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Comparative field efficacy of synthetic insecticides and plant extracts against *Tuta absoluta* (Lepidoptera: Gelechiidae) in Lubumbashi, DR Congo

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Abstract

The invasive tomato leafminer, *Tuta absoluta* (Meyrick), is a very destructive pest that poses a major threat to tomato (*Solanum lycopersicum* L.) production in the Democratic Republic of Congo (DRC), causing extensive yield losses through larval feeding on leaves, stems, and fruits. Chemical insecticides remain the primary control method, but resistance development, biodiversity loss and environmental concerns necessitate alternative strategies. This study aimed at evaluating the efficacy of synthetic and botanical insecticides against *T. absoluta* during two consecutive cropping seasons 2023-2024 in Lubumbashi, DRC, under both dry and rainy season conditions. Two tomato seedling varieties (Tanya F1 and Tovi Star F1) were treated with four synthetic insecticides (Dudu acelamectin 5% EC, cypermethrin 200 EC, lambda-cyhalothrin 50 EC and Occasion Star 200SC) and two botanical treatments (*Tephrosia vogelii* extract and Nimbecidine) at the recommended doses in a randomized complete block design. Pest incidence, larval density, leaf damage, and yield were assessed over multiple intervals. Results showed that synthetic insecticides, particularly Dudu acelamectin 5% EC, lambda-cyhalothrin 50 EC, and Occasion Star 200SC, significantly reduced *T. absoluta* larval infestations compared to cypermethrin 200 EC, which failed to control the pest due to suspected potential resistance. Botanical insecticides were also proved effective, with *T. vogelii* extract reducing leaf damage by 48% and Nimbecidine by 38%. The Tovi Star F1 variety exhibited inherent resistance, with lower pest incidence and higher yields than Tanya F1. Yield losses were strongly correlated with pest incidence and larval density, emphasizing the need for timely interventions. These findings highlight the potential of integrating synthetic and botanical insecticides with resistant tomato varieties for sustainable *T. absoluta* management in Lubumbashi. Future research should explore long-term resistance monitoring, cost-benefit analyses for smallholder farmers, and synergetic combinations of biopesticides to enhance efficacy while minimizing environmental impacts.

Keywords: *Tuta absoluta*, botanicals, synthetic insecticides, *Solanum lycopersicum*, integrated pest management

Introduction

Tomato (*Solanum lycopersicum*) is one of the best fresh market and processing vegetable crops belonging to the Solanaceae family. As an economic crop, tomato is grown by both small and commercial vegetable growers throughout the year in the fields or greenhouses [1]. The tomato fruit is a well-balanced and healthy food for human consumption, as it is rich in vitamins, minerals, essential amino acids, dietary fiber, and sugar [2]. In addition, tomato production plays a vital role in improving livelihoods, particularly for smallholder farmers, through employment and household income generation [3,4]. In the DR Congo, tomato production has grown by an average of 0.4% yearly since 1966. By 2026, it is predicted to reach 51,410 metric tons, compared with world-leading countries such as India and China [5]. Despite its importance, tomato cultivation in the DR Congo is severely constrained by several biotic stresses, particularly insect pests and diseases, which substantially reduce both yields and the quality of marketable fruits [6]. The quantitative and qualitative yield losses have been aggravated by the invasion of the tomato leafminer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), an invasive pest of South American origin now established in Africa [7].

The invasive and highly destructive *T. absoluta*, is one of the most serious insect pests restraining tomato production and productivity globally [8,9,10,11]. The pest feeds on solanaceous crops such as potato, sweet pepper, eggplant, but with a high preference for tomato, on which it causes the greatest economic damage [12,13,14]. It is originally from Peru, South America, but it has started spreading to other continents, including Europe, Asia and Africa during the last decades [15,7]. It has since become a major constraint to global tomato production. In central Africa, the pest emerged as a serious threat following its initial outbreaks in Rwanda in 2015 [16], from where it has continued to spread into neighboring countries, including the DR Congo [6].

In the DR Congo, *T. absoluta* was detected for the first time in 2016 in Kinshasa province, based on morphological identification of adult insect individuals. Its presence was further confirmed using molecular identification with primers targeting the mitochondrial cytochrome oxidase subunit I (COI) gene sequences [6]. Since then, the pest rapidly invaded other provinces within the country, inflicting significant damage and yield losses in both open field and greenhouse tomato production systems. A significant reason for its rapid spread is the popularity of tomatoes and their export to many countries without robust phytosanitary quarantine procedures/measures to monitor its occurrence in the producing countries and prevent its entry into the importing countries [17,6].

The economic losses caused by *T. absoluta* are mainly due to damage by larval feeding inside leaves, stems and fruits [10,13,18]. Females lay approximately 260 eggs on the underside of leaves and stems of the tomato plant. After hatching, neonate larvae penetrate leaves and feed on the mesophyll tissues at any phenological stage of host plant development, creating irregular mines that progressively become necrotic with time [12,19]. These irregular mines reduce the photosynthetic capacity of the plant, induce leaf necrosis, and may compromise the plant's ability to resist other biotic stresses [20]. Besides, larval feeding also reduces fruit quality by creating pin holes prone to secondary fungal infections, reducing the quality of tomatoes and rendering them unmarketable [21,22]. Through cryptic feeding in the stem, the larvae can create extensive galleries that weaken the stem and affect the development of the host plant. Severe damage to the tomato plant by the larvae results in complete defoliation and drying of the plant [17]. Potential yield loss in terms of quality and quantity is highly significant and can reach 100% if the pest is not adequately controlled [23].

The use of chemical insecticides is the primary control approach against *T. absoluta*, which could provide up to 95% control of the pest at 14-21 days after treatment [24,11]. A range of synthetic insecticides has been employed in many locations in the management of the pest in order to boost tomato productivity [25]. However, repeated and excessive sprays of insecticides of the same type result in the emergence of resistant pest populations due to continuous selection pressure in the field, making *T. absoluta* control very challenging [26,27]. Besides, the endophytic behavioral feeding and cryptic nature of the pest larvae render the widely used contact insecticides ineffective. Because of this concealed feeding behavior, the pest could escape from most of the synthetic insecticides currently being applied, hindering effective management of *T. absoluta* [28]. Furthermore, the abusive use of these synthetic pesticides causes significant adverse environmental, biodiversity and human health effects and increased resistance development in *T. absoluta* [24,28]. It is therefore paramount to develop and promote environmentally friendly control strategies to overcome these challenges. As a viable alternative to the misuse of synthetic insecticides, the development of biological control approaches using botanicals such as Neem-based products could be explored to sustainably tackle *T. absoluta*.

Plant extracts or botanicals can be effectively used as an alternative to chemical insecticides as they offer a more sustainable means in tackling this offensive and invasive pest [24,29]. In the DR Congo, information on the efficacy of both synthetic insecticides and plant extracts against *T. absoluta* is lacking. Therefore, the present study aimed to assess and compare the efficacy of some selected bio- and synthetic insecticides in the control of *T. absoluta* under experimental field conditions.

