plant Protection Organization (EPPO) [20], *F. occidentalis* is present in Ecuador and the island region. Although literature on this insect in tomato crops is limited in our country, Syngenta [21] states that there are two predominant species in our country, such as *F. occidentalis*, a species that predominates in the dry season and is favored by temperatures close to 30 °C, while *T. tabaci* predominates in months with cooler temperatures around 20 °C.

On the other hand, the mite *Polyphagotarsonemus latus* Banks, 1904 (Acari: Tarsonemidae), is considered a very important pest in vegetables and flowers worldwide, causing severe and persistent physiological damage resulting in ablation of the leaf epidermis, enlargement and compaction of mesophyll cells and accumulation of polyphenolic compounds in the collapsed epidermis and growth inhibition, in addition, females are dispersed by phoresy mainly by whitefly [22].

Consequently, the control of these pests depends on the intensive use of agrochemicals, which not only represents a danger to humans, the soil, and the environment, but also reduces the population of natural enemies, favors the development of insecticide resistance, and the emergence of secondary pests [23]. Many pests require corrective interventions

with insecticides, which perpetuate the cycle of resistance and to mitigate this pattern, the most effective management consists of early and comprehensive monitoring of pest species [18]. In this context, the transition to greenhouse cultivation systems in Ecuador, specifically in the Litoral region, has been promoted as a strategy to reduce environmental impact, improve resource efficiency, and maintain year-round production [24]. These structures reduce the exposure of vegetables to adverse climatic factors and pests, offering opportunities to increase yields and implement more sustainable management [25].

The lack of information on greenhouses adapted to the tropical climate of the Ecuadorian coast and its influence on pest dynamics has hampered the transition to these cultivation systems. This study seeks to determine pest emergence dynamics, compare treatment thresholds, and evaluate the influence of climate on infestation in two cultivation systems: open field and greenhouse. The work was carried out under real management conditions and free infestation, which allowed for control decisions to be based on the thresholds reached at each moment, simulating the dynamics faced by farmers. In addition, it seeks to verify the effectiveness of a greenhouse adapted to regional climatology, to optimize pest management and support the reactivation of a crop that constitutes a significant source of income on the coast.

2. Materials and Methods

2.1. Study Area

This research was carried out in San Isidro, Guayas province, Ecuador. Arredondo et al. [26] mention that the coastal region is characterized by a humid tropical and megathermal climate, with excessive rainfall during the rainy months, which requires the use of protective structures for short-cycle crops. In addition, they mention that during dry periods, the implementation of irrigation systems is required and the average temperature ranges between 20 °C and 31 °C, with an average relative humidity between 81.9 and 84.8%. The soil is clayey loam with low water permeability and high water and nutrient retention capacity.

The study was conducted during the dry season, from April to October, since these are the months of greatest infestation.

2.2. Experimental Design

The greenhouse and open-field trials were carried out using the tomato hybrid var. Zodiac, which is characterized by being indeterminate and resistant to Tomato yellow leaf curl virus (TYLCV), nematodes, Fulvia fulva and Tomato mosaic virus [27]. The study was conducted with a Completely Randomized Block Design (CRBD) with three replications. Both systems had 306 plants divided into 5 rows with a planting distance of 0.50 cm between plants and 1.20 cm between rows.

The trial was conducted in a 1000 m^2 greenhouse adapted to the dry tropical climate of the Ecuadorian coast, which was characterized by a structure of native bamboo (*Guadua angustifolia* Kunth) with a height of 4.10 m at the gutter, 6.35 m at the ridge and a distance between pillars of 5 m, and it had a roof vent. The perimeter surface and the roof vent were covered with a 26 × 40 filaments $inch^{-2}$ gauge 12 mesh, which constituted 47% of the greenhouse surface. The plants were cultivated in 1 L bags with a substrate composed of river sand, rice husk, and topsoil (50:25:25 v/v). Constant pruning of shoots, old leaves, and stems was performed to obtain a balanced architecture and reduce pest infestation.

In both systems, the crop was left under free infestation and monitored twice a week (excluding borders) to determine thresholds and make decisions. Control was carried out generally or in foci, and pesticide application was performed based on the Integrated Pest Management (IPM) scheme, selecting products from the lowest to the highest toxicological

category. For Rossi et al. [28]. and Deguine et al. [29]. IPM integrates preventive measures, monitoring and threshold-based decision-making. In addition to the evaluation of the effectiveness of interventions [30]. Selective chemical inactivation methods, such as biopesticides and selective/targeted pesticide applications, are applied in that order, when other methods prove insufficient [31]. These same authors highlight that this approach allows efficient pest control, reducing health and environmental risks, and is complemented by local and sustainable strategies adapted to each cultivation system.

2.3. Climatic Parameters

Temperature (°C) and relative humidity (%) were recorded every 15 min using an Elitech 6G Data Logger thermohygrometer (Elitech Technology Inc., San Jose, CA, USA) [32]. They were placed 1.50 m from the ground in the center of the crop, protected from direct sunlight inside a box to avoid inappropriate captures. The average temperature, maximum temperature, and relative humidity were calculated.

2.4. Presence of Pests

Infestation was evaluated at different phenological stages of the crop through stratified sampling, according to the preference of each pest in the plant, taking a defined number of samples from 105 plants, in addition to subsamples for each pest, to estimate the presence and distribution of insects in the crop.

2.5. Determination of Treatment Thresholds

To determine the treatment threshold for different tomato pests, 105 plants were evaluated using binomial sampling (presence or absence), considering the sampling and thresholds determined in previous research for each pest type. Using 40 mm and 60 mm magnification entomological magnifying glasses and an integrated LED light, plants in the preferential stratum were directly observed, observing a variable number of subsamples for each species and estimating population density.

2.5.1. Treatment Thresholds of *P. longifila*

In each plant, five shoots or flowers were randomly selected, recording the presence of live larvae. The treatment threshold was established at 10% infestation [13].

2.5.2. Treatment Thresholds of *T. absoluta*

The sampling was adjusted to plant size: (a) <40 cm, complete evaluation of the plant; (b) 40 cm–1.60 m, inspection of the upper half; and (c) >1.60 m, inspection of visible leaves from the middle zone upwards. The presence of the pest was considered positive with $\geq$1 larva per plant in the first 30 days and $\geq$3–5 larvae per plant in later stages [11]. The treatment threshold was defined at 10% of leaflets with active galleries [33].

2.5.3. Treatment Thresholds of *F. occidentalis*

In the vegetative stage, three young leaves from the upper stratum were randomly evaluated, and in the reproductive stage, three flowers. The treatment threshold was established at $\geq$2 thrips per sample [34].

