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# Climate-driven integrated management of *Neohydatothrips signifer* (Thysanoptera: Thripidae) to improve sustainability and export compliance in yellow passion fruit from Huila (Colombia)

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**Introduction:** Yellow passion fruit (*Passiflora edulis* f. *flavicarpa*) is a key tropical crop in Colombia, with export potential limited by thrips *Neohydatothrips signifer* infestations. The objective of this study was to propose and implement an integrated thrips management strategy that complies with the phytosanitary requirements of the European market. This strategy combined climatic models, environmental indicators, insecticide efficacy assessments, and an economic analysis to promote sustainability and regulatory compliance in export-oriented production.

**Methods:** Field monitoring was conducted from 2022 to 2024 in a commercial orchard located in Suaza, Huila, southern Colombia. Thrips populations were distributed across sampling points, applying a standardized tapping method on vegetative terminals. Climate variables such as temperature, relative humidity, precipitation, and solar radiation were recorded and analyzed using regression-based models to predict pest dynamics, monitored twice per week across nine experimental units using 54 randomly distributed sampling points. Insecticide efficacy, individually and in mixtures, was evaluated using a modified Abbott model, while environmental impact was quantified based on the Environmental Impact Quotient (EIQ). Economic analysis was conducted to estimate thrips management costs in relation to the phytosanitary strategy.

**Results:** Thrips populations peaked during flowering (>20 individuals per terminal shoot) and declined under higher rainfall, with abundance significantly correlated with minimum temperature ( $r = 0.63$ ) and relative humidity ( $r = -0.57$ ;  $p < 0.05$ ). The best climate-based predictive model was the negative binomial, with temperature and rainfall as the main drivers. Insecticide mixtures did not improve the efficacy of control applications, with antagonistic interactions being observed on several

occasions. The Environmental Impact Quotient (EIQ) associated with chemical applications during the study period was 19.7, while residue analyses confirmed compliance with European Union maximum residue limits (EU MRLs).

**Discussion:** Thrips management accounted for 38% of total phytosanitary costs, with the highest expenditures occurring during the flowering (42%) and fruiting (35%) stages. These results show that combining predictive climate models, targeted insecticide mixtures, and sustainability management improves thrips management efficiency, cost effectiveness, and export compliance.

#### KEYWORDS

botanical insecticides, maximum residue levels, pesticides, phytosanitary problems, temperature

## 1 Introduction

In Colombia, yellow passion fruit “*Passiflora edulis* f. *flavicarpa*” (Degener, 1932) is one of the most important passion fruit species due to its economic potential (Ocampo et al., 2013). Despite the increase in crop production in recent years, exports to European Union countries have been constrained by rising infestations by the insect pest “*Neohydatothrips signifer*” or also called “Thrips”. *N. signifer* attacks the vegetative terminals of the plant, sealing them and inhibiting their development (Monje et al., 2012).

Several studies have reported that *N. signifer* populations are directly influenced by climatic variables, particularly temperature (Atakan, 2024; Santos Amaya et al., 2012; Shafique et al., 2025). Therefore, climate must be considered a key factor in the management of these insect pests. The study of Cao et al. (2018) demonstrated the optimal development and reproduction for *Thrips hawaiiensis* at 27°C. At this temperature, the insect reached its highest survival rate (75%), fecundity (95.80 eggs), and intrinsic rate of increase (0.200). On the other hand, high relative humidity associated with rainfall can negatively influence population size (Waijanjo et al., 2008). In relation to prediction models, some studies have evaluated several regression models including linear models, machine learning models and generalized linear models, to predict the thrips populations in function of environmental variables (Kucharczyk et al., 2019; Devi and Mahadevappa, 2021; Dos Santos et al., 2022; Porta et al., 2025; Shafique et al., 2025).

The use of pesticides for pest control and to enhance agricultural productivity has been crucial for agriculture in recent years (Mao et al., 2022). However, excessive application may lead to the development of resistance to these products by the target organisms (Boedeker et al., 2020; Warpechowski et al., 2024; Gao et al., 2012). Furthermore, non-controlled applications may also result in the non-compliance with European Parliament regulations on Maximum Residue Limits (MRLs) of pesticides allowed in food products (from plant and

animal origin), imposed to safeguard consumer health and mandatory for entering the European market (EUR-Lex, 2023) and may cause negative effects on the environment (FAO, 2008; Mwangi et al., 2020; Muhammetoglu and Uslu, 2007).

Pesticides, and specifically products for the control of arthropod pests in crops, are often used by farmers in the form of mixtures with the objective to obtain a better effect on the target organism to improve effectiveness, selectivity and resistance mechanisms (Bisset, 2002; Tabashnik, 1989). However, these mixtures may have resulted in antagonistic effects, reducing overall control efficacy. (Lindquist, 2002). In order to increase the likelihood of identifying solutions to phytosanitary problems, different methodologies can be used to diagnose the main constraints affecting farmers and to understand how these problems are currently managed, as a first step toward participatory work. One of them is the Participatory Rural Appraisal (PRA), which has been successfully applied in some countries such as India (Banerjee et al., 2020). Likewise, farmers’ perception and knowledge of the phytosanitary problems they have in their crops is important to generate solutions (Rezaei et al., 2020; Karar et al., 2021; Islam et al., 2020; Nabirye et al., 2003; Nkunika, 2002), as is the joint work between researchers and farmers to achieve them (Zoundji et al., 2024).

In this research, the aim was to test a phytosanitary management scheme for thrips (*N. signifer*) in an export-type yellow passion fruit crop that complies with European market standards. The study was based on an interactive process between researchers and yellow passion fruit growers from the ASOPROFRUG Suaza association in the municipality of Suaza (Huila, Colombia). The outcome was a management proposal that included continuous monitoring of the phytosanitary problems under study, the use of products of different origin (biological, botanical, mineral, chemical) and agronomic practices. The use of climatic models and environmental indicators, together with analyses of insecticide efficacy and economic performance.

## 2 Materials and methods

### 2.1 Location of the research project

The monitoring campaign was conducted in a commercial yellow passion fruit orchard located in Suaza, southern Colombia (1°52'33.291" N, 75°49'0.467" W), at 962 m a.s.l., with a total area of 2 ha. The experiment was conducted during three consecutive years, from 2022 to 2024. According to the land suitability map developed by UPRA (Unidad de Planificación Rural Agropecuaria – UPRA, 2020), the site is classified as highly suitable for passion fruit cultivation (Figure 1). The location has an average annual temperature of 22.3°C and an average precipitation of 731 mm.

### 2.2 Integrated pest management practices

#### 2.2.1 Participatory meetings

Prior to the initiation of the field study, several surveys were conducted with passion fruit farmers from the ASOPROFRUG SUAZA association to document crop characteristics, agronomic practices, and the occurrence and management of pests and diseases. Based on this information, a workshop on pest and disease management (IPM) was carried out which included both exporting and non-exporting producers. During this workshop,

production constraints were identified and prioritized, with *N. signifer* being recognized as the most critical factor limiting crop system performance. Consequently, a management strategy was proposed.

#### 2.2.2 Integrated pest management strategy

Based on the information obtained from the literature review, farmers surveys, and the participatory phytosanitary workshops, an integrated phytosanitary management plan was proposed, led by the project's research team and approved by the producers belonging to the association. The strategy considered several pests, with particular emphasis on thrips, since inadequate management increases the risk of exceeding maximum residue limits (MRLs), which restricts passion fruit access to the European market. The proposed management approach was structured around systematic monitoring adoption of adequate crop management practices including the application of products of different origins (chemical, botanical, biological, and mineral). Applications were determined according to products type, doses, pre-harvest interval, crop phenology, damage thresholds, and the estimated harvest dates. The entire study area received applications of thrips control products. During crop development, complementary practices were implemented to support *N. signifer* control, including the placement of blue and yellow plastic traps coated with agricultural glue on the stakes. Weed control was