Materials and methods

Study site and period

The experiments were established at the Garden of Hope, Glen Hill Farm, Lubumbashi (11.6876° S, 27.5026° E), and Mutonkole farm, Mimbulu village (11.6904° S, 27.4555° E), DR Congo. The two field trial sites were approximately 5 km and were established in areas where tomato is highly cultivated in open fields in rainy and dry seasons with remarkable natural infestation of *T. absoluta*. The climate in Lubumbashi is of climate with dry winters (Cwa) type following the Köppen classification [30]. The average annual temperature and rainfall are 25.5 °C and 1238 mm, respectively. The rainy season starts in November and ends in March and the dry season from May to September, with April and October being transitional months between the two seasons [31]. The field experiments were conducted over two consecutive cropping seasons during 2023-2024. In 2023, the two trials were established during the rainy season at the Mutonkole farm, whereas in 2024, the trials were conducted during the dry season at Glen Hill.

Plant materials and treatments

Two tomato varieties (Tanya F1 and Tovi Star F1) were chosen as plant materials in this study based on their preference by farmers. The seeds of these two varieties were obtained from the local Agrochemical shop “New Semences” in Lubumbashi, DRC. Seven treatments were evaluated against the occurrence of *T. absoluta*: four synthetic insecticides (Dudu-acelamectin

5% EC, Cypermethrin 200 EC, Lambda-cyhalothrin 50 EC and Occasion Star 200SC), one botanical insecticide (Azadirachtin), one plant extract (*Tephrosia vogelii*) and the control (sterile distilled water). These pesticides were also obtained from the Agrochemical shop “New Semences” in Lubumbashi, DRC. The leaves of *T. vogelii* were obtained from Sun city neighborhood (11°4149 S, 27.3125° E) in Lubumbashi, DRC. Detailed information on these insecticides are provided in Table 1 below.

Tephrosia vogelii material collection and extraction procedure

The plant extract was obtained from the leaves of *T. vogelii* collected from the Sun City neighborhood (11°4149 S, 27.3125° E) in Lubumbashi, DR Congo. The plant material was taxonomically identified and authenticated at the Faculty of Agricultural Sciences, University of Lubumbashi, Lubumbashi, DR Congo. The specimen has also been deposited in the Herbarium repository of the Faculty of Agricultural Sciences under the reference number UNILU/FACAGRO/SNN/051/2023. The leaves were collected in the dry season (September-October, 2023 and 2024) because of the seasonal variation in plant secondary metabolites [32]. The collected leaves were neither very old nor very fresh and were chosen because of their high concentration in active compounds [33,32,34]. Upon collection, the leaves were thoroughly washed using tap water to remove dust and debris. The washed leaves were air-dried in a well-ventilated room at an ambient temperature around 24-28 ^{o}C for two weeks. The dried leaves were grinded and sieved into fine powder using a local wooden mortar and a 0.2 mm wire mesh. The obtained powder was weighed, packed and sealed in biodegradable plastic bags and kept under room temperature until further use. Prior to field treatment, the extraction of the plant was carried out by adding 150 g of powder to one liter (1 L) of sterile distilled cold water and soaked in a clean plastic bucket at room temperature (24 - 30 ºC). Generally, cold water (25 ºC) was chosen as opposed to hot water to evade reabsorption during cooling and that may affect the active ingredients in the leaves of *T. vogelii* [35]. The resulting solution was stirred constantly for about 5 minutes and left to stand for 12 hours and later filtered with a clean muslin cloth before application in the field. Finally, the filtered solution was diluted into one liter (1 L) using cold water to obtain a concentration of 15% weight volume (w/v) [36]. The incorporation of 0.01% soap early in the process of extraction also helped to ensure that the active ingredients in the plant materials are well extracted and dispersed. Rotenoids are less soluble in water; hence, soap was used to increase the extraction procedure [32].

Land preparation and trials set-up

The experimental field was meticulously cleared of weeds, crop residues, and other debris to reduce biotic stress and interspecific competition. Subsequently, the soil underwent deep tillage to a depth of 20–30 cm, improving soil aeration, water infiltration, and root system development. Raised ridges, measuring 30 cm in height and 1–1.2 m in width, were constructed in each season to enhance surface drainage, mitigate waterlogging, and facilitate efficient irrigation and other cultural operations.

Basal application of a balanced compound fertilizer (17-17-17 NPK) was applied to ensure adequate nutrient availability during early vegetative growth stage of the tomato plants. A drip irrigation system was installed and operated for four hours daily (two hours in the morning and two hours in the evening) to maintain optimal soil moisture, avoiding the high susceptibility of tomato plants to water stress. The experiment was conducted in a randomized complete block design (RCBD) consisting of six treatments and the control as described above. Each experimental unit area was 9 m^2 and consisted of four rows. For each experiment in each season, a total of 28 plots were established for a total area of 252 m^2. The plots were separated by a 1.5 m wide path from each other to reduce the drift effect of the treatments. Transplanting was carried out using twenty-two-day old seedlings in March 2023 and June 2023 and March 2024 and June 2024 in the field plots in the evening to prevent too much water loss and wilting in the newly transplanted seedlings. Drip irrigation was applied every 2-3 days during early growth and daily during flowering and fruiting. The seedlings were spaced at 50 cm x 60 cm, equivalent to 33,333.33 plants per hectare. The total density of the entire experimental field was 216 plants, at the rate of 12 plants per plot for each variety. Each treatment was replicated four times within each block. In each treatment, 10 plants were randomly selected and labelled for periodical inspection and data recording. Apart from insecticide applications, all experimental units received uniformly regular agricultural practices (e.g., weeding, seedling thinning, fungicide application, etc.). Natural pest incidences were monitored by visual observation soon after transplanting until the final harvest.

Insecticides application

The insecticides used in these trials were purchased from the local Agricultural products store “New Semences” in Lubumbashi, DRC. The application of treatments started one week after transplanting the tomato seedlings that were not showing any visible symptoms of *T. absoluta* and continued at 20-day intervals until the final harvest. Each treatment had a separate knapsack sprayer, and insecticides were applied in evening hours (5 pm) to evade the damaging effects of sunlight [37,38,39]. The spray volume for each treatment was 1000 L ha^{-1} using a knapsack sprayer. The dosages used were 1.5 ml L^{-1} for Dudu acelamectin 5% EC, 200 g L^{-1} for Cypermethrin 200 EC, 1 ml L^{-1} for Lambda-cyhalothrin 50 EC, 0.15 ml L^{-1} for Occasion Star 200SC, 5 ml L^{-1} for Nimbecidine (Azadirachtin 0.03% EC), 15% weight volume (w/v) for *T. vogelii* and 1 ml L^{-1} of sterile water for the control. The dilution rate of the pesticides was based on the manufacturer’s recommendations. Continuous agitation was maintained during each treatment application to prevent precipitations and ensure a homogenous suspension.