2.5.4. Treatment Thresholds of *B. tabaci*

Monitoring was carried out on two leaves from the upper stratum, observing the underside. In the inflorescence stage, the "key leaf" (below the highest inflorescence with at least one open flower) and another random upper leaf were evaluated. The treatment threshold was set at $\geq$3 adults per plant [35].

2.5.5. Treatment Thresholds of *Diabrotica* sp. Chevrolat, 1837

Although this pest is uncommon in tomato, the criteria of Peruzzi et al. [36] were applied, evaluating 10 leaves from the middle and upper third, and defining the treatment threshold as >3 plants with damage.

2.5.6. Treatment Thresholds of *P. latus*

The presence of the white mite was recorded when damage symptoms appeared on the plant, using the same criteria for pesticide application [37]. This is because this pest can cause severe damage even at low densities.

2.5.7. Treatment Thresholds of *S. sunia*

The threshold proposed by Arias et al. [38] was used, consisting of 20% infestation with the presence of 3 larvae/plant in the early growth stages and 1 larva per plant during the production stage.

2.6. Applied Treatments

Pesticide applications were carried out according to the habit of each pest, prioritizing the initial use of products with the lowest toxicological category (Table 1), applied once the treatment threshold was exceeded. The selection of pesticides included: botanical, semi-synthetic, microbial, and synthetic compounds with different modes of action to evaluate their impact on pests. *Azadirachta indica* is a botanical insecticide with translaminar action that alters development and has phagorepellent action [39,40]. Abamectin is a semi-synthetic insecticide, with translaminar action, antifeedant effect that causes damage to the cells of the midgut and the nervous system of insects [41,42]. Spinetoram is a semi-synthetic insecticide of natural origin with translaminar action that acts on nicotinic receptors and gamma-aminobutyric acid (GABA) [43]. *B. thuringinsis* is a bacterium selective for lepidopterans [44]. *B. bassiana* is a generalist fungus whose spores penetrate and feed on the interior of the insect [45]. Imidacloprid is a systemic neonicotinoid that interferes with the nicotinic receptors of the central nervous system, causing excitatory symptoms, with uncoordinated tremors, hyperexcitability and spontaneous movements [46,47]. Thiamethoxam + Lambda-cyhalothrin is a systemic neonicotinoid and pyrethroid that modifies the functioning of ion channels, producing an interruption of the nerve impulse [46,48]. Acetamiprid is a systemic neonicotinoid with translaminar activity, characterized by rapid insecticidal activity that causes symptoms of excitation [49].

Table 1. Products used in the trials, listed from lowest to highest toxicological category.

Treatment	Product	Active Ingredient	Formulation	Doses
1	Neem X	*Azadirachta indica*	EC	1.5–2 L/ha
2	*Bacillus thuringiensis*	*Bacillus thuringiensis*	UFC/ml	1–2 L/ha
3	Beaussiana	*Beauveria bassiana*	WG	1–1.5 L/ha
4	Abamectina	Abamectin	EC	90–100 mL/100 L
5	Radiant	Spinetoram	CS	175 mL/ha
6	Confidor	Imidacloprid	CS	200 mL/ha
7	Thala	Thiamethoxam + lambda-cyhalothrin	CS	80 mL/ha
8	Deva-Z	Acetamiprid	SP	300 g ha

Note: Emulsifiable concentrate (EC), Concentrated suspension (CS), Soluble powder (SP), Water dispersible Granules (WG).

A manual backpack sprayer equipped with a hollow cone nozzle was used for pesticide application. The application frequency was carried out when pests exceeded the

treatment thresholds, and pesticide doses were adjusted according to the manufacturer's recommendations.

Abbott's efficacy formula was used to determine the effectiveness of treatments [50]. The effectiveness of the different pesticides was calculated using the following formula:

$$\text{Efficacy}(\%) = \frac{\text{Initial Population} - \text{Post} - \text{treatment Population}}{\text{Initial Population}} \times 100$$

2.7. Statistical Analysis

Data analysis was performed in the RStudio programming environment (version 4.5.1) using packages such as *t* test, agricolae, emmeans, and glmmTMB. Initially, the Student *t* test for independent samples was applied to compare mean pest infestation rates between the two environments (open field and greenhouse). When significant differences were detected, Tukey's post hoc comparisons ($p < 0.05$) were performed to identify groups with differences.

Subsequently, Generalized Linear Mixed Models (GLMMs) from different families were used to analyze the response variable and pest infestation. For the analysis of pest infestation and climatic parameters (mean temperature, relative humidity, and maximum temperature) in both cropping systems, a Tweedie GLMM was used, considering climatic parameters as fixed factors, infestation as the response variable, and assessments as a random effect, given the repeated nature of the observations over time. To facilitate the biological interpretation of the coefficients, continuous predictors were centered. When statistical significance was detected, a Generalized Additive Model (GAM) was also fitted to explore the relationship between climatic parameters and infestation.

Similarly, a Tweedie GLMM model was applied to estimate pesticide efficacy, considering the infestation percentage as the response variable and the treatments applied as fixed factors. This model did not include random effects or climatic variables to optimize the convergence and precision of the estimates.

Finally, diagnostic residual tests were performed to verify the model assumptions using the DHARMa package. Homoscedasticity and dispersion were assessed using the nonparametric dispersion test (DHARMa), which compares the variance of the fitted and simulated residuals. The uniformity of the residuals was tested using the Kolmogorov–Smirnov test (testUniformity). Furthermore, zero inflation was assessed using the DHARMa zero inflation test, verifying that the observed proportion of zeros matched that expected based on the fit. The final models were selected based on the absence of deviations from the assumptions and the lowest Akaike Information Criterion (AIC) values, ensuring parsimony and statistical robustness of the results.

3. Results

3.1. Population Fluctuation of Pests in Open Fields and Greenhouse

Pest infestation varied significantly among cropping systems (Table 2). In open fields, *P. longifila*, *Diabrotica* sp., *S. sunia*, *P. latus*, *F. occidentalis*, and *B. tabaci* were detected. In greenhouses, *P. longifila*, *P. latus*, *F. occidentalis*, *S. sunia*, and *B. tabaci* were detected. *T. absoluta* was not detected in any of the systems.

Table 2. Average infestation percentage of the different pests detected in tomato crops, both in open fields and in greenhouses on the Ecuadorian coast.

Pests	Open Field *	Greenhouse *
P. longifila	18.09 ± 3.70 a	5.66 ± 1.04 b
B. tabaci	0.09 ± 0.04 a	0.01 ± 0.01 a
F. occidentalis	0.03 ± 0.02 a	0.17 ± 0.07 a
S. sunia	6.85 ± 1.14 a	4.14 ± 1.35 b
P. latus	0.19 ± 0.19 a	2.72 ± 0.68 b
Diabrotica sp.	2.13 ± 0.82 a	0.00 ± 0.00 b

* Different letters indicate statistically significant differences between cropping systems for the same pest (Tukey's HSD test, $p < 0.05$).