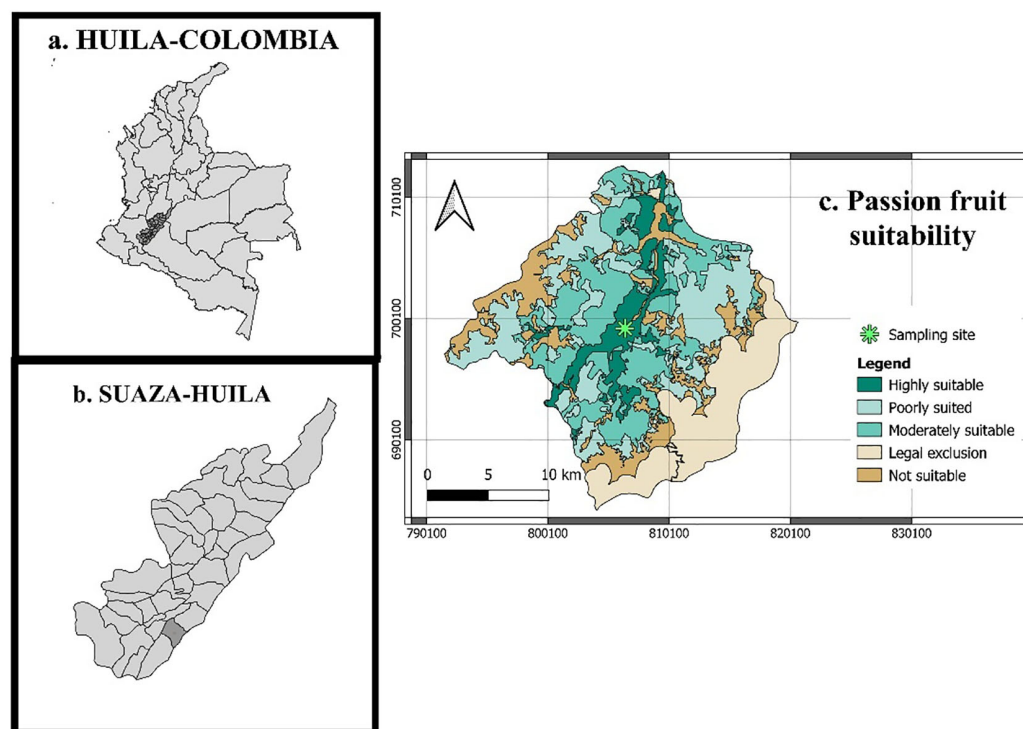


FIGURE 1

Monitoring location map. (a) Geographic location of Colombia, (b) Geographic location of Huila department, (c) Suitability map for yellow passion fruit (*Passiflora edulis* f.) cultivation, highlighting zones of high, moderate, poorly suitable, not suitable and legal exclusion. The map is adapted from the UPRA (Unidad de Planificación Rural Agropecuaria – UPRA, 2020) suitability zoning study conducted at a 1:100,000 scale. The experimental site is indicated with a green asterisk.

carried out periodically. Insecticides were applied sporadically to the weeds and the soil.

All applications were carried out uniformly within the experimental plot, and the application dates of each pesticide were recorded. The doses applied corresponded to the manufacturer's recommendations. Decisions regarding the application of phytosanitary products were based on three considerations: (1) the current phenological stage of the crop, (2) the pre-harvest interval (during the fruiting stage, only products without a pre-harvest interval were applied), and (3) the incidence of thrips, with applications performed when more than 50% of the evaluated plants showed the presence of the insect.

## 2.3 Field data collection

### 2.3.1 Fruit sampling

To assess the effectiveness of the proposed phytosanitary management strategy for thrips in relation to European market export requirements, two random fruit samples were performed, one per harvest. Sampling followed the Instructions for Sampling of Agricultural Products for Pesticide Residue Analysis (Agrocalidad, 2018). Three 1-kg fruit samples were randomly collected in pre-labeled plastic bags, placed in a portable expanded-polystyrene (EPS) cooler, and transported under cold-chain conditions to the laboratory.

### 2.3.2 Maximum residue limit analysis

Samples from the first harvest (June 2023) were analyzed for 567 active substances at the A&T Food Control Laboratory, accredited by TURKAK (Turkish Accreditation Agency), following AOAC methods 985.07 and 2007.01. While samples from the second harvest (November 2023) were analyzed for 225 molecules at the pesticide residue laboratory of the AGROSAVIA C.I. La Libertad research center accredited by ONAC (National Accreditation Body of Colombia, according to the NTC 6412:2021-02-17 Colombian norms. The limit of detection (LOD) was 0.003 mg/kg, and the limit of quantification (LOQ) was 0.01 mg/kg. Both laboratories are certified under the international standard ISO/IEC 17025 (testing and calibration laboratory competence) and are recognized for pesticide residue detection. Sample preparation followed the QuEChERS method, and analyses were performed using high-performance liquid chromatography coupled with tandem mass spectrometry (HPLC-MS/MS) and gas chromatography with mass spectrometry (GC-MS/MS).

### 2.3.3 Climate variables

To ensure accurate climatic monitoring, an agricultural WS-ZL6B meteorological station was installed at the site. The information was recorded using a ZL6 METER GROUP datalogger during the period from October 2022 to January 2024. The station was equipped with an ECRN-100 rain gauge, a QSO-S PAR solar radiation sensor, an ATMOS 14 sensor for air temperature and relative humidity. Climate data were recorded daily.

### 2.3.4 Monitoring of *N. signifer* populations

Thrips monitoring was conducted as an observational study with no manipulation of experimental factors, following a spatially stratified random monitoring design under natural field conditions in a commercial passion fruit orchard of 1.8 hectares. The monitoring design consisted of nine sampling units (plots) systematically distributed across the orchard to ensure representative coverage of the area. Each sampling unit contained six passion fruit plants, with a total of 54 randomly selected sampling points over the whole field (Figure 2). At each monitoring event, the crop phenological stage was recorded. Monitoring was carried out from October 2022 to January 2024, evaluating one vegetative terminal per plant. Each terminal was tapped three times over a white surface, and all thrips individuals were counted regardless of developmental stage. Observations were conducted twice per week in the morning, when thrips are more active and exhibit greater movement (Zhang et al., 2023). The crop cycles included in the study were: vegetative 1, flowering 1, flowering 2, fruiting 1, fruiting 2, and vegetative 2 (Figure 3).

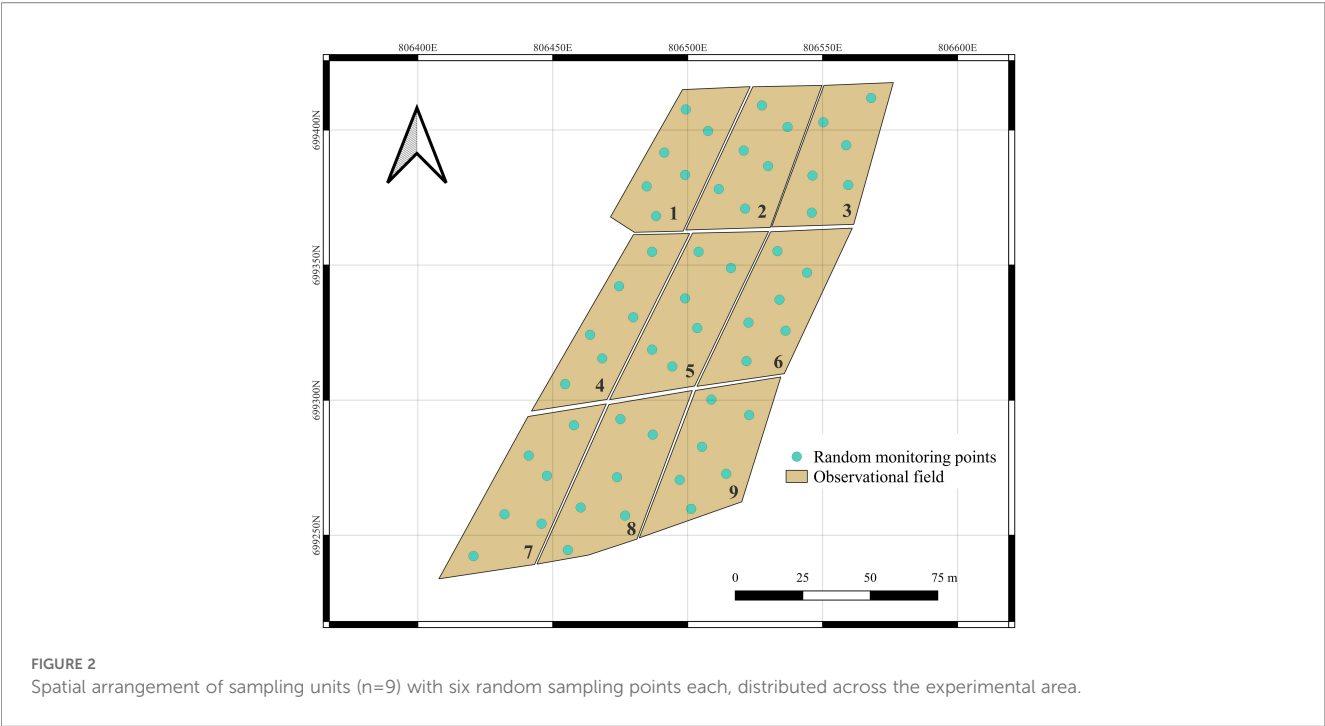
## 2.4 Statistical analysis

### 2.4.1 Correlation between thrips and climate

Abundance data of *N. signifer* were analyzed using descriptive statistics, calculating measures of central tendency and dispersion. Frequency histograms, box plots and multivariate temporal series were constructed to evaluate population distribution and compare variability across crop phenological stages. Prior to correlation analysis, data normality was assessed using the Shapiro-Wilk test for all climatic variables (temperature, rainfall, and relative humidity) and thrips population counts across seven phenological stages (two vegetative, two flowering, and two fructification stages). Most variables (89.3%, 25/28) showed non-normal distributions (Shapiro-Wilk test,  $p < 0.05$ ) (Supplementary Table 1). Consequently, Spearman's rank correlation coefficient ( $r_s$ ) was used for all analyses, as this non-parametric method does not require normality assumptions and ensures consistent methodology across all phenological stages (Schober et al., 2018).