Assessment of infestation parameters and yield

Leaves and stems showing typical symptoms of the pest were assessed on five randomly selected plants of each variety from each experimental plot before and after application at 1, 3, 5, 7 and 10 days post-treatment. Another sample of non-treated infested plants were sampled in the control plots. The number of larvae per plant and the number of larvae in each treatment plot were determined by counting. An average number of larvae per plot, without age classification, was then determined based on the larval density observed in each sampled plant. The incidence was determined solely in each treatment from the 20 randomly selected plants per treatment based on the irregular mines and galleries observed on tomato leaves, stems and fruits. Leaf damage was evaluated as the percentage of leaves mined by *T. absoluta*; whereas leaflet damage was evaluated as the percentage of leaflets mined by *T. absoluta* from three randomly selected leaves located in the middle canopy of each plant [40]. The number of damaged leaflets and the total number of leaflets were recorded. In addition, the number of mine blotches per leaf were counted from each sampled plant.

The yield recorded during each harvest was pooled for the entire season, and the total fruit yield of each treatment was derived from the replicated treatment. During harvesting, the number of damaged and healthy fruits were separated and counted as the number of marketable and unmarketable fruits. The ratio was calculated as follow:

$$\text{Ratio} = \frac{\text{Number of marketable fruits in a treatment plot}}{\text{Number of unmarketable fruits in a treatment plot}+1}$$

Three yield parameters such as the number of marketable and unmarketable of fruits, fruit weight, and yield were collected in the manner outlined by Liu et al. [41], where the total number of fruits per plant and the individual fruit weight were obtained by counting and weighing each marketable fruit. The yield (kg plant^{-1}) within a plot was obtained by totalling the weight of all fruits harvested from each treatment plant and plot. The yield estimation in tons per ha was calculated using the formula described by Ali et al. [42]:

$$\text{Yield (T ha}^{-1}\text{)} = \frac{\text{Yield per plot (kg) x 10,000}}{\text{Area occupied by plot (m}^{2}\text{) x 1,000}}$$

Statistical analysis

All statistical analyses were conducted in R version 4.4.1 [43]. Prior to analysis, all the data collected were subjected to normality and homogeneity test of variances using Shapiro-Wilk [44] and Levene test respectively (at $p < 0.05$ significance level). Due to significant deviations from parametric assumptions, non-parametric tests were implemented. Aligned rank transform (ART) analysis of variance (ANOVA) was used to analyse pest infestation (incidence and larval density) in the tomato crop using the *ARTool* package [45]. The full factorial model (treatment × season × variety) was applied to rank-transformed data aligned by experimental blocks (Rep), with Type III SS F-tests for fixed effects. Significant effects were followed by ART-contrasts using Holm-Bonferroni-adjusted pairwise comparisons of aligned ranks. Treatment efficacy was quantified through median differences with 95% confidence intervals. Kruskal-Wallis test was used to evaluate the effects of treatment, variety and season on the ratio, number of marketable and unmarketable fruits, and yield per plant variables. For significant Kruskal-

Wallis results, post-hoc pairwise comparisons were performed using Dunn's test with Benjamini-Hochberg adjustment for multiple comparisons. Leaf damage count data (representing the number of galleries) were analysed using a Poisson Generalized Linear Mixed Model (GLMM) fitted by maximum likelihood using the package *lme4* [46]. Treatment, variety, season, and day were incorporated as fixed effects and replicate as a random effect (1|Rep) to account for experimental blocking. Model assumptions were verified using the package *DHARMa* for residual diagnostics, and significant effects were evaluated by type III analysis of deviance. Mean comparisons were further examined via Sidak-adjusted pairwise comparisons of estimated marginal means using the package *emmeans*. The relationship between incidence and yield and larval density and yield was assessed using Spearman's rank correlation stratified by season and tomato variety. A linear regression model assessed yield prediction from incidence and larval density, with season and variety included as an interaction term to test for differential effects. All tests were set at a significance level of 5%. All plots were generated using the *ggplot2* R package [47].

Results

Differential effectiveness of control methods against *Tuta absoluta* in tomato

The ART-ANOVA analysis revealed significant effects of treatment, variety, and season on tomato leaf-miner infestation (Figure 1). Pest incidence varied strongly by treatment ($F_{(6)}$ = 235.72; $p < 0.001$), with controls showing the highest infestation, while synthetic (e.g., λ-cyhalothrin) and botanical (e.g., *T. vogelii*) treatments were most effective with low infestation levels. Variety had a major influence ($F_{(1)}$ = 1234.43; $p < 0.001$), as Tovi Star F1 consistently exhibited lower pest incidence than Tanya F1. Season differences were also significant ($F_{(1)}$ = 101.68; $p < 0.001$), with higher pest incidence in the dry season than in the rainy season. A strong treatment × variety interaction ($F_{(6)}$ = 304.8; $p < 0.001$) revealed that synthetic pyrethroids (e.g., Cypermethrin 200 EC) reduced incidence more in Tovi Star F1 than Tanya F1. The treatment × season interaction ($F_{(6)}$ = 20.84; $p < 0.001$) further indicated season-dependent efficacy. For example, Dudu acelamectin performed equally well for both seasons, whereas Occasion Star 200SC was more effective in the rainy season than dry season. The three-way interaction (treatment × season × variety, $F_{(6)}$ = 5.93; $p < 0.001$) highlighted complex dynamics, such as Nimbecidine's greater suppression of the pest on Tovi Star F1 versus Tanya F1 in the rainy season, but not in the dry season.

For larval density, treatment effects were significant ($F_{(6)}$ = 102.37; $p <$ 0.001), with controls averaging six larvae/plant versus one larva for Occasion Star 200SC, *T. vogelii* and Nimbecidine. Similarly, Tovi Star F1 again outperformed Tanya F1 ($F_{(6)}$ = 105.22; $p < 0.001$), though season had no significant effect ($F_{(1)}$ = 1.17; $p = 0.278$). The treatment × variety interaction

($F_{(6)}$ = 26.16; $p < 0.001$) showed that synthetic treatments (e.g., Cypermethrin 200 EC) significantly reduced the larval density more in Tovi Star F1 than in Tanya F1. Other interactions (season × variety, three-way) were not significant. Overall, integrating synthetic chemicals with resistant varieties (e.g., Tovi Star F1) provided the most robust pest suppression, with efficacy modulated by season-specific factors.