Figure 1 shows the population dynamics and infestation intensity of pests at different phenological stages of the crop.

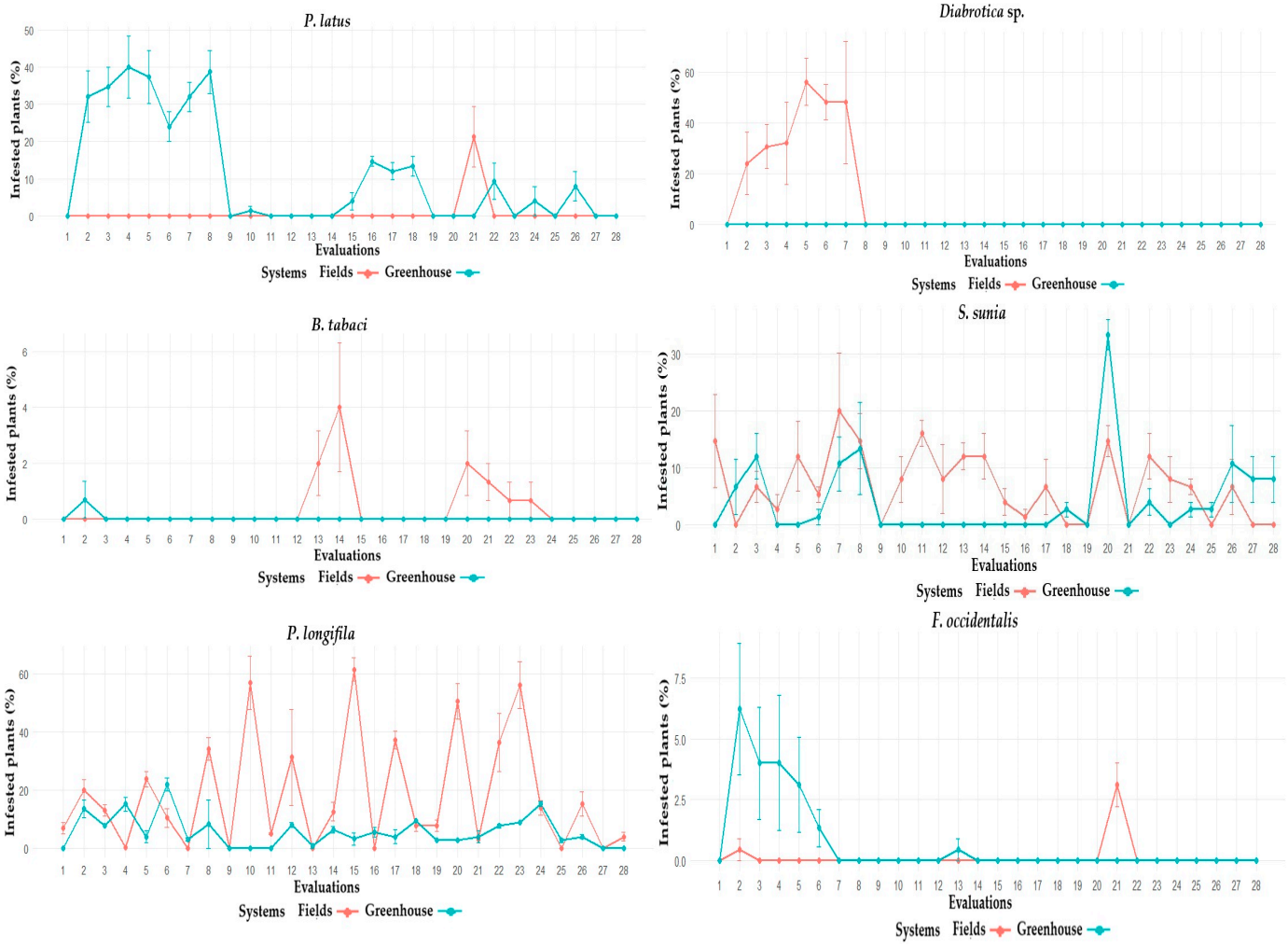


Figure 1. Percentage of infested plants in open fields and greenhouse; bars indicate standard error.

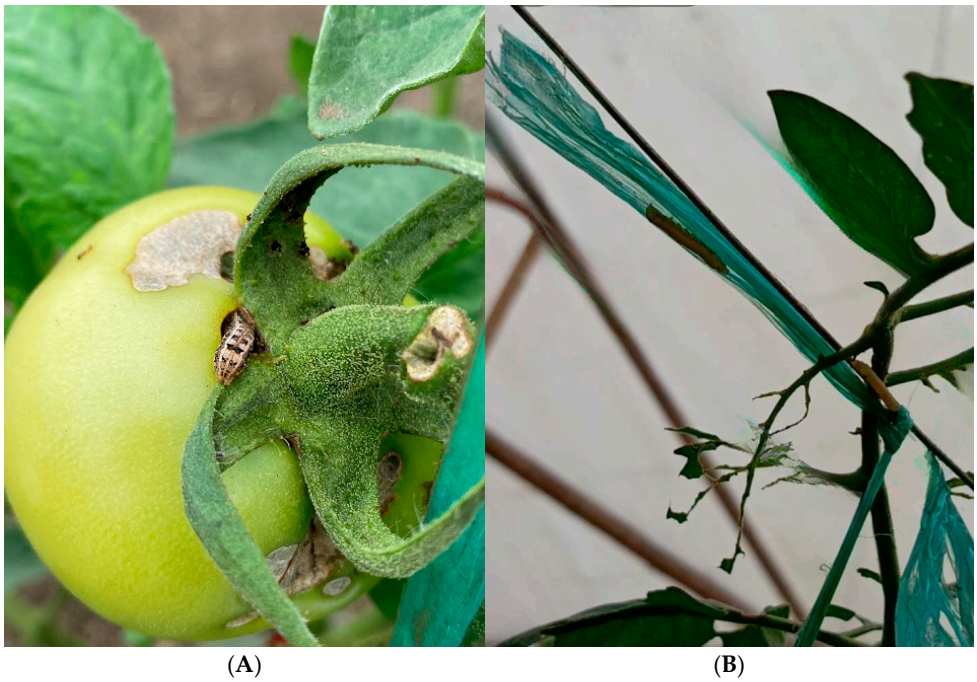
P. longifila showed the highest incidence in both systems, with continuous infestations from the second week of the crop (Figure 2). It reached maximum levels of 61% in the open field and 22% in the greenhouse during flowering and fruit set, confirming its role as the main entomological constraint.