### 2.4.2 Climate-based modeling of *N. signifer* populations

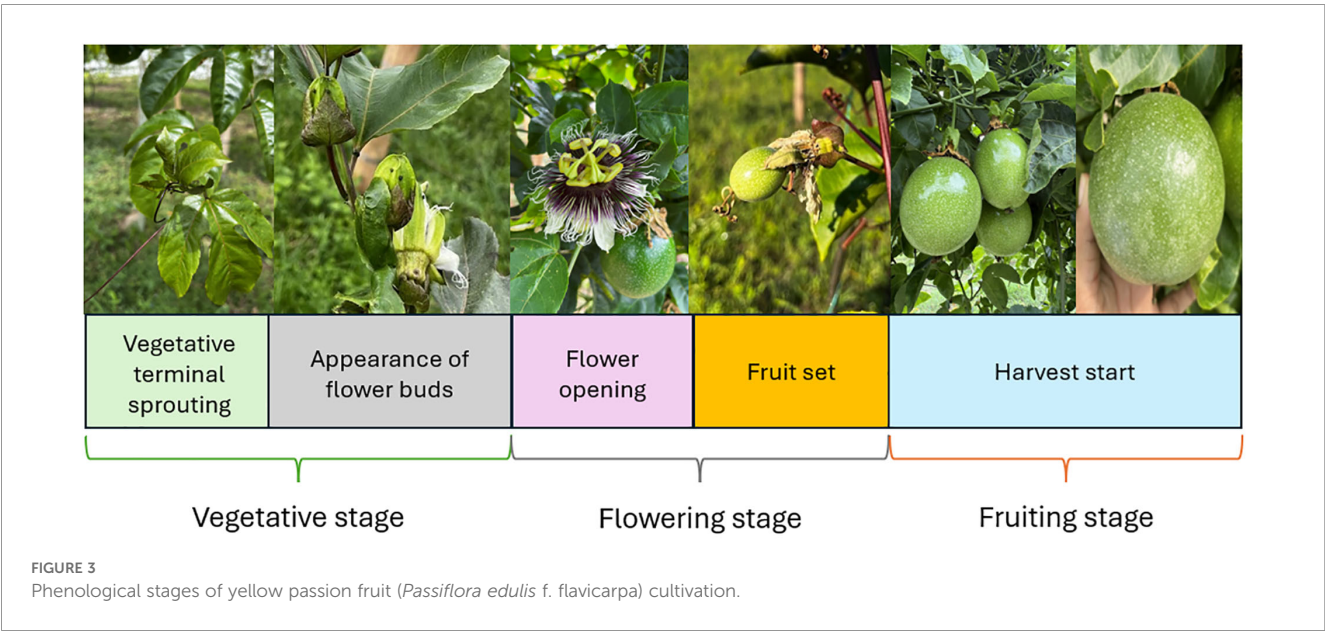
Scatterplots were made to assess the relationships between *N. signifer* populations and climatic variables at each phenological stage of the passion fruit crop. The dataset was divided into 70% for training and 30% for validation. Six generalized linear models were employed to predict *N. signifer* populations using phenological and climatic variables: two Poisson models (intercept-only and, two-way interactions), two negative binomial models (intercept-only, and two-way interactions) and two Conway-Maxwell Poisson (COM-Poisson) regression (intercept-only, and two-way interactions). The negative binomial and COM-Poisson models were assessed because the count data exhibited overdispersion (variance-to-mean ratio  $> 2$ ), contravening the equidispersion assumption inherent in Poisson regression (Forthmann and Doeblér, 2021). A stepwise model



selection process based on Akaike Information Criterion (AIC) criteria followed, using both forward and backward elimination methods.

Root means square error (RMSE) and means absolute error (MAE) were used to measure prediction accuracy. Pearson correlation coefficients between observed and predicted values, and the AIC and Bayesian Information Criterion (BIC) were used to compare the models. To evaluate the model assumptions, diagnostic tests were

implemented using the DHARMA package. First, a Kolmogorov-Smirnov test was performed to verify the uniformity of the scaled residuals, assessing whether they followed the expected distribution under the correctly specified model. Second, a nonparametric dispersion test was applied based on the comparison of the standard deviation of the observed versus simulated residuals. Third, a bootstrapped outlier test was performed to identify anomalous



extreme values by comparing the observed frequency of outliers with the theoretically expected frequency. These three tests provided a comprehensive assessment of the model's assumptions and the adequacy of the fit to the data. Multicollinearity was evaluated using the *check\_collinearity* function and the variance inflation factor. Analysis of variance (ANOVA) was used to determine the statistical significance of each predictor and interaction term. The final model was selected because it had the lowest AIC value, better predictive performance metrics, and biological interpretability of the interaction effects. All statistical analyses were performed using the statistical package R version 4.4.0 (R-Core Team, 2024).

## 2.5 Indicators of insecticide efficacy and environmental impact in thrips management

### 2.5.1 Efficacy of insecticides in single and mixed applications

Product efficacy was calculated based on monitoring data recorded for the nine experimental units, all of which received thrips control applications; therefore, no untreated absolute control was included in the present study. To estimate the individual efficacy of each product, populations of *N. signifer* were evaluated before and after application. Given the absence of an absolute control, treatment efficacy (%) was calculated using Equation 1 based on Abbott (1925) because it is a reference as adjusted by Albeltagy (2021):

$$\text{Efficacy (\%)} = ((Pb - Pa)/Pb) \times 100 \quad (1)$$

Where:

Pb: Population before application.

Pa: Population after application.

The combined efficacy of two or three active ingredients was assessed to establish whether it exceeded, matched, or fell below the efficacy expected from their individual effects, using the modified Abbott model, as follows:

For the mixture of two insecticides (Equation 2).

$$EE = E1 + E2 - (E1 \times \frac{E2}{100}) \quad (2)$$

And for the mixture of three insecticides (Equation 3):

$$EE = E1 + E2 + E3 - (((E1 \times E2) + (E1 \times E3) + \frac{(E2 \times E3)}{100}) + (\frac{(E1 \times E2 \times E3)}{10000})) \quad (3)$$

Where EE is the expected efficacy and E1, E2 and E3 are the individual efficacy (%) of each of the insecticides included in the mixture.

The observed efficacy (OE) was compared as follows:

- EO > EE: Synergy.
  - EO ≈ EE: Additivity.
  - EO < EE: Antagonism.
- (Colby, 1967).

Based on the above equations, average values of application efficacy were obtained for the products applied both individually and in mixtures.

### 2.5.2 Environmental impact of insecticides in thrips control

The Environmental Impact Quotient (EIQ) quantifies the potential impact of active ingredients on human health, non-target organisms and the environment. For the estimation of the EIQ For the estimation of the Environmental Impact Quotient (EIQ) generated by pesticide applications during the study period, the environmental impact calculator tool developed by Cornell University was used (Cornell CALS, 2024). This tool was designed taking into consideration the method proposed by Kovach et al. (1992) and Equation 4. EIQ value is first calculated for the active ingredient of each pesticide using the three components of the production system (farmer, consumer, and ecologist). After determining the EIQ for the specific active ingredient, the field-level EIQ can then be calculated.

$$EIQ_{Field*} = EIQ_{I.A**} \times \% \text{ Active ingredient} \times \text{Rate} \quad (4)$$

Where  $EIQ_{Field*}$ : Environmental Impact Quotient caused by a pesticide under field conditions. It includes the average three components:

$$EIQ_{Field} = \frac{(\text{Farmer component} + \text{Consumer component} + \text{Ecological component})}{3}$$

$EIQ_{I.A**}$ : Environmental Impact Quotient for the active ingredient (the calculator provides a reference database with standard values for each pesticide).