Modelling the leaf damage by the tomato leaf miner

The Poisson GLMM (Table S1), supported by Type III analysis of deviance, revealed highly significant main effects of Treatment (GLMM: $\chi^2_{(6)} = 31.02$; $p < 0.001$), Variety (GLMM: $\chi^2_{(1)} = 78.99$; $p < 0.001$), and Day (GLMM: $\chi^2_{(1)} = 34.5$; $p < 0.001$), confirming these factors' strong overall effect on leaf damage. While season showed marginal significance (GLMM: $\chi^2_{(1)} = 15.69$; $p < 0.001$), its effect was most pronounced in interactions. The botanical insecticide *T. vogelii* showed superior efficacy, reducing damage by approximately 48% compared to controls, followed by synthetic treatments Occasion Star 200SC and Nimbecidine, while Cypermethrin 200 EC was least effective (Figure 2). The Tovi Star F1 variety demonstrated inherent resistance, equivalent to 37% lower damage, though this advantage has diminished/reduced in the rainy season. The ANOVA's significance for treatment × Variety interaction (GLMM: $\chi^2_{(6)} = 2.71$, $p = 0.012$) aligns with GLMM estimates, showing Nimbecidine's enhanced efficacy on Tovi Star F1, while the significance of variety × season interaction (GLMM: $\chi^2_{(1)} = 14.56$;

$p < 0.01$) corroborates with the GLMM's finding of reduced Tovi Star F1 resistance in rainy season. Notably, the non-significant three-way interaction (GLMM: $\chi^2_{(6)} = 1.87$; $p = 0.082$) in ANOVA corresponds to the GLMM's season-specific treatment failures (e.g., Lambda cyhalothrin's effect on Tovi Star F1 in the rainy season). Temporal analysis showed increased damage, with protection degrading significantly after day 7 post-treatment, corroborated by the strong day effect.

Tomato yield in response to *Tuta absoluta* control treatments

The Kruskal-Wallis test results indicated highly significant differences in crop yield across pest control treatments and varieties, but no significant effect was observed with regard to season (Figure 3). When considering the treatment effect (Figure 3a), Dudu acelamectin and Occasion Star 200SC had the highest yield, while control and Cypermethrin 200 EC recorded the lowest yields ($H_{(6)} = 46.2$; $p < 0.001$). *T. vogelli* botanical recorded intermediate yields, serving as a viable organic alternative to synthetic insecticides. Tovi Star F1 consistently outperformed Tanya F1 ($H_{(1)} = 81.4$; $p < 0.001$) (Figure 3c). However, no significant difference in yield was found as regard to the seasons ($H_{(1)} = 0.1$; $p < 0.138$) (Figure 3c).

The Kruskal-Wallis tests and subsequent post-hoc pairwise comparisons revealed significant treatment, variety, and season effects across all measured yield components (Figure 4). For the ratio, measuring the effectiveness of pest control approaches or their impact on fruit yield, treatments formed three efficacy tiers. Occasion Star 200SC significantly outperformed both Dudu acelamectin/Nimbecidine/*T. vogelii* as the intermediate group and the control/Cypermethrin 200 EC as the lowest group ($H_{(6)}$ = 200; $p < 0.001$). Number of marketable fruits results mirrored this pattern, with Dudu acelamectin/ *T. vogelii* and Occasion Star 200SC surpassing Lambda cyhalothrin, Nimbecidine and the control ($H_{(6)}$ = 110; $p < 0.001$), though pairwise tests revealed nuanced differences. For the number of unmarketable tomato fruits, all the treatments equally reduced damage versus the control ($H_{(6)}$ = 186; $p < 0.001$). When considering varietal effects, Tanya F1 had a lower number of marketable ($H_{(1)}$ = 15.4; $p < 0.001$) and unmarketable fruits ($H_{(1)}$ = 3.92; $p = 0.044$) than Tovi Star F1, suggesting a trade-off between total yield and quality. Season effects further modified the yield outcomes: Rainy season had a higher number of marketable fruits ($H_{(1)}$ = 4.05; $p = 0.05$) than dry season, implying environmental or management influences on fruit quality consistency (Figure 4a). These stratified results underscore that Occasion Star 200SC and Dudu acelamectin were top-performing treatments, but variety and season critically modulate their effectiveness, recommending Tovi Star F1 for maximum yield (despite quality risks) in the rainy season, and Tanya F1 for quality-focused production in the dry season (Figure 4b).

The results demonstrated robust negative associations between pest incidence and yield, as well as between larval density and yield, supported by both correlation and regression analyses (Figure 5). The linear regression model (R^2 = 0.136, $F(3,556)$ = 29.24, $p < 0.001$) showed 13.6% of yield variation from season, considering the incidence (Figure 5d). In the dry season, each unit increased in incidence reduced yield by 7.15 folds (t = -8.57; $p < 0.001$), while in the dry season, the effect was attenuated to 3.75 folds (interaction $t = 2.59$; $p = 0.009$). The variety analysis revealed Tovi Star F1's higher baseline yield ($t = 5.85$, $p < 0.001$) but greater sensitivity to the pest incidence (Figure 5c) (interaction $t = -1.81$; $p = 0.070$), with the model explaining 21.1% of variance ($R^2 = 0.21$, $F(3,556) = 49.45$, $p < 0.001$). These results suggested the need for season-specific management, particularly in the dry season, and showed that Tovi Star F1 performed better in low-incidence conditions. The larval density-yield relationship, while significant, showed less variance than incidence when considering the season effect (R^2 = 0.08; $F(3,556) = 16.42$; $p < 0.001$) (Figure 5b). Dry season showed a 61.94-fold yield reduction per larval density increase (t = -6.57; $p < 0.001$), substantially greater than the rainy season's 22.42-fold reduction (interaction $t = 2.95$, $p = 0.003$). The variety-specific model ($R^2 = 0.17$, $F(3,556) = 38.72$, $p < 0.001$) (Figure 5a) indicated significant main effects for both larval density (t = -3.96; $p < 0.001$) and variety (t = 4.03; $p < 0.001$), but no significant interaction (t = 0.65, p = 0.515) was observed. Tovi Star F1 maintained higher baseline yields with comparable larval sensitivity to Tanya F1.

Discussion

In Africa, the introduction and spread of alien species has been accelerated in recent decades, posing significant threats to agriculture, biodiversity, and ecological stability [48,49]. In the DR Congo, tomatoes are seen as a highly promising crop for horticultural expansion; however, its production is currently threatened by invasive insect pests such as *T. absolut*a which puts the future of this cash crop in jeopardy. While the study provides valuable insights for the Lubumbashi region, the findings are derived from only two sites over two seasons. Further validation across broader agroecological zones and longer timeframes would strengthen their generalizability.