(**A**) (**B**)

Figure 2. *P. longifila* larvae. (**A**) Monitoring with the presence of live larvae. (**B**) Extreme infestation in stems.

Spodoptera sunia showed intermittent infestations, with peaks of 20% in the field during flowering and 33% in the greenhouse at the beginning of harvest, being statistically higher in the open field (Figure 3).



(**A**) (**B**)

Figure 3. *S. sunia* larvae. (**A**) Larva piercing the fruit. (**B**) The larvae move to other plants through the tutoring wires.

Diabrotica sp., a defoliating species, was detected only in the open field from the second week of the crop, remaining until 28 days after transplanting (DAT) with a maximum of 60% at pre-flowering, disappearing afterwards (Figure 4).

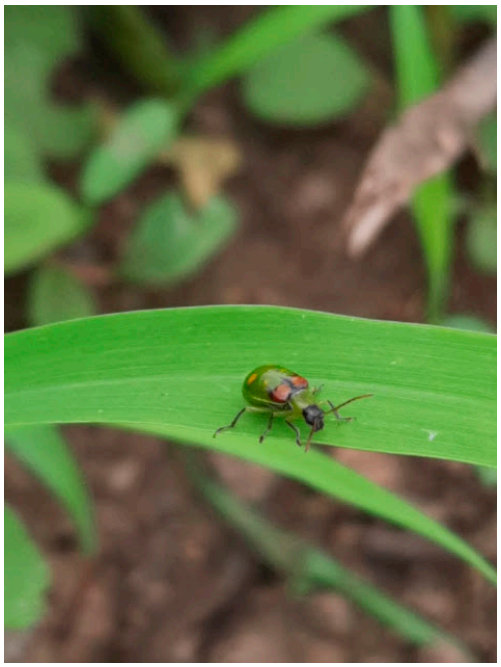


Figure 4. *Diabrotica* sp. in weeds.

The white mite *P. latus* recorded low infestations in the field with a maximum of 22% at harvest, concentrating on plants near the edges, while in the greenhouse its activity was predominant from 14 DAT, reaching a maximum of 40% at the beginning of flowering, remaining active until 70 DAT.

B. tabaci populations were detected at a specific time in both cultivation systems, while *F. occidentalis*, although not showing significant differences between systems, prevailed in the greenhouse, reaching the treatment threshold on 3 occasions.

In Figure 5 shows the critical moments when pests exceeded the treatment thresholds, which determined the need to apply control measures. In the open field, 18 pesticide applications were carried out, while in the greenhouse the number of applications was 12.

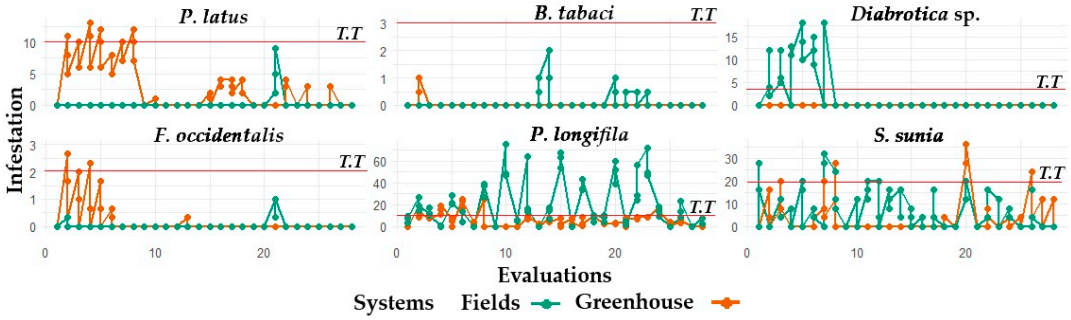


Figure 5. Treatment thresholds for different pests: *P. longifila*, *S. sunia*, *P. latus*, *Diabrotica* sp., and *F. occidentalis* and *B. tabaci* in two cropping systems. Notes: the red line indicates the treatment threshold.

In both systems, priority was given to the use of biopesticides and botanical extracts, such as *Azadirachta indica*, *Beauveria bassiana* and *Bacillus thuringiensis*, which represented between 40–50% of the total applications. The use of synthetic insecticides, including abamectin, spinetoram, acetamiprid, and the thiamethoxam + lambda-cyhalothrin, was limited to moderate to extreme situations.

The rotation of active ingredients was intended to reduce the risk of resistance and improve control efficacy. However, it was observed that the response of each species varied depending on the cropping system. In addition, some applications targeting specific pests

had an indirect impact on other organisms, such as an increase in secondary populations, highlighting the need for continuous monitoring in IPM programs.

3.2. Influence of Climatic Parameters and Pesticide Applications on Pest Dynamics Under Both Cropping Systems

The average climatic conditions recorded during the trial were as follows: the average temperature was higher in the greenhouse (26.3 °C) than in the open field (25.2 °C), with maximum values of 34.4 °C and 32.1 °C, respectively. In contrast, the average relative humidity was slightly lower in the greenhouse (79.4%) than in the open field (81.6%). While these differences remained within ranges compatible with tomato growth, they could have influenced pest dynamics and pesticide efficacy in both systems.

3.2.1. *Prodiplosis longifila* Gagné, 1986

Under open field conditions, the Tweedie GLMM did not detect significant effects of climatic parameters, although the average open field infestation was estimated at 6.2%, under medium temperature conditions ($p < 0.001$) (Table 3). In the greenhouse, the expected mean infestation was 3.5% ($p < 0.001$), with a positive and significant effect of maximum temperature ($p = 0.0498$), whereas mean temperature and relative humidity showed no influence.

Table 3. GLMM (Tweedie) parameter estimation for *P. longifila* infestation in field and greenhouse systems.

System	Parameter	Estimate *	IC 95% *	Z Value	*p*-Value
Open field	Intercept	6.21	[2.85, 13.52]	4.603	4.16×10^{-6} **
	Mean temperature	0.89	[0.22, 3.62]	−0.158	0.875 ns
	Maximum temperature	0.67	[0.28, 1.59]	−0.903	0.367 ns
	Mean relative humidity	0.88	[0.58, 1.33]	−0.621	0.534 ns
Greenhouse	Intercept	3.51	[2.21, 5.59]	5.337	9.45×10^{-8} **
	Mean temperature	0.46	[0.15, 1.41]	−1.364	0.1726 ns
	Maximum temperature	1.64	[1.00, 2.69]	1.961	0.0498 *
	Mean relative humidity	1.15	[0.84, 1.57]	0.893	0.3720 ns

* Estimate and IC 95% original scale. Z values on a logarithmic scale. Significance levels: ** $p < 0.001$ (highly significant); * $p < 0.05$ (significant); ns = not significant.