Active ingredient (%): Percentage of active ingredient in the pesticide formulation.

Rate: Application rate (dose).

After the  $EIQ_{Field}$  was determined for the total dose of each pesticide applied during the study period (seven active ingredients), the combined Environmental Impact Quotient (EIQ) was calculated as the sum of the individual impacts.

## 2.6 Cost allocation of thrips control within phytosanitary management

The economic analysis quantified the relative cost of insecticide applications for *N. signifer* control within the overall phytosanitary management of yellow passion fruit (*Passiflora edulis* f. *flavicarpa*). Records of pesticide applications between October 2022 and January 2024—including product type, date, dosage, and frequency—were combined with local market prices to calculate total expenditures on insecticides specifically targeting *N. signifer*. To capture the temporal dynamics of pest management, costs were disaggregated by phenological stage of the crop (Vegetative, Flowering, Fruiting). For each stage, expenditures on labor and products for thrips control were estimated and compared with the total cost of all phytosanitary

inputs applied in that stage (fungicides, bactericides, acaricides, and insecticides for other pests).

The proportion of resources allocated to thrips management was then calculated as the ratio of thrips control costs to the total phytosanitary cost per phenological stage, as well as at the crop level **Equation 5**. This procedure follows methodologies commonly applied in farm-level economic assessments of Integrated Pest Management (IPM), where pest-specific input costs are analyzed relative to total crop protection expenditures (Fleischer et al., 1999; Mwangi et al., 2020).

Thrips control cost (%)

$$= \frac{\text{Cost of inputs for } N. \text{ signifer}}{\text{Total phytosanitary input cost}} \times 100 \quad (5)$$

## 3 Results

### 3.1 IPM management strategy

The list of products used in the experimental plot (**Supplementary Table 2**) was compiled according to the characteristics of each pesticide. Additionally, products mentioned by farmers during the participatory phytosanitary workshop were included, and, as a final criterion, consideration was given to their accessibility to producers in terms of cost and availability. The products used in the management scheme represented different proportions according to their origin: biological (16%), botanical (20%), mineral (12%), and chemical (52%).

The analysis of maximum residue limits (MRLs) of pesticides included the evaluation of organochlorines, organophosphates, pyrethroids, (carbamates, triazines, benzimidazoles, neonicotinoids, anilides, dinitrophenols chlorophenoxy acids, substituted ureas and miscellaneous compounds. This analysis showed that fruit samples did not contain detectable pesticide residues <0.01 mg/kg in any of the

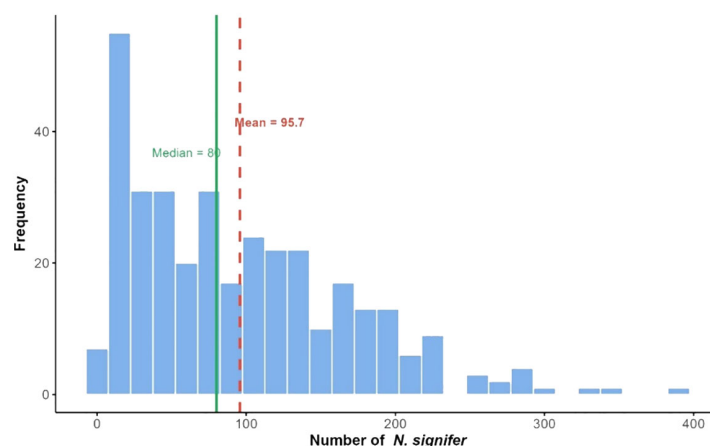
harvests evaluated in accordance with European Union regulations (Regulation (EC) No 396/2005 and amendment). These results demonstrate that the integrated phytosanitary management strategy for thrips, designed for export-oriented production, can be effectively applied to passion fruit cultivation under the conditions of Suaza, Huila, with a high probability of compliance with international MRL requirements.

### 3.2 Environmental determinants of *N. signifer* population variation

**Figure 4** shows a frequency histogram in the abundance distribution of *N. signifer* during the study period. The distribution presents a positive asymmetric pattern (right skewed). Most observations are concentrated at low abundance values. The population median was 80 individuals (green line), considerably lower than the mean of 95.7 individuals (red dashed line). Approximately 60% of records ranged from 0–100 individuals, whereas values above 200 were rare and represented sporadic population peaks.

The *N. signifer* populations showed different temporal patterns closely related to the phenological stages of the crop and seasonal temperature (**Figure 5a**). The highest densities were observed during the fruiting stages (Fr.1), exceeding 1,100 *N. signifer* individuals per sample in March 2023, when average temperatures ranged between 24 and 26°C. During the first vegetative stage (Veg.1), there was a steady rise from October to December 2022, reaching moderate densities of 200–300 individuals per sample. At the onset of flowering (Fl.1), populations ranged from 71 to 775 individuals per sample (mean ± SE: 368 ± 51), with the peak of 775 individuals observed in mid-January 2023.

During the second flowering stage (Fl.2) in July and August 2023, the populations were lower and more stable, with only 100 to 300 individuals per sample. A secondary fruiting period (Fr.2) in



**FIGURE 4**  
Frequency distribution of *Neohydatothrips signifer* abundance.

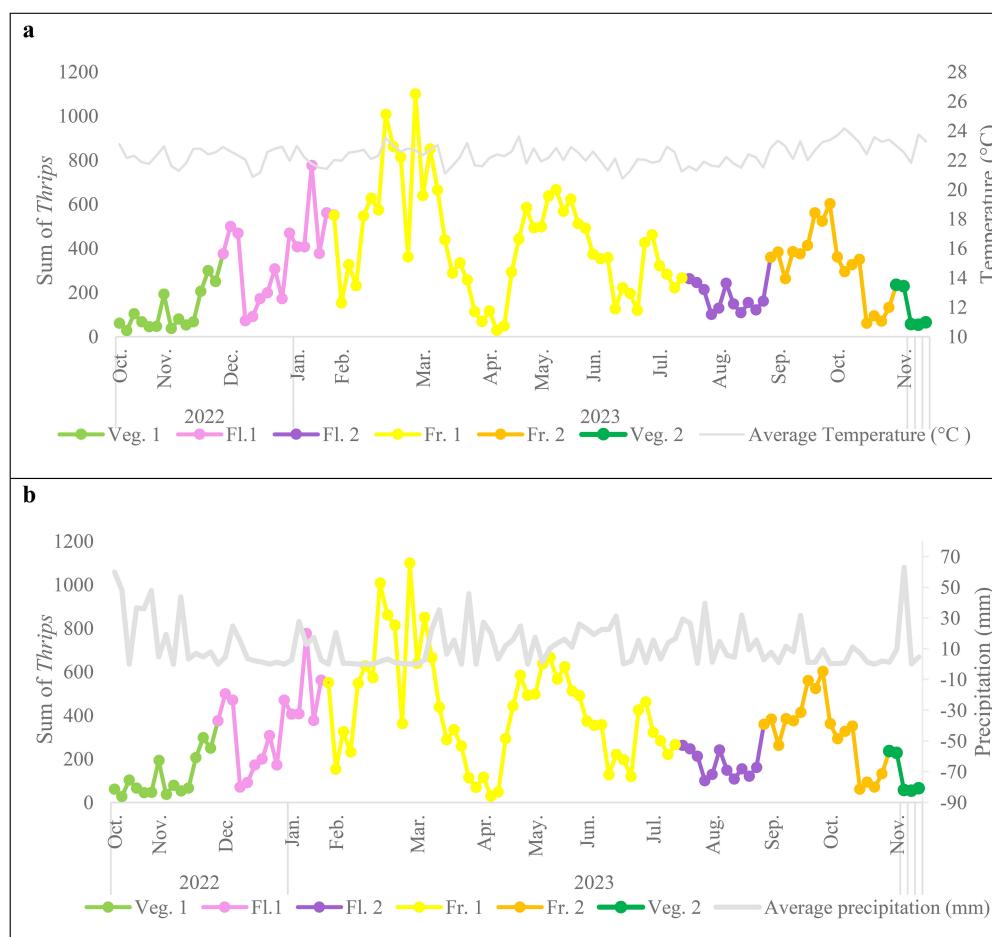


FIGURE 5

Seasonal population dynamics of *Neohydatothrips signifer* in relation to crop phenology. (a) And temperature variation. (b) And precipitation variation.

September–October 2023 showed moderate population recovery (300–600 individuals per sample) before declining during the final vegetative stage (Veg.2) in November 2023. *N. signifer* presented a strong phenological relationship with crop reproductive stages, with fruiting periods showing the most favorable conditions for population development.