Chemical insecticides are one of the most common and widely used methods for controlling *T. absolut*a around the world because they have rapid action and strong toxicity against the target pest. Among the synthetic insecticides used in this study, Dudu- acelamectin, Lambda cyhalothrin and Occasion Star 200SC showed better insecticidal efficacy than cypermethrin 200 EC against *T. absolut*a. The effectiveness of Dudu-acelamectin stems from its quick action and ability to control a wide range of pests on crops through disruption of their nervous systems, leading to paralysis and ultimately death [50]. However, Dudu acelamectin should be used with caution because of its non-target effects and the risk of resistance development. The results of the current study are consistent with a previous study conducted in Uganda, where Dudu-acelametin outperformed other treatments in controlling *T. absolut*a on tomato under field conditions [51]. Lambda-cyhalothrin is a synthetic pyrethroid insecticide widely used to control many insect pests, including *T. absoluta,* by disrupting the nervous system. It interferes with the sodium channels in nerve cells, causing overstimulation, paralysis, and ultimately, death of the insect [52]. Lambda-cyhalothrin exerts both contact and stomach poisoning effects, and has no internal absorption effect. It is mainly used to control pests with chewing or piercing and sucking mouthparts [53,54]. In this study, lambda-cyhalothrin significantly reduced *T. absoluta* infestation, making it one of the most effective chemical insecticides tested against the pest. These findings align with previous reports indicating that lambda-cyhalothrin effectively controlled *T. absolut*a both inside and outside mined leaves, achieving high larval mortality rates [55,56,57].

In this study, cypermethrin 200 EC exhibited complete failure against *T. absolut*a populations in both studied seasons, suggesting that the tomato leafminer populations in the current region may have developed resistance to this insecticide, making it unsuitable for effective control [58,59]. However, because resistance mechanisms were not confirmed through molecular or biochemical assays, this interpretation remains inferential and should be validated in future studies. Cypermethrin-treated plots showed higher pest incidence compared to other tested synthetic insecticides. This possible resistance is likely a result of extensive and repeated use of cypermethrin by local tomato growers in the region, which may have exerted strong selection pressure favoring resistant individuals within *T. absolut*a populations. Similar findings have been reported in Brazil, where cypermethrin completely failed to control *T. absolut*a populations [59]. Although cypermethrin 200 EC may not effectively control *T. absoluta* larvae in both seasons, it can still cause sublethal effects like reduced lifespan and egg-laying in surviving insects [60]. Insecticides resistance in *T. absolut*a has been reported for various chemical classes including organophospahtes, spinosyns, cartap, pyrethroids, diamides, indoxacarb, avemermectins and benzoylureas [61,62,63,64].

Novel insecticides, with their unique modes of action and specific targeting of pests, offer promising solutions for effective and environmentally sound pest management. They can be particularly useful in integrated pest management strategies, offering alternatives to older, broad-spectrum insecticides [65,66]. In this study, the novel insecticide Occasion Star 200SC was effective in controlling *T. absolut*a populations with lower pest incidence in both studied seasons. It is a unique brand-new insecticide combination of emamectin benzoate and indoxacarb with contact and stomach action for broad spectrum control of chewing insect pests. This insecticide was recently introduced to the field of plant protection with novel modes of action that prevent, or delay build up resistance against different insect pests including *T. absoluta* [66]. Indoxacarb, an oxadiazine insecticide group, disrupts nerve function by blocking sodium channels, while emamectin benzoate, an avermectin compound, interferes with neurotransmission of the pests by acting as an agonist for gamma-aminobutyric acid and glutamate-gated chloride channels, leading to disruption of nerve impulses and subsequent pest mortality [67,68]. The observed efficacy of Occasion Star 200SC aligns with previous studies demonstrating the superior performance of emamectin benzoate against *T. absolut*a compared to cypermethrin [69]. Roby and Hussein [70] reported that emamectin benzoate exhibited high toxic effect against *T. absoluta*, among tested insecticides for second-instar larvae. Similarly, Simmons et al. [22] documented over 90% mortality of *T. absoluta* with emamectin benzoate and spinosad treatments. Beyond tomato leafminer, emamectin benzoate has demonstrated efficacy against other lepidopteran pests, including *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) on maize [71] and *Spodoptera littoralis* (Boisduval) (Lepidoptera: Noctuidae) on cotton [72]. Notably, the persistence of these treatment effects beyond the 10-day assessment period was not evaluated, and longer-term efficacy studies would be beneficial to inform application schedules.

In this study, the tomato Tovi Star F1 variety demonstrated inherent resistance to *T. absoluta*. Such resistance or tolerance is often associated with specific traits, including high trichome density on leaves and the presence of particular allelochemicals. These findings are in harmony with previous studies showing that type VI glandular trichomes in tomato deter herbivory by producing high concentrations of toxic specialized metabolites within their glandular fluid [73]. When insects like *T. absoluta* interact with these trichomes, the glands rupture, releasing the toxic fluid, which deters or kills the pests [74,75,73]. Apart from its morphological defenses against *T. absoluta*, Tovi Star F1 is also resistant to several common tomato diseases including early/late blight, Fusarium crown and root knot, *Fusarium oxysporum*, Tomato Mosaic Virus, Tomato yellow leaf curl virus Verticillium wilt and various nematodes including *Meloidogyne arenaria*, *M. incognita* and *M. javanita* [76]. In contrast, Tanya F1 exhibits resistance only to Alternaria stem cancer, gray leaf spot and Verticillium wilt [77]. The specific mechanisms conferring resistance in Tovi Star F1 were not investigated in this study, and further research exploring the physiological or genetic basis would help clarify the traits involved.

Botanical insecticides are widely used in various countries to control *T. absolut*a, one of the most destructive pests of tomato. In the current study, *T. vogelii* and Nimbecidine demonstrated strong efficacy in suppressing *T. absoluta* populations due to their insecticidal properties. The potency of *T. vogelii* is attributed to its rotenoid compounds, a group of flavonoids known to be strongly toxic to leaf-eating insects [32]. Compounds such as rotenone act by inhibiting mitochondrial electron transport, disrupting cellular respiration, and ultimately causing insect death [78]. The finding of the current study congruent with earlier research showing the effectiveness of *T. vogelii* against bean aphid, *Aphis fabae* Scopoli (Hemiptera: Aphididae) on common bean [79] and in protecting stored legume seeds from bruchids damage [80]. Similarly, previous studies reported high efficacy of other botanical extracts against *T. absolut*a. For instance, leaf extract of *Thymus vulgaris* and seed extracts of *Ricinus communis* were shown to cause up to 95% and 58% larval mortality, respectively [81]. More recently, the efficacy of neem and garlic extracts against *T. absoluta* was demonstrated, with the neem extract causing 93.8% larval mortality with an LT_{50} value of 1.21 days [82].