Among these factors, constant recolonization from external sources and generational overlap, characteristics of uncontrolled environments, could play a predominant role in the recurrence and persistence of infestations.

The application of the Generalized Additive Model (GAM) indicated a low positive correlation ($R^2 = 0.009$) between maximum temperature and greenhouse infestation, equivalent to a 64% increase in infestation with increases in this variable (Figure 6). This reflects that, in closed environments, the population depends mainly on the reproduction of present individuals, and that higher temperatures can accelerate their biological cycle.

To evaluate pesticide efficacy, climatic parameters and the random effect in the greenhouse were excluded due to their limited contribution to the model. In open fields, efficacy percentages ranged from 33% to 88%, with no statistically significant differences between products. *A. indica* showed low initial efficacy, requiring the application of abamectin to reduce infestation. Subsequently, *A. indica* reached 100% efficacy at thresholds of 14–15%, while spinetoram reached 100% efficacy at moderate thresholds (24–34%), and neonicotinoids were most effective at high infestations (61%), reducing the infestation by 94%. Similarly, acetamiprid showed 100% efficacy above thresholds of 31%, decreasing its efficacy (79%) as the infestation became more intense. The efficacy of acetamiprid and thiamethoxam + lambda-cyhalothrin decreased with repeated applications, suggesting a

possible loss of pest sensitivity. *B. thuringiensis* did not affect *P. longifila* because the pest was absent at the time of application, and *B. bassiana* had a negative effect, possibly due to unwanted interactions with other pesticides. Overall, pesticide efficacy depended on the initial infestation: A. indica was useful at low levels, biorationals at moderate infestations, and neonicotinoids at high infestations.

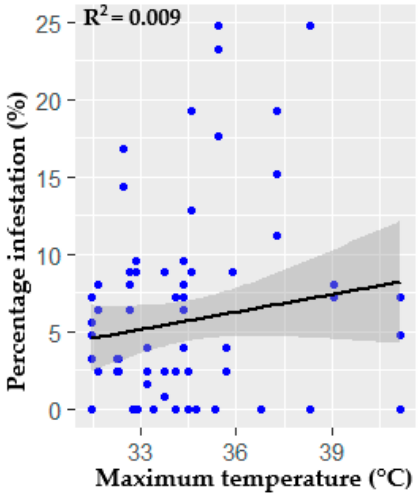


Figure 6. Effect of maximum temperature on *P. longifila* infestation in greenhouses.

In greenhouses, *B. bassiana* showed the highest efficacy (100%), followed by *B. thuringiensis*, abamectin, and spinetoram. The biorational *A. indica* showed efficacy of 43% and 74% at thresholds of 14% and 15%. Spinetoram reached 87% efficacy at a threshold of 27%. Abamectin reached 100% efficacy at a threshold of 25%, and 71% and 82% efficacy at thresholds of 9% and 15%, respectively. It is important to highlight that microbial insecticides were applied to other pests, and that *P. longifila*, by sheltering in shoots, is partially out of reach of these products. Therefore, spinetoram (86.6%) and abamectin (80.7%) are the most effective formulations for this pest (Table 4).

Table 4. Comparison of pesticide effectiveness in the two cropping systems.

Pesticides Used in the Open Field	Efficacy (%) *	Pesticides Used in the Greenhouse	Efficacy (%) *
A. indica	37 a	*A. indica*	52.5 a
Abamectin	58.5 a	*B. thuringiensis*	100 ab
Spinetoram	70.6 a	*B. bassiana*	100 b
Imidacloprid	88 a	Abamectin	80.7 ab
Thiamethoxam + lambda-cyhalothrin	47.8 a	Spinetoram	86.6 ab
Acetamiprid	86.4 a	Thiamethoxam + lambda-cyhalothrin	89.9 b

* Different lowercase letters indicate statistically significant differences among treatments (Tukey's HSD test, $p < 0.05$).

3.2.2. *Frankliniella occidentalis* Pergande, 1895

In the open field, *F. occidentalis* infestation was extremely low, with an expected value of 0.00007 individuals per plant and no significant effects of temperature or humidity (Table 5). The wide confidence intervals are associated with the low pest pressure on the crop, likely due to intensive applications targeting *P. longifila*.

Table 5. GLMM (Tweedie) parameter estimation for *F. occidentalis* infestation in field and greenhouse systems.

Systems	Parameter	Estimate *	IC 95% *	Z Value	*p*-Value
Open field	Intercept	0.00007	[2.28×10^{-7}, 0.02]	−3.279	0.0010 **
	Mean temperature	0.60	[0.001, 292.6]	−0.160	0.8730 ns
	Maximum temperature	1.35	[0.029, 62.94]	0.153	0.8786 ns
	Mean relative humidity	1.18	[0.19, 7.48]	0.178	0.8590 ns
Greenhouse	Intercept	0.01	[0.0006, 0.11]	−3.601	0.0003 **
	Mean temperature	3.40	[0.18, 64.3]	0.816	0.415 ns
	Maximum temperature	2.39	[0.62, 9.19]	1.273	0.203 ns
	Mean relative humidity	1.92	[0.82, 4.50]	1.496	0.135 ns

* Estimate and IC 95% original scale. Z values on a logarithmic scale. Significance levels: ** $p < 0.001$ (highly significant); ns = not significant.

In the greenhouse, infestation was also low (0.008 individuals/plant), concentrated only in the first few weeks. The observed values remained below the intervention threshold (0.5 individuals), indicating minimal economic risk.

F. occidentalis represented an entomological problem in the greenhouse system at three specific time points, and applications of *A. indica* achieved partial reductions (22–36%). However, this pesticide was discontinued from the application program due to the burning it caused, and applications of abamectin and spinetoram were required to achieve complete suppression (Table 6).

Table 6. Comparison of the effectiveness of pesticides in greenhouses.

Pesticides Used in the Greenhouse	Efficacy (%) *
A. indica	38.9 a
Spinetoram	100 a

* Different lowercase letters indicate statistically significant differences among treatments (Tukey's HSD test, $p < 0.05$).

In the open field, abamectin and spinetoram showed comparable efficacy (100%). Although no statistically significant differences were detected, spinetoram had a significantly higher mean efficacy (100%). The variance explained by the model (marginal $R^2 = 1$) indicates that efficacy depended primarily on the pesticide type, while the effect of the assessments was uninformative due to the low infestations of this insect.