The *N. signifer* populations exhibited variable responses to precipitation patterns throughout the study period (Figure 5b). During periods of high precipitation (40–60 mm) in October–November 2022, thrips populations remained low (50–150 individuals per sample), indicating possible adverse effects of excessive rainfall on population establishment. On the other hand, from December 2022 to March 2023, moderate precipitation levels (10–30 mm) were associated with some population increases, with peak densities of 1,100 individuals per sample. During the fruiting stages, the higher population peaks happened when there was moderate precipitation (15–25 mm). The second population peak in September–October 2023 corresponded with moderate precipitation levels (10–20 mm). These patterns suggest that

*N. signifer* populations are negatively affected by both drought stress and excessive rainfall, with intermediate precipitation levels providing the most favorable conditions for population growth.

### 3.2.1 Correlation with temperature

Figure 6 shows the correlation between *N. signifer* populations and climatic factors. In temperature, there were significant positive correlations at various phenological stages. The strongest correlations occurred during Vegetative 1 ( $r_s = 0.738$ ;  $p < 0.001$ ), Flowering 2 ( $r_s = 0.630$ ;  $p < 0.001$ ), and Fruiting 1 ( $r_s = 0.480$ ;  $p < 0.001$ ). These results indicate that temperature is a key climatic factor regulating thrips phenology. It represents a primary driver of biological activity during the study period (October 2022–November 2023).

### 3.2.2 Correlation with relative humidity and rainfall

In contrast, rainfall and relative humidity presented different relationships throughout the evaluation period. During *Fruiting 1*

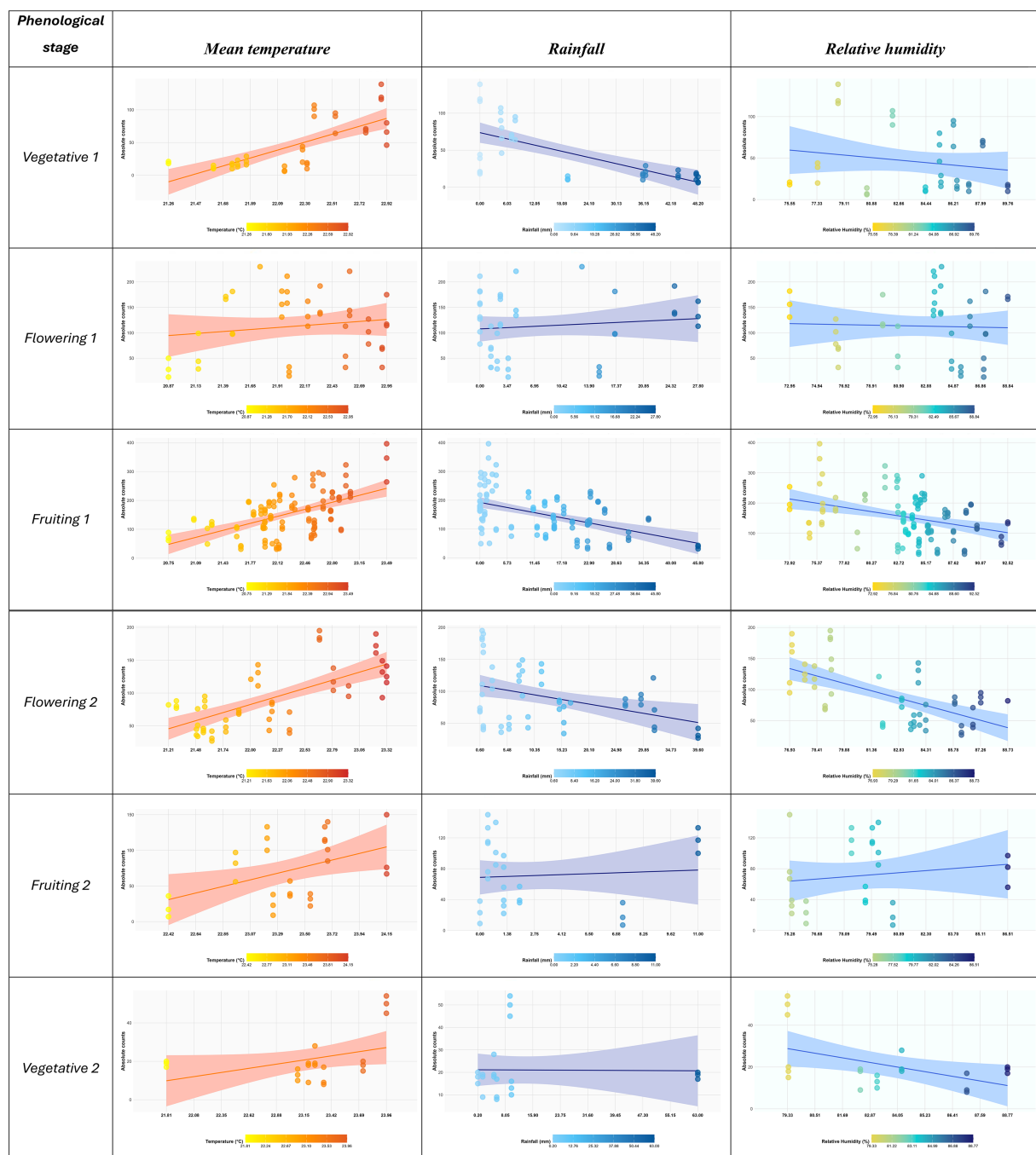


FIGURE 6

Relationships between *Neohydatothrips signifer* abundance and climatic variables (mean temperature, rainfall, and relative humidity) across crop phenological stages.

and *Flowering 2* showed significant inverse correlations ( $p < 0.001$ ) in both variables (Supplementary Table 3). In *Vegetative 1*, only rainfall was inversely and statistically significant ( $r_s$ : -0.697,  $p=0.001$ ). These findings suggest that water availability and water vapor present in the air influence the population fluctuation of *N. signifer* in the passion fruit crop.

### 3.3 Climate-based modeling of *N. signifer* populations

The comparative analysis of count models for *N. signifer* abundance (Supplementary Table 4) revealed that the negative binomial regression incorporating main effects and two-way

interactions provided the best fit. This model was selected as the most appropriate, as it demonstrated a robust fit, reliable diagnostics, and optimal predictive performance, evidenced by the lowest AIC (2096.81) and BIC (2179.88) values among all alternatives. Also, presented the lowest prediction errors ( $RMSE = 42.93$ ,  $MAE = 33.413$ ) and the highest PCC with ( $r = 0.7460$ ). The Poisson models (Intercept-only and with two-way interactions) exhibited severe overdispersion (Dispersion  $\approx 53.5$  and  $20.0$ , respectively,  $p < 0.001$ ), a high percentage of statistical outliers ( $>46\%$ ), and poor uniformity ( $p < 0.001$ ). All metrics showed improvements as the models moved from intercept-only to main effects, and the inclusion of two-way interaction terms further improved model fit and predictive accuracy, revealing intricate relationships between predictor variables that help explain the dynamics of thrips populations.

Based on the negative binomial GLM, *N. signifer* population dynamics were strongly dependent on crop phenological stage and exhibited stage-specific responses to temperature and rainfall (Table 1). Using the initial vegetative stage (Veg\_1) as the reference, the highest relative abundances occurred during early reproductive phases, particularly at Fr\_1, where populations peaked at approximately 2.9 times the baseline level, followed by FL\_1 (2.4-fold), corresponding to the highest risk levels. In contrast, the Veg\_2 stage showed a pronounced and significant population decline ( $\approx 84\%$  lower than Veg\_1), identifying this period as the lowest-risk stage.

Temperature exerted a consistently positive effect across all stages, although its magnitude and statistical significance varied: while Veg\_1 exhibited a moderate but highly significant increase, Fr\_2 showed the greatest thermal sensitivity, with population levels increasing by nearly sevenfold per°C, albeit with higher variability. Rainfall effects were stage dependent, showing significant population reductions in Veg\_1 and FL\_2, but marked increases in Veg\_2, suggesting a shift in the insect's ecophysiological response toward the end of the crop cycle. Overall, these findings highlight early reproductive stages as critical windows of phytosanitary risk and emphasize the need to explicitly incorporate phenology-climate interactions into *N. signifer* forecasting and integrated pest management strategies.

## 3.4 Evaluation of efficacy and environmental of products for thrips control

### 3.4.1 Evaluation of the thrips control products efficacy applied individually and in combination

The products applied for thrips control in passion fruit showed varying levels of efficacy when applied individually, with garlic- and chili-based products, potassium vegetable oil, and entomopathogenic fungi demonstrating the highest effectiveness (Table 2).