The toxicity of plant extracts, however, can vary significantly even against a single insect species. Such variation is influenced by the type and concentration of secondary metabolites, the origin of the plant, application timing, extraction methods, solvents used, and bioactive compound stability [83,84]. Unlike many synthetic pesticides, *T. vogelii* does not leave residues on crops, as the rotenone it contains breaks down rapidly after application due to exposure to light and heat, thereby reducing environmental and food safety risks. Similarly, azadirachtin, the active ingredient in neem-based insecticides such as Nimbecidine, functions as an anti-feedant, repellent, and has feeding induction effect over the instars of *T. absoluta*. It interferes with vital life processes of the pest like ovi-position, molting, and feeding resulting in growth disorders of *T. absoluta*. However, its application is relatively more effective against the early two larval instars than during the later stages of *T. absolut*a [85]. Notably, azadirachtin is most effective against early larval instars compared to later developmental stages of *T. absoluta*. In this study Nimbecidine showed low infestation and enhanced efficacy when applied to the Tovi Star F1 variety. The secondary metabolites present in these plants exhibit broad biological activity against insect pests, thereby supporting their role in integrated pest management. In addition to their efficacy, biologically active plant materials provide environmentally sustainable alternatives, as they degrade more rapidly than synthetic pesticides and reduce risks to human health, non-target organisms, and ecosystems. Thus, *T. vogelii* and Nimbecidine represent promising alternatives for tomato growers, particularly in regions where synthetic pesticide resistance is prevalent, chemical inputs are costly, or environmental and health concerns are paramount [86,87]. Importantly, because they are generally compatible with beneficial arthropods, botanicals can be integrated with biological control agents such as parasitoids (*Telenomus remus*, *Trichogramma* spp., *Coccygidium luteum*, *Chelenus curvimaculatus*) and predators (*Nesidiocoris tenuis*, *Macrolophus pygmaeus*) that naturally regulate *T. absoluta* populations [88,89,90]. However, while many botanical products are relatively compatible with biological control agents, some may still produce species-specific lethal or sublethal effects depending on the formulation, dose, and exposure conditions [91]. Therefore, careful selection and evaluation of botanical products are necessary to ensure minimal impact on beneficial organisms. Such integration enhances the sustainability of control strategies while reducing reliance on synthetic insecticides, making botanical- based approaches a cornerstone in the development of ecologically sound IMP packages for tomato growers. In the present study, the compatibility of the tested botanical insecticides with local natural enemies was not assessed, representing a gap that should be addressed by future research to fully support IPM recommendations.

The management of *T. absolut*a has become a challenging task due to its high capacity to develop resistance to synthetic insecticides and its concealed feeding behaviors [92,19]. The constant application of pesticides against the pest is a common practice with farmers in Lubumbashi region [93]. These farmers predominantly rely on the extensive use of synthetic pesticides rather than integrating alternative control strategies. Nevertheless, *T. absoluta* has demonstrated a relatively rapid development of resistance to several conventional insecticides [94,95]. Resistance cases have been documented across multiple continents, including in Africa, where reduced efficacy of commonly used active ingredients such as pyrethroids, organophosphates, and spinosyns has been reported [58,96,27]. The findings of the study revealed that the high efficiency of some of the insecticides such as Occasion Star 200SC and Dudu Acelamectin, may be attributed to several factors. These products are relatively new in the field of crop protection and exhibit novel or distinct modes of actions, which may delay or prevent the development of resistance compared to conventional insecticides that have been intensively applied for years [11,66].

In the present study, pest incidence was significantly higher during the dry season than the rainy season, indicating a strong seasonal influence on the population dynamics of *P absoluta*. This pattern is consistent with earlier reports, which showed that *T. absoluta* populations peak during the dry season and decline significantly during periods of high rainfall [97,98]. The dry season provides favorable conditions for the pest’s survival and reproduction, including higher temperatures, lower relative humidity, and reduced larval mortality from rainfall and fungal pathogens. In contrast, heavy rains can physically dislodge eggs and larvae from host plants and create unfavorable microclimate conditions that suppress population growth of the pest [99].

Generally, seasonal dynamics of *T. absoluta* are regulated by a combination of climatic conditions, host plant development stage, and pest control practices [10]. For example, in South-Kivu, early maize planting has been shown to reduce infestation by *Spodoptera frugiperda*, while late plating increases larval density and crop damage, highlighting planting date as an important cultural strategy for sustainable pest management [101]. Understanding these seasonal population dynamics is therefore essential for designing and implementing effective integrated pest management strategies. Adjusting planting schedules to coincide with periods of lower pest pressure, combined with appropriate pest management practices, can help farmers optimize tomato production while minimizing crop losses and maximizing yield. The current study did not include a cost-benefit analysis of season-specific management strategies, which would be particularly valuable for smallholder farmers, who constitute the majority of tomato growers in the region.

The dissemination of *T. absoluta* can be favored by international trade and commerce, particularly for African countries where phytosanitary and quarantine procedures are not robust, and in some cases absent [6,102]. In Lubumbashi, for instance, farmers frequently import agricultural inputs such as seeds, seedlings, fruits and containers from neighboring countries including Zambia, Tanzania and Kenya. Interestingly, previous studies have documented that the spread of this invasive pest to new areas is primarily driven by the movement of infested seedlings, tomato fruits, and associated parking materials, as well as by contaminated agricultural equipment and vehicles [7]. The high invasion success of *T. absolut*a in the Lubumbashi region may also be attributed to the abundance of suitable solanaceous host crops combined with favorable climatic conditions, which together provide an ideal environment for the pest's establishment and proliferation [16]. Importantly, *T. absolut*a is listed as a quarantine pest [25], leading to trade restrictions on tomato, reduced market value of infested fruits, increased crop protection costs, and ultimately higher consumer prices for tomatoes [103].

Conclusion

*Tuta abs*oluta is an invasive cosmopolitan threat to sustainable tomato production worldwide with a tremendous capacity of acquiring resistance to most pesticides used for its management. In this study, the potency of both synthetic and botanical insecticides in the management of *T. absoluta* was documented under field conditions. Synthetic insecticides such as Dudu acelamectin 5% EC, Lambda-cyhalothrin 50 EC and Occasion Star 200SC exhibited significantly higher control efficacy against *T. absoluta* compared to cypermethrin 200 EC, which showed relatively low efficacy. Botanical insecticides including Nimbecidine and *T. vogelii* extract, also demonstrated promising insecticidal activity, highlighting their potential as alternative management options. Integrating chemical and botanical insecticides offers a sustainable strategy to maintain *Tuta absoluta* infestations below economic damage thresholds, thereby supporting consistent tomato yields in Lubumbashi, DR Congo.

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Credit authorship contribution statement

S.N. Mbuya contributed to conceptualization of the study, development of the methodology, coordination and execution of field experiments, data curation, visualization of results and preparation of the original manuscript draft. **O.M. Kankonda** contributed to the study design and methodology development and provided critical revisions and editing of the manuscript methodology. **N. Fallah** contributed to data curation, organization of datasets, and review and editing of the manuscript. **K.S. Akutse** contributed methodology design, technical guidance during experimentation, and critical revision and editing of the manuscript. **M.C. Cokola** contributed to methodology development, formal statistical analysis, data curation, generation of visual outputs, and review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Ethics approval

The research reported here was conducted in strict accordance with ethical guidelines and regulations outlined in the standard operating procedures of the University of Lubumbashi (UNILU/Lubumbashi-DR Congo). The collection of *Tephrosia vogelii* plant material was approved under authorization reference number UNILU/VDR/AGRO/025/2223.