3.2.3. *Polyphagotarsonemus latus* Banks, 1904

In the open field, the presence of P. *latus* was minimal, being detected only in one evaluation with an average of nine plants with symptoms. The GLMM intercept was significant ($p = 0.0316$), but the wide confidence intervals reflected the high uncertainty associated with the low infestation (Table 7). None of the climatic parameters showed an effect on the population, indicating that the pest was effectively suppressed in this system. In the greenhouse, populations were higher, although without statistical significance for either the intercepts or the evaluated climatic parameters, suggesting that other factors, such as internal reproduction and the mite's biology, determine its population dynamics.

The mite population exceeded the treatment threshold on several dates, with infestations of 6–8 plants per sampling unit. Characteristic foliar damage was observed: roughness, thickening, and curling of young leaves, without symptoms of TSWV, confirming that the foliar deterioration was exclusively caused by *P. latus* (Figure 7).

Table 7. GLMM (Tweedie) parameter estimation for *P. latus* infestation in field and greenhouse systems.

Systems	Parameter	Estimate *	IC 95% *	Z Value	*p*-Value
Open field	Intercept	0.00005	$[1.42 \times 10^{-8}, 0.15]$	−2.150	0.0316 **
	Mean temperature	1.50	[0.0001, 27,391.8]	0.082	0.9350 ns
	Maximum temperature	1.46	[0.006, 380.9]	0.133	0.8940 ns
	Mean relative humidity	1.21	[0.07, 21.00]	0.133	0.8943 ns
Greenhouse	Intercept	0.65	[0.24, 1.77]	−0.844	0.3988 ns
	Mean temperature	0.82	[0.12, 5.47]	−0.202	0.8396 ns
	Maximum temperature	2.06	[0.89, 4.81]	1.676	0.0937 ns
	Mean relative humidity	1.35	[0.77, 2.36]	1.036	0.3002 ns

* Estimate and IC 95% original scale. Z values on a logarithmic scale. Significance levels: ** $p < 0.05$ (significant); ns = not significant.



(**A**) (**B**) (**C**)

Figure 7. Damage caused by *P. latus* in a greenhouse. (**A**,**B**) leaf shine and (**C**) leaf blade deformation.

In Table 8, the analysis of acaricide efficacy in the greenhouse showed a high explanatory power of the model (marginal $R^2 = 0.998$). Abamectin reached 100% efficacy, followed by *B. bassiana* (66.97%), while *A. indica* showed limited efficacy (4–7%).

Table 8. Comparison of the effectiveness of pesticides in greenhouses.

Pesticides Used in the Greenhouse	Efficacy (%) *
A. indica	4.35 a
B. bassiana	66.97 b
Abamectin	100 b

* Different lowercase letters indicate statistically significant differences among treatments (Tukey's HSD test, $p < 0.05$).

3.2.4. *Spodoptera sunia* Guenée, 1852

Table 9 shows that in the open field, the GLMM intercept was highly significant ($p < 0.001$), indicating an expected infestation of 4.76 larvae per plant, above the treatment threshold (3 larvae). No climatic parameter showed a significant effect, and the low marginal R^2 (0.048) reflected that climatic variables contributed minimally, while the conditional R^2 (0.587) indicates that most of the variability is associated with differences between evaluations, probably related to external foci.

Table 9. GLMM (Tweedie) parameter estimation for *S. sunia* infestation in the field.

Systems	Parameter	Estimate *	IC 95% *	Z Value	*p*-Value
Open field	Intercept	4.78	[2.87, 7.95]	6.027	0.001 **
	Mean temperature	0.98	[0.45, 2.12]	−0.064	0.949 ns
	Maximum temperature	1.10	[0.68, 1.78]	0.381	0.703 ns
	Mean relative humidity	1.10	[0.87, 1.39]	0.766	0.443 ns

* Estimate and IC 95% original scale. Z values on a logarithmic scale. Significance levels: ** $p < 0.001$ (highly significant); ns = not significant.

Table 10 shows that the analysis of pesticide efficacy revealed no significant differences between treatments, although the numerical efficacies varied. *A. indica* and spinetoram presented efficacy percentages between 60–100% over thresholds of 7–15% and 56–100% over thresholds between 15–20%, respectively. Abamectin was not effective, even being associated with population increases. Among the biopesticides, *B. thuringiensis* reached 37% and *B. bassiana* 50%, while thiamethoxam + lambda-cyhalothrin showed variable efficacy, possibly due to interaction with other applications or overlapping generations. The results highlight the efficacy of spinetoram, *B. thuringiensis*, and *A. indica*, with average ranges of 70.8–72.4%.

Table 10. Comparison of pesticide efficacy in the open field.

Pesticides Used in the Open Field	Efficacy (%) *
A. indica	70.84 a
B. thuringiensis	71.36 a
B. bassiana	35.82 a
Abamectin	49.90 a
Spinetoram	72.40 a
Thiamethoxam + lambda-cyhalothrin	49.48 a

* Different lowercase letters indicate statistically significant differences among treatments (Tukey's HSD test, $p < 0.05$).

In the greenhouse, the model was not conclusive due to low pest pressure. Nevertheless, *S. sunia* exceeded the treatment threshold on six occasions, highlighting the 100% efficacy of *B. thuringiensis* in three applications. Abamectin also showed high efficacy, whereas *B. bassiana*, *A. indica*, and spinetoram did not consistently reduce populations, with subsequent increases even observed. The punctual reduction of 25% with *B. bassiana* suggests a limited effect due to low population pressure or residues from other pesticides (Figure 8).

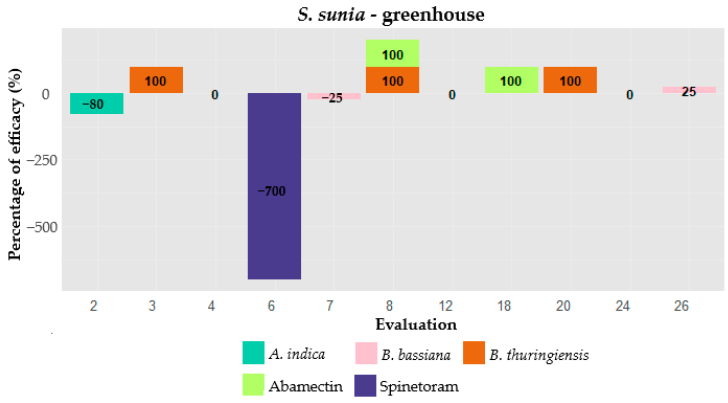


Figure 8. Percentages of S. sunia effectiveness in greenhouses; negative values indicate an increase in the pest population in treated plants, suggesting low or no efficacy of the product under these conditions.