When applied as mixtures, there were several cases of antagonism, in which the efficacy of the mixtures was lower than expected based on the individual products. However, several cases of synergism were also identified, particularly for mixtures that included the active ingredient malathion (Table 3).

### 3.4.2 Evaluation of the environmental impact of the application of chemical products for thrips control

In the present study, 66 applications of chemical products of 7 active ingredients for the control of thrips were registered in the cultivation of yellow passion fruit. In the present study, a total of 66 applications of chemical products representing seven active ingredients were recorded for thrips control in yellow passion fruit cultivation. Table 4 presents the field-level Environmental Impact Quotient generated  $EIQ_{Field}$  by each product applied for the control of thrips (*N. signifer*), as well as the cumulative  $EIQ_{Field}$  resulting from the total number of applications, which reached a value of 19.7. Lower EIQ values correspond to products that contribute to greater sustainability of the production system, whereas higher EIQ values may compromise long-term sustainability.

## 3.5 Economic assessment of thrips management

Thrips management represented 17–69% of total phytosanitary costs, depending on the phenological stage (Table 5). The highest

TABLE 1 Stage-specific thrips (*Neohydatothrips signifer*) population dynamics, and climatic sensitivities based on negative binomial GLM (reference: Veg\_1).

| Stage | Order | Population vs Veg_1* | Risk level | Temperature effect**  | Rainfall effect***      |
|-------|-------|----------------------|------------|-----------------------|-------------------------|
| Veg_1 | 1     | 1.0×BASE             | LOW        | +0.815*** (+2.3%/°C)  | -0.033*** (-3.2%/mm)    |
| FL_1  | 2     | 2.4×higher*          | HIGH       | +0.374 (ns) (x1.5/°C) | +0.006** (+0.60%/mm)    |
| Fr_1  | 3     | 2.9×higher*          | PEAK       | +0.359 (.) (x1.4/°C)  | -0.024 (ns) (-2.37%/mm) |
| FL_2  | 4     | 1.8×higher*          | MODERATE   | +0.461 (ns) (x1.6/°C) | -0.001** (-0.10%/mm)    |
| Fr_2  | 5     | 1.2×similar(ns)      | VARIABLE   | +1.952* (x7.0/°C)     | -0.031 (ns) (-3.05%/mm) |
| Veg_2 | 6     | 0.16×(84%less)*      | MINIMUM    | +0.912 (ns) (x2.5/°C) | +0.036*** (3.67%/mm)    |

\*Population levels represent fold-change relative to vegetative stage 1 (baseline). \*\*Temperature effects expressed as multiplication factors per degree Celsius [exp(coefficient)]; \*\*\*rainfall effects as percent change per millimeter [(exp(coefficient)-1)×100]. Significance levels: \*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ , (.)  $p < 0.1$ , ns, not significant. Humidity effects were non-significant across all phenological stages ( $p > 0.05$ ).

Colored circles indicate relative population risk levels: green = low/minimum risk; yellow = moderate/variable risk; red = high/peak risk.

TABLE 2 Percentage of average individual efficacy of products applied for the control of yellow passion fruit thrips (*Neohydatothrips signifer*) in a crop in the municipality of Suaza (Huila, Colombia). Period 2022–2024.

| Active ingredient*                                                                                                                          | Dosis     | Ef observed average | SE  |
|---------------------------------------------------------------------------------------------------------------------------------------------|-----------|---------------------|-----|
| Allicin, Capsaicin, Piperine**                                                                                                              | N.A.      | 17%                 | 10% |
| Allicin, Capsaicin                                                                                                                          | 2 cc/L    | 36%                 | 22% |
| Spinetoram                                                                                                                                  | 0,3 L/ha  | 0%                  | 0%  |
| Potassium vegetable oleate                                                                                                                  | 2–3 cc/L  | 45%                 | 16% |
| Malathion                                                                                                                                   | 2 L/ha    | 9%                  | 9%  |
| Cyantraniliprole                                                                                                                            | 1 L/ha    | 16%                 | 7%  |
| <i>Beauveria bassiana</i> <i>Metarhizium anisopliae</i> , <i>Le canicillium lecanii</i> , <i>Bacillus thuringiensis</i> Var <i>Kurstaki</i> | 1 g/L     | 44%                 | 0%  |
| Spinosad                                                                                                                                    | 140 cc/ha | 19%                 | 16% |
| Allicin, capsaicin, limonene, diallyl disulfide, carotenoids, nicotinic acid                                                                | 1 cc/L    | 0%                  | 0%  |

\*The products were applied according to the label recommendations regarding dosage and pre-harvest interval.  
\*\*Prepared by farmers using artisanal methods.

absolute cost occurred during Fruiting 1 (USD 345.9 ha<sup>-1</sup>; 35%). This stage coincided with optimal temperatures (24–26°C) and moderate rainfall, which promoted the maximum population peak.

The highest relative burden was observed in Fruiting 2 (69%; USD 185.4 ha<sup>-1</sup>). This stage occurred under moderate precipitation and high commercial sensitivity of the crop, which intensified control interventions.

Vegetative 1 also showed high costs (USD 271.1 ha<sup>-1</sup>; 52%). This stage exhibited the strongest positive temperature–population correlation ( $r_s = 0.738$ ;  $p < 0.001$ ). Early thermal activation triggered preventive chemical applications. In contrast, Flowering 2 and Vegetative 2 showed the lowest costs ( $\leq$  USD 31.1 ha<sup>-1</sup>; 17–18%). These stages coincided with higher rainfall and relative humidity, which were negatively associated with thrips abundance.

High expenditures were linked to the recurrent use of Spinetoram and Malathion, which showed low or inconsistent efficacy. Several high-cost mixtures exhibited antagonistic interactions, increasing economic inefficiency. These products achieved only 0–9% control when applied individually. In contrast, potassium vegetable oleate and biological formulations achieved moderate efficacy (44–45%) at lower costs, indicating higher cost-effectiveness.

Overall, thrips management costs were driven by climate variability, phenological sensitivity, and product performance. The results support climate-driven, stage-specific IPM strategies (see detailed cost structure in [Supplementary Table 5](#)).

The environmental impact analysis (Section 3.4) reinforces this imbalance. Products with elevated costs, notably Malathion and Imidacloprid, were associated with high Environmental Impact Quotients (EIQ = 6.4 and 7.5), whereas some lower-impact

TABLE 3 Evaluation of synergies and antagonisms in products applied individually for the control of yellow passion fruit thrips (*Neohydatothrips signifer*) in a crop in the municipality of Suaza (Huila, Colombia). Period 2022–2024.

| Active ingredient*                                                                                                                                                      | Ef observed average | SE  | Ef expected mixtures | Relationship |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|-----|----------------------|--------------|
| Spinetoram + Malathion                                                                                                                                                  | 16%                 | 16% | 9%                   | Synergy      |
| Spinetoram + ( <i>Beauveria bassiana</i> <i>Metarhizium anisopliae</i> , <i>Le canicillium lecanii</i> , <i>Bacillus thuringiensis</i> Var <i>Kurstaki</i> )            | 0%                  | 0%  | 44%                  | Antagonism   |
| Potassium vegetable oleate + Malathion                                                                                                                                  | 22%                 | 10% | 53%                  | Antagonism   |
| Malathion + (allicin, capsaicin)                                                                                                                                        | 63%                 | 23% | 45%                  | Synergy      |
| Cyantraniliprole + Malathion                                                                                                                                            | 66%                 | 0%  | 25%                  | Synergy      |
| Spinosad + (allicin, capsaicin, piperine)**                                                                                                                             | 0%                  | 0%  | 36%                  | Antagonism   |
| Spinosad + Malathion                                                                                                                                                    | 18%                 | 9%  | 35%                  | Antagonism   |
| Spinosad + (allicin, capsaicin, limonene, diallyl disulfide, carotenoids, nicotinic acid)                                                                               | 22%                 | 0%  | 0%                   | Synergy      |
| (allicin, capsaicin, limonene, diallyl disulfide, carotenoids, nicotinic acid) + Malathion                                                                              | 8%                  | 8%  | 9%                   | Antagonism   |
| Spinosad + Malathion + (allicin, capsaicin, limonene, diallyl disulfide, carotenoids, nicotinic acid)                                                                   | 0%                  | 0%  | 27%                  | Antagonism   |
| Spinetoram + ( <i>Beauveria bassiana</i> <i>Metarhizium anisopliae</i> , <i>Le canicillium lecanii</i> , <i>Bacillus thuringiensis</i> Var <i>Kurstaki</i> ) + Spinosad | 15%                 | 0%  | 63%                  | Antagonism   |
| Spinetoram + Malathion + Potassium vegetable oleate                                                                                                                     | 15%                 | 0%  | 53%                  | Antagonism   |
| Spinosad + Malathion + Malathion                                                                                                                                        | 0%                  | 0%  | 36%                  | Antagonism   |

\*Label-recommended doses were used for products applied individually, and the longest pre-harvest interval among the products in each mixture was adopted.  
\*\*Prepared by farmers using artisanal methods.