Ethical statement

This study did not involve human participants or vertebrate animals. The collection and use of plant materials for extract preparation were conducted in accordance with applicable institutional and national guidelines. No endangered or protected species were used.

Data availability

The data used and/or analyzed in this study are available within the paper and its supplementary materials and will also be provided upon request from the corresponding author.

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Tables and figures legends

Table 1. Synthetic and botanical insecticides used

Synthetic insecticide	Chemical family	Manufacturer name	Registration number	Active ingredients	Mode of action	Do e/2 1
Dudu acelamectin 5% EC	Avermectin group and Neonicotinoid group	Bukoola Cchemical Industries Ltd	Ugc/2021/002701/h/RSR	Abamectin 20g/L + Acetamiprid 3%	Larvicide	30
Cypermethrin 200 EC	Pyrethroid	Zhengzhou Delong Chemical Co., Ltd	L4644 Act/Wet No. 36 of/van 1947	Alpha-cypermethrin	Larvicide/adulticide	20
Lambda-cyhalothrin 50 EC	Pyrethroid	Green Island Investments (Pty) Ltd.	L 11652 Act/Wet No.36 of/van 1947	Lambda-cyhalothrin	Adulticide	20
Occasion Star 200SC	Avermectin and Indoxacarb	Agro-Pests Solutions	PCPB (CR 1553)	Emanmectin benzoate + Indoxacarb	Larvicide/adulticide	3 m
Botanical insecticide						
Nimbecidine (Azadirachtin 0.03% EC)	Meliaceae	Osho Chemical Industries Ltd	KSh203-KSh8,625	Azadirachtin	Larvicide	100
***Tephrosia vogelii* extract**	Fabaceae			Rotenone	Larvicide	15% w/v
Sterile distilled water	-			-	-	

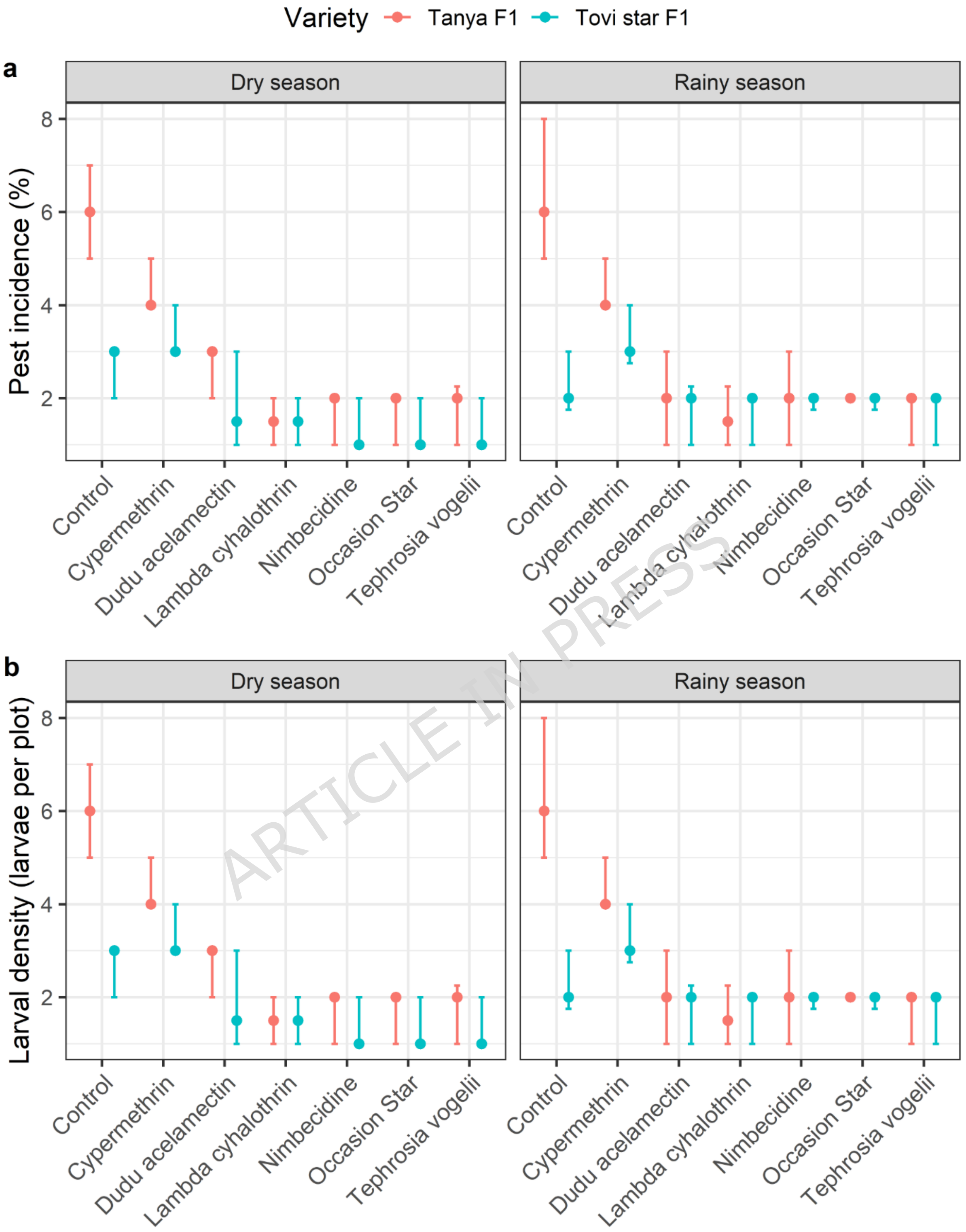

Figure 1. Tomato leaf-miner infestation in response to the application of treatments, stratified by season and tomato variety. **a:** Median pest incidence

across treatments; **b:** Median number of larvae across treatments. Bars represent median values with interquartile ranges. Points represent raw data. Orange data points/bars represent Tanya F1 variety, while blue data points/bars represent Tovi Star F1 variety.