3.2.5. *Diabrotica* sp., Chevrolat, 1837

In open field, GLMM analysis showed no significant effects of climatic parameters on *Diabrotica* sp ($p > 0.05$). *Diabrotica* sp. exceeded the treatment threshold during six consecutive evaluations, with infestations affecting between 6 and 18 plants per sampling unit (Table 11).

Table 11. GLMM (Tweedie) parameter estimation for *Diabrotica* sp. infestation in the field.

Systems	Parameter	Estimate *	IC 95% *	Z Value	*p*-Value
Open field	Intercept	0.006	$[2.7 \times 10^{-5}, 1.37]$	−1.845	0.0650 ns
	Mean temperature	6.00	[0.07, 544.2]	0.779	0.4360 ns
	Maximum temperature	1.26	[0.045, 35.67]	0.136	0.8920 ns
	Mean relative humidity	2.42	[0.56, 10.47]	1.185	0.2360 ns

* Estimate and IC 95% original scale. Z values on a logarithmic scale. Significance levels: ns = not significant.

The confidence intervals are wide because the pest was present during the first weeks of cultivation, which increased the variability between assessments. However, diagnostic tests confirmed the stability and adequacy of the fitted models.

The analysis of pesticide efficacy showed that *A. indica*, abamectin, and spinetoram were ineffective, with a slight population increase observed after their application. B. *thuringiensis* showed an apparent efficacy of 100%. However, this effect cannot be directly attributed to biopesticide, as its action does not affect adult beetles (Table 12). This suggests that the observed reduction could be due to environmental factors or the residual effect of previous applications targeting *P. longifila*. The model presented a marginal R^2 of 1, while the conditional R^2 was not estimable, indicating that all the explained variance is associated with the treatments and that repeated evaluations did not contribute significantly.

Table 12. Comparison of pesticide efficacy in the field.

Pesticides Used in the Open Field	Efficacy (%) *
A. indica	25 a
B. thuringiensis	100 a
Abamectin	16.6 a
Spinetoram	14.5 a

* Different lowercase letters indicate statistically significant differences among treatments (Tukey's HSD test, $p < 0.05$).

3.2.6. *Bemisia tabaci* Gennadius, 1889

In both cropping systems, open field and greenhouse, the low observations of *B. tabaci* and the intensity of the applied treatments hindered precise estimation of the GLMM, generating coefficients with very wide confidence intervals and high uncertainty. This suggests that the population pressure was minimal during the trial, probably because of intensive management targeting other pests.

4. Discussion

P. longifila is considered the most problematic pest on the Ecuadorian Coast, present from seedling to production, with infestation levels generally exceeding the treatment thresholds. In this study, infestations in the open field exceeded 60% during the months of highest infestation in August and September, and in the greenhouse reached 22%. These results are consistent with Peña et al. [51], who highlighted the occurrence of the pest throughout the year in both systems. Similarly, Valarezo et al. [13] documented up to 50% infestation in the field. Additionally, the evaluated greenhouses were covered with

saran-type shade netting with thread spacing of approximately 2.5–3 mm and openings between the roof and sides, which facilitated the entry of insect vectors and *P. longifila*. In contrast, in the present study, the installation of aphid-proof mesh (0.98 × 0.64 mm) without openings functioned as an efficient physical barrier, limiting the re-entry of *P. longifila* and preventing the entry of larger pests such as *Diabrotica* sp.

Regarding pesticides, all evaluated products showed efficacy in the field, but their choice and effectiveness depended on infestation levels. *A. indica* was suitable for low infestations (10–15%), whereas abamectin and spinetoram were effective at moderate levels (16–25%), consistent with Lopez & Liburd [52] on the efficacy of spinetoram against the gall midge *Dasineura oxycoccana*. In extreme infestations, neonicotinoids such as imidacloprid and acetamiprid reduced populations to 0% when infestation reached 67%, in agreement with Valarezo et al. [13], who used thiamethoxam and imidacloprid to reduce infestations below the threshold. These decisions align with the IPM approach, which allows data-driven decisions on the necessity and timing of pest management interventions, prioritizing biorational and "reduced-risk" products first and reserving higher-impact molecules for epidemic peaks or late outbreaks [31]. In the greenhouse, although *B. bassiana* reached 100% efficacy, its effect is not entirely attributable to this entomopathogen, since the applications were foliar and *P. longifila* larvae shelter in young shoots, unlike the study by Cedano & Cubas [53], who reported higher potential through soil applications. Other products, such as thiamethoxam + lambda-cyhalothrin and the biorationals spinetoram and abamectin, exceeded 80% efficacy, consistent with Cardona et al. [54], where abamectin was highlighted as the most effective, followed by thiamethoxam + lambda-cyhalothrin.

The highly significant intercepts of *F. occidentalis* indicate that this pest can reach infestation levels even under normal temperature and humidity conditions, being more problematic in the greenhouse, where it exceeded the treatment threshold in several evaluations during the first weeks of the crop. However, climatic parameters did not show a significant effect on its abundance, despite being within the optimal range for the insect (25.2–34.4 °C; RH 79.4–81.6%). Steiner et al. [55] demonstrated that relative humidity above 80% favors larval survival, being optimal for pupae around 90%, while lower levels affect survival and distribution within crops. Zhang et al. [56] indicate that temperatures between 20–25 °C prolong adult longevity and reproduction, whereas at 30 °C adult longevity and nymph numbers decrease. Recent studies show that thrips can tolerate 35–37 °C due to increased antioxidant enzymes such as SOD, POD, and GST, although these defenses decline near 41 °C [57]. Therefore, thermal stress can be used as a physical control method, achieving reductions of up to 84.5% in adult density with exposures of 42–46 °C for 2 h, as determined by Zhang et al. [58], although prolonged use is limited by thrips' thermal tolerance and crop sensitivity [59]. Furthermore, brief exposures to sublethal low or high temperatures increase thrips survival [60].

Regarding chemical control, spinetoram achieved total control (100%) of *F. occidentalis*, clearly surpassing *A. indica*, which reached only 38.9%. The high efficacy of spinetoram is due to its semisynthetic origin from spinosyns J and L, with a broad spectrum and residual activity [43], although its use requires caution due to the risk of resistance development by several thrips' species, including *F. occidentalis* [61]. In contrast, *A. indica* showed limited efficacy, consistent with its slower action and anti-reproductive effect. Previous studies indicate that it can inhibit fecundity, prolong preoviposition, and is more effective in systemic soil applications targeting pupae [62]. Thus, the combination of neem as a population regulator and spinetoram as a shock tool constitutes an integrated strategy that allows delaying resistance and reducing dependence on synthetic insecticides.