TABLE 4 Environmental impact quotient (EIQ) of chemical products applied for the control of yellow passion fruit thrips (*Neohydatothrips signifer*) in a crop in the municipality of Suaza (Huila, Colombia). Period 2022–2024.

| Active ingredient                         | % Active I. | Doses/ha | Consumer EIQ | Farmer EIQ | EIQ ecological | <i>EIQ<sub>Field</sub></i> |
|-------------------------------------------|-------------|----------|--------------|------------|----------------|----------------------------|
| Thiamethoxam                              | 25          | 58 gr    | 0,2          | 0,4        | 0,8            | 0,5                        |
| Imidacloprid                              | 70          | 151 gr   | 4,5          | 5,6        | 12,4           | 7,5                        |
| Spinetoram                                | 6           | 235 cc   | 0,1          | 0,8        | 0,7            | 0,5                        |
| Malathion                                 | 57          | 329 cc   | 1,1          | 9,1        | 9,0            | 6,4                        |
| Spirotetramat                             | 15          | 360 cc   | 1,1          | 3,1        | 1,3            | 1,8                        |
| Cyantraniliprole                          | 10          | 321 cc   | 0,6          | 1,0        | 3,2            | 1,6                        |
| Spinosad                                  | 12          | 205 cc   | 0,3          | 1,6        | 2,3            | 1,4                        |
| Total environmental impact quotient (EIQ) |             |          |              |            |                | 19,7                       |

alternatives (e.g., Spinetoram) showed limited or inconsistent efficacy. The cumulative EIQ of 19.7 indicates that current practices impose considerable ecological pressure without corresponding economic or technical benefits.

## 4 Discussion

### 4.1 Population dynamics and crop phenology

Our model showed that temperature had a significant effect on thrips population size, increasing the absolute number of

individuals across all phenological stages, although population levels differed among stages. Temperature significantly influences population thrips dynamics across multiple species, with development rates and reproductive success varying within species-specific optimal ranges, typically 20–30°C (Cao et al., 2018; Lin et al., 2021; Gao et al., 2022). Temperature strongly influences the development, longevity, and population growth (Lin et al., 2021). In the present study, a significant correlation was found between thrips populations and some climatic variables, such as temperature in a direct relationship (in a significant ( $p<0.05$ )  $r_s$  range between 0.434 and 0.738) and with relative humidity and precipitation in an inverse way (in a significant ( $p<0.05$ )  $r_s$  range between -0.333 and -0.550). The positive correlation with

TABLE 5 Costs by phenological stage for the control of yellow passion fruit thrips (*Neohydatothrips signifer*) in a crop in the municipality of Suaza (Huila, Colombia). Period 2022–2024.

| Phenological stage | Cost category            | Labour cost (USD ha <sup>-1</sup> ) | Input/product cost (USD ha <sup>-1</sup> ) | Total cost (USD ha <sup>-1</sup> ) | Thrips control share of total phytosanitary costs (%) |
|--------------------|--------------------------|-------------------------------------|--------------------------------------------|------------------------------------|-------------------------------------------------------|
| Vegetative 1       | Total Phytosanitary Cost | 182.07                              | 340.44                                     | 522.51                             |                                                       |
|                    | Thrips Control Cost      | 75.82                               | 195.32                                     | 271.14                             | 52                                                    |
| Flowering 1        | Total Phytosanitary Cost | 110.36                              | 159                                        | 269.36                             |                                                       |
|                    | Thrips Control Cost      | 25.53                               | 63                                         | 88.53                              | 33                                                    |
| Fruiting 1         | Total Phytosanitary Cost | 199.91                              | 795.29                                     | 995.21                             |                                                       |
|                    | Thrips Control Cost      | 76                                  | 269.92                                     | 345.92                             | 35                                                    |
| Flowering 2        | Total Phytosanitary Cost | 84.75                               | 85.11                                      | 169.86                             |                                                       |
|                    | Thrips Control Cost      | 13.87                               | 17.23                                      | 31.1                               | 18                                                    |
| Fruiting 2         | Total Phytosanitary Cost | 58.82                               | 208.88                                     | 267.7                              |                                                       |
|                    | Thrips Control Cost      | 18.75                               | 166.66                                     | 185.41                             | 69                                                    |
| Vegetative 2       | Total Phytosanitary Cost | 96.33                               | 67.44                                      | 163.77                             |                                                       |
|                    | Thrips Control Cost      | 19.4                                | 8.75                                       | 28.16                              | 17                                                    |
| Flowering 3        | Total Phytosanitary Cost | 131.56                              | 194.98                                     | 326.53                             |                                                       |
|                    | Thrips Control Cost      | 49.74                               | 73.04                                      | 122.78                             | 38                                                    |

temperature corroborates Santos Amaya et al. (2012), who reported similar patterns for this pest in passion fruit orchards within the same region. In other studies, Halimi et al. (2022) documented temperature-dependent dynamics of *Neohydatothrips amygdali* in olive groves. The abundance peaked occurred when temperatures fluctuated between 20°C and 30°C, with the species being completely absent during winter and summer months outside this range. The study of Keough et al. (2018) found that *N. variabilis* capture rates were related to temperature, with peak activity occurring in mid-August when this species served as the primary vector for Soybean vein necrosis virus. These results indicate that the thermal conditions recorded during the study period were highly conducive to the development of *N. signifer*. The temperature and the range of conditions were conducive to the development of *N. signifer* within the present study.

While Santos Amaya et al. (2012) found no significant relationship between thrips populations and precipitation and relative humidity variables, our study aligns with more recent studies that demonstrate that these climatic parameters as crucial populations drivers (Dos Santos et al., 2022; Ingole et al., 2024; Porta et al., 2025; Rakesh et al., 2025). Regarding precipitation, Dos Santos et al. (2022) indicates rainfall as the leading factor associated with temporal dynamics of *F. schultzei* in commercial soybean crops, indicating that increases in rainfall up to 15 mm/day tended to reduce *F. schultzei* abundance. This inverse relationship also was found to the frequency of haplotype H1 in *Thrips tabaci* populations in Uruguay. Specifically, the binomial regression analysis indicates that for every additional millimeter of precipitation, the probability of heteroplasm occurrence in H1 is reduced by 1.4% (Porta et al., 2025). In relation to relative humidity, some studies on tomato crops showed strong negative correlations between thrips populations and both morning ( $r = -0.621$ ) and evening ( $r = -0.754$ ) relative humidity, with weather parameters explaining up to 98% of population variation (Ingole et al., 2024); also, field studies of *Scirtothrips dorsalis* confirmed that both maximum and minimum relative humidity negatively correlated with thrips populations during certain seasons (Rakesh et al., 2025). Also, thrips densities varied according to the phenological stage of passion fruit. The fructification ( $1 = 428 \pm 37$ ;  $2 = 324 \pm 42$ ) and flowering ( $1 = 355 \pm 53$ ;  $2 = 270 \pm 31$ ) stages presented higher populations. However, although the populations in vegetative stages ( $1 = 127 \pm 28.2$ ;  $2 = 101 \pm 42.5$ ) were lower, it is important because *N. signifer* has been reported with a potential for damage of up to 95% in vegetative terminals (Monje et al., 2012). The main relationship with vegetative and fructification stages have been explained due to many species of thrips feed on young leaves and developing fruits (Mound et al., 2022). In flowering, the potential of damage is around 75% of the flower buds (Salamanca Bastidas et al., 2010). In addition to the climatic and phenological factors discussed, recent advances in artificial intelligence (AI) offer promising tools to enhance integrated pest management strategies. AI-driven approaches, such as predictive modeling, stress detection, and data-driven decision support systems, have been successfully applied to optimize crop production and pest management (Ali et al., 2025; Hussain et al., 2025). Integrating such

technologies with climate-based thrips monitoring could provide more precise, real-time management recommendations, thereby improving the sustainability and efficiency of pest control in passion fruit systems.