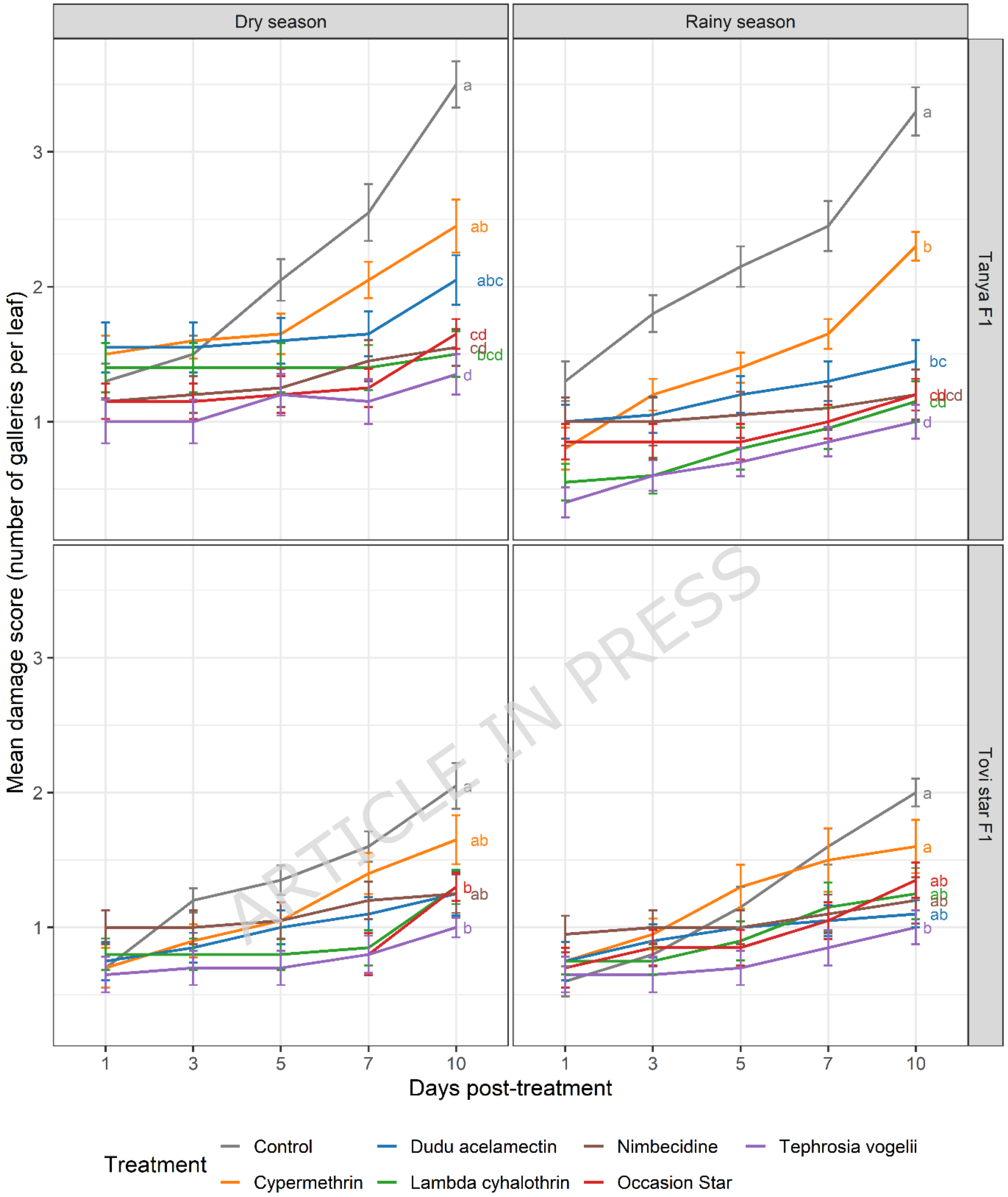

Figure 2. Evolution of leaf damage caused by *Tuta absoluta* on tomato according to treatment stratified by season and variety across time. Damage score represents the number of galleries in the leaf. Means ± standard error for each treatment followed by identical letters in each graph are not

statistically different at the significance level considered (α = 0.05), according to Sidak-adjusted pairwise comparisons of estimated marginal means.

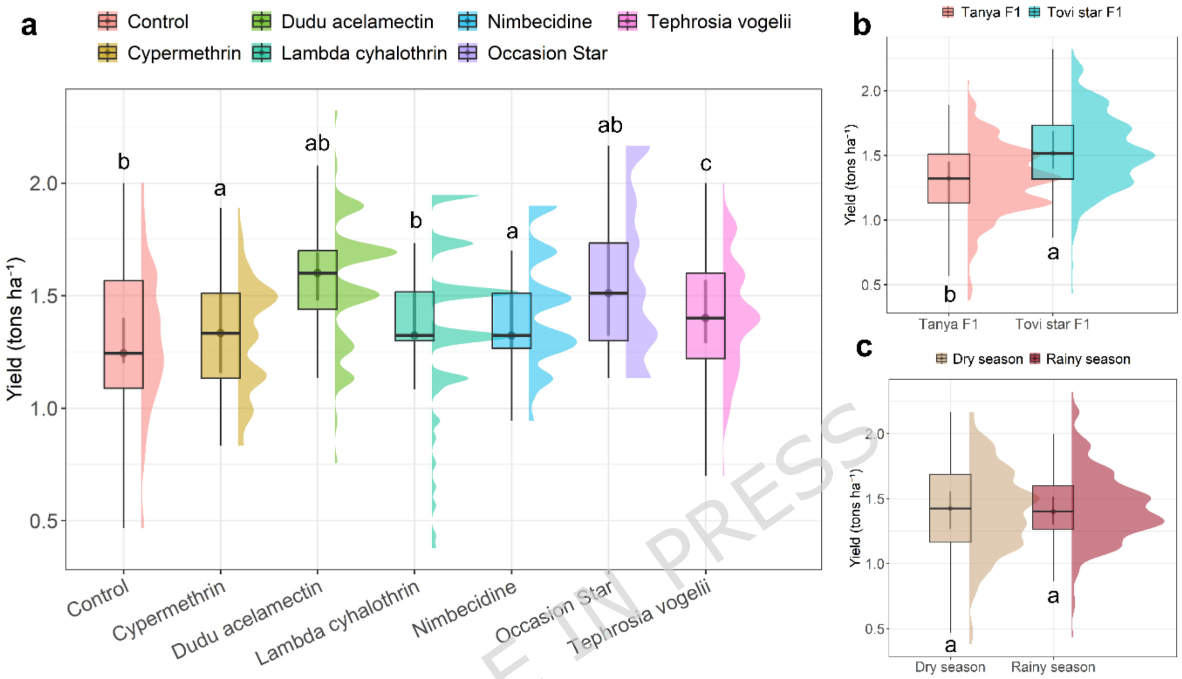

Figure 3. Rain cloud plot illustrates the variation of tomato yield. **a:** Yield variation across pest control treatments; **b:** Yield variation across crop varieties; **c:** Yield variation across seasons. The plot shows the raw data, probability density and summary statistics. Colors represent treatment types (magenta for *Tephrosia vogelii*; purple for Occasion Star 200SC; blue for Nimbecidine; teal for Lambda cyhalothrin; green for Dudu acelamectin; olive for Cypermethrin 200 EC; pink for Control), cultivars (pink for Tanya F1 and turquoise for Tovi Star F1) and seasons (