The white mite *P. latus* is a common polyphagous pest in greenhouses [63], and its body dimensions between 0.10 mm and 0.2 mm allow access to greenhouses covered with

netting; therefore, it does not offer a total physical exclusion for this species [64]. It is also able to select more attractive hosts due to the induction of jasmonic acid in tomato, which affects its behavior and degree of damage [22]. In Ecuador, it is not considered a relevant tomato pest; however, in our trials, it predominated in the greenhouse, exceeding treatment thresholds from the beginning of the crop and causing characteristic symptoms such as reduced growth, downward-folded leaves, and bronzed appearance, associated with epidermis ablation and mesophyll cell compaction [22]. In open field, its presence was sporadic, with minor damage, probably due to intensive pesticide applications targeting *P. longifila*. Although conditions of 25.2–34.4 °C and 79.4–81.6% RH are favorable for the mite [65], climatic parameters did not show a significant effect on infestation. The intercepts showed that, under normal conditions, infestations were very low in the field (0.00004) and higher in the greenhouse (0.65), indicating that other factors, mainly pesticide applications, determined its population dynamics. Abamectin showed total efficacy (100%) in both systems, whereas *B. bassiana* reached 66.97%, agreeing with previous reports where abamectin significantly affected mite population growth and acted as a repellent, and *B. bassiana* achieved mortalities of 57–70% in the greenhouse and up to 66% in the field depending on the strain [66].

Spodoptera sunia populations were detected from early crop stages, exceeding the treatment threshold on several occasions, with the highest records during flowering and fruit set in the open field. The intercept indicated that, under normal temperature and humidity conditions, infestation is expected; however, the analysis of climatic parameters individually showed no direct influence, likely because intensive pesticide applications prevented insect establishment. Spinetoram, *B. thuringiensis*, and *A. indica* showed high efficacy percentages of 72.4%, 71.4%, and 70.8%, respectively, in the field, whereas in the greenhouse, abamectin and repeated applications of *B. thuringiensis* achieved 100% control. These results are consistent with studies on related species, such as *Spodoptera littoralis*, where abamectin toxicity decreases in late instars but shows a notable increase in efficacy in sixth-instar larvae, due to differential toxicity depending on metabolic processes [67], and spinetoram reduces adult emergence by more than 75% [68], whereas *B. thuringiensis* in commercial formulations achieves mortalities higher than 70% when concentration and instar are adjusted [69]. In contrast, *A. indica* in *S. litura*, at doses of 12 µL/L, decreases larval weight, pupation (up to 27.8%), and emergence (37.2%) after 5–7 days, especially in young instars [70], and induces apoptosis in the midgut [39]. These findings suggest that azadirachtin acts primarily as a population retardant rather than an immediate lethal insecticide, serving as a valuable complement in integrated pest management (IPM) strategies.

In Ecuador, *Diabrotica* sp. is mainly recognized in crops such as watermelon, melon, and cucumber, where adults cause circular perforations in the leaves, resulting in significant damage to young plants [71]. In our study, the entry of this pest into the greenhouse was effectively prevented by the aphid-proof mesh; however, in the open field, populations exceeded treatment thresholds on several dates, being particularly notable up to 30 days after transplant, generating extensive foliar perforations that required control applications. This coincides with Gallo et al. [72], who reported that the tomato leaf beetle *Diabrotica speciosa* causes productive losses due to defoliation at the beginning of the crop, potentially destroying it completely if not controlled in time. Statistical analysis did not show a direct effect of climatic parameters on *Diabrotica* sp., probably due to intensive pesticide applications, although the average relative humidity of 81.6% could favor defoliation and colonization, as indicated by Antonie & Spánu [73], who associate defoliation with humidity and its ability to colonize new areas. Moreover, oviposition is favored by humidities between 22–63% [74], requiring the use of insecticides such as beta-cyfluthrin, methamidophos, acephate, and methyl parathion, which are considered effective for controlling

this insect [75]. Although *Diabrotica* sp. is not considered a primary pest in tomato, its occasional presence can cause significant damage if not managed promptly. Among the pesticides evaluated, *B. thuringiensis* reached 100% efficacy; however, this result is probably not attributable to the *kurstaki* subspecies (Btk), which mainly acts on Lepidoptera, and the observed mortality is more likely due to additional factors such as the effect of other pesticides that showed statistical equivalence, including *A. indica*, abamectin, and spinetoram. Although spinetoram is a molecule targeted to lepidopterans, recent studies show its significant efficacy against stored-grain coleopterans, such as *Tribolium castaneum* and *Acanthoscelides obtectus*, achieving mortalities above 90% in appropriate applications. This suggests that spinetoram could contribute to the control of *Diabrotica* sp., although specific evidence is still emerging [76]. Furthermore, Vörös & Ledóné [77] demonstrated that seed treatment with concentrations higher than 50% of *A. indica* significantly reduced larval density and root damage. In coleopterans, this active ingredient has been observed to act as a repellent and development retardant, effects that could contribute to indirect mortality or population suppression in *Diabrotica* sp. [78].

In summary, the dynamics of tomato pests showed a strong dependence on the cultivation system and applied management, with *P. longifila* being the most persistent and limiting species in both environments. Other pests, such as *S. sunia*, *F. occidentalis*, *P. latus*, and *Diabrotica* sp., responded differentially to treatments and the cultivation system, highlighting the effectiveness of strategies based on biorationals and active ingredient rotation to minimize resistance risks. Climatic parameters played a secondary role because pesticide applications prevented their establishment, while factors such as pest re-entry, mitigated by physical barriers in greenhouses, explained much of the observed variability. These findings demonstrate that the use of greenhouses in the Ecuadorian coast is feasible, as internal pest populations can be managed with low-toxicity pesticides, given that aphid-proof mesh effectively limits pest re-entry.

5. Conclusions

Greenhouses, combined with physical barriers and low-toxicity pesticides, significantly reduced pest pressure compared to open-field cultivation

Pesticide efficacy depended on infestation levels and the product used: biorationals such as *A. indica*, *B. thuringiensis*, and *B. bassiana* allowed partial pest population recovery, while synthetic insecticides, including abamectin, spinetoram, and neonicotinoids, were more effective at moderate to high infestation levels. The combination of products with different modes of action and selectivity aligns with Integrated Pest Management (IPM) strategies, prioritizing biorationals at low infestation levels to minimize disruption before using higher-toxicity insecticides.

Among the pests studied, *P. longifila* and *S. sunia* were the most problematic, while others remained manageable through targeted strategies.

Integrating physical barriers, continuous monitoring, and staged applications provides a solid foundation for sustainable IPM. This study demonstrates that integrating physical barriers with staged pesticide use optimizes pest control while reducing chemical inputs, offering a sustainable IPM approach for tomato crops on the Ecuadorian coast.

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