## 4.2 Efficacy of pesticide mixtures

Previous studies have reported variable outcomes regarding the application of insecticide mixtures. Willmott et al. (2013) reported high levels of synergism among products used for the control of the thrips *Frankliniella occidentalis*. In contrast, Anju Viswanathan et al. (2019); Iglesias et al. (2021) reported predominantly antagonistic effects for the control of *Scirtothrips dorsalis* and *Thrips tabaci*, respectively. Consistent with these findings, several insecticide mixtures evaluated in the present study exhibited antagonistic effects. These results highlight the need for further research on insecticide mixtures for thrips management in passion fruit in order to identify combinations that provide effective control. It should be noted that the present study did not include untreated control and was based on a limited number of treatment replications; therefore, statistical analyses could not be performed. As a result, efficacy values are presented descriptively for products applied individually and in mixtures. This descriptive approach has also been adopted in previous studies assessing the efficacy of insecticides applied individually and in combination for thrips control (Anju Viswanathan et al., 2019), as well as for the individual application of insecticides against lepidopteran pests in cotton (Albeltagy, 2021).

Likewise, the number of 66 applications of 7 active ingredients for thrips control registered in this study is considered high, if compared with other studies such as that of Rodríguez-Quispe et al. (2023) in whose study between 33 and 42 pesticide applications with 27 active ingredients were recorded for tomato crops; between 36 and 45 applications with 28 active ingredients for bell pepper crops; 22 applications with 19 active ingredients for cucumber crops; 8 applications with 11 active ingredients for carrot crops; and 12 applications with 15 active ingredients for lettuce crops, considering that the applications corresponded to the entire phytosanitary management of the crops.

The environmental impact quotient (EIQ) value of 19.7 obtained in this study provided insight into the effects of the evaluated pesticide applications on the environment and human health. The EIQ found in this study is high compared to that found by Muhammetoglu and Uslu (2007) who reported a value between 3 y 18 for the control of *Myzus persicae* and *Bemisia tabaci* respectively in tomato crop in Turkey. The Environmental Impact Quotient (EIQ) value of 19.7 highlights the environmental and health implications of the chemical control strategies evaluated. This value is higher than those reported by Muhammetoglu and Uslu (2007) for *Myzus persicae* and *Bemisia tabaci* in tomato crops (EIQ range: 3–18). Although the EIQ observed here is substantially lower than values reported for full-crop pest management programs such as those documented by Rodríguez-Quispe et al. (2023) for tomato (541.30), pepper (595.97), and cucumber (125.38) it should

be noted that the present EIQ corresponds exclusively to the control of a single arthropod pest. It is necessary to consider that the EIQ calculation in the present study is only for the control of one arthropod pest, which highlights the importance of thrips on yellow passion fruit in the study area. The economic results, integrated with climatic and phenological patterns, indicate that thrips management costs in yellow passion fruit are shaped not only by pest abundance but by growers' risk-averse responses during stages of high economic vulnerability. Control expenditures concentrated in Fruiting 1, Fruiting 2, and Vegetative 1, coinciding with optimal temperatures (24–26°C) and moderate rainfall that favored *N. signifer* population growth. However, the highest relative costs did not always correspond to the highest population levels, suggesting preventive interventions driven by phenology rather than real-time pest pressure. This behavior is consistent with the economic damage threshold framework, which states that control decisions are strongly influenced by the expected economic consequences of damage during critical growth stages (De Rossi et al., 2022). Cost patterns also reflect product performance. High expenditures were linked to repeated use of products with low or inconsistent efficacy (Spinetoram and Malathion). Antagonistic mixtures further reduced technical efficiency, increasing the risk of high expenditure without proportional control. In contrast, botanical and biological options showing moderate efficacy at lower cost profiles indicate opportunities for improved cost-effectiveness. It is important to note that the absence of absolute control plots and limited field replication may constrain the generalizability of the results. Future studies should include replicated control plots to more accurately assess the effects of integrated pest management strategies related to natural population fluctuations and environmental variables (Deguine et al., 2021).

### 4.3 Environmental and economic implications

Within this broader economic context, the role of *N. signifer* in yellow passion fruit becomes comparable to that of other key insect pests in Colombian agriculture. As observed in this study, thrips management accounted for a substantial share of phytosanitary expenditures, reflecting both biological pressure and growers' aversion to economic risk during critical phenological stages. Similar cost concentration patterns have been documented in other crops, such as cotton, where management of the boll weevil (*Anthonomus grandis*) represents 52% of total pest control costs and 8.4% of total production costs (Conalgodón, Sena, Sac, and FFA, 2018), and in coffee, where control of the coffee berry borer (*Hypothenemus hampei*) accounts for approximately 7% of total production costs (Duque, 1994). These comparisons reinforce the notion that a single pest can dominate both economic risk and management decisions within a production system (Polo-Murcia et al., 2025), particularly when control strategies are driven by perceived vulnerability rather than strictly by pest density.

### 4.4 Implications for IPM strategies

It is important to note that the EIQ converts toxicological and physicochemical information on pesticide active ingredients, as well as exposure-related variables, into qualitative scores that are subsequently weighted into a composite index (Kniss and Coburn, 2015). According to these authors, pesticides with higher toxicity (imidacloprid and malathion, Category II) were expected to exhibit higher EIQ values. Therefore, lower EIQ values can be associated with products that contribute to greater sustainability of the production system, whereas higher EIQ values indicate products that may compromise long-term sustainability. Moreover, it is also important to note that this quotient basically takes into account active ingredients of chemical products and does not consider other types of inputs such as botanicals and minerals, among others, which were applied to the crop in this study. There are no references of studies of this type for yellow passion fruit cultivation in the country of Colombia.

Thrips populations in the field typically exhibit an aggregated distribution, with generally low to moderate densities; however, occasional episodes of high population density were observed, associated with favorable environmental conditions or specific phenological stages of the host crop. The control outcomes under the proposed phytosanitary management strategy included the use of products alternative to conventional chemical molecules, consisting of 16% biological, 20% botanical, 12% mineral, and 52% chemical inputs, which may contribute to reducing resistance development in thrips populations. The application of these products in a differentiated manner according to phenological stage, combined with phytosanitary practices and continuous monitoring, was associated with effective functional control of thrips throughout the study period.

## 5 Conclusions

An integrated phytosanitary management approach was evaluated for the control of *N. signifer* in yellow passion fruit, combining climatic and insect population monitoring, growers' cultural practices, and the use of inputs from different sources across crop phenological stages. The results showed that mean temperature significantly influenced thrips population dynamics, with a strong positive correlation during most phenological stages, whereas precipitation and relative humidity exhibited inverse relationships with pest dynamics. The use of control products in mixtures generally resulted in antagonistic interactions and did not improve control efficacy, as several combinations produced antagonistic effects. These findings highlight the need for robust studies to clarify the potential effectiveness of insecticide mixtures involving different active ingredients. Thrips management required a high number of product applications (approximately 66), involving seven active ingredients, which increased economic costs to 30.6% of total phytosanitary expenditures. The

Environmental Impact Quotient indicator (EIQ = 19.7) was relatively high, mainly due to the large number of applications. Although the phytosanitary management strategy evaluated in this study for thrips control in yellow passion fruit complied with European Union export standards (MRL < 0.01 mg kg<sup>-1</sup>), the findings indicate that control practices predominantly based on chemical products are neither economically efficient nor environmentally sustainable under the current management approach. Future research incorporating replicated control plots will be essential to confirm these findings and strengthen causal inference. In addition, future strategies should focus on reducing pesticide dependence through the integration of biological and botanical products, optimizing application timing using climate-based predictive tools, and promoting farmer participation to strengthen the adoption of sustainable integrated pest management practices.

## Data availability statement

The original contributions presented in the study are included in the article/**Supplementary Material**. Further inquiries can be directed to the corresponding author.

## Author contributions

SR: Writing – original draft, Investigation, Data curation, Writing – review & editing, Methodology, Formal analysis. EV: Investigation, Conceptualization, Writing – review & editing, Writing – original draft, Validation, Data curation, Methodology, Formal analysis. NC: Conceptualization, Validation, Project administration, Data curation, Methodology, Supervision, Investigation, Writing – original draft, Resources, Funding acquisition, Visualization, Software, Formal analysis, Writing – review & editing. CJ-B: Formal analysis, Data curation, Writing – original draft, Methodology, Visualization, Investigation, Writing – review & editing, Software, Validation. CF: Data curation, Writing – original draft, Methodology, Visualization, Investigation, Writing – review & editing. SO: Supervision, Methodology, Writing – original draft, Investigation, Writing – review & editing, Conceptualization, Visualization, Formal analysis, Validation. SP-M: Conceptualization, Methodology, Writing – original draft, Visualization, Formal analysis, Writing – review & editing, Data curation, Investigation, Validation.

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## Conflict of interest

Authors EV, NC, CJ-B, CF, and SO were employed by the company Corporación Colombiana de investigación Agropecuaria (AGROSAVIA).

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2026.1725079/full#supplementary-material>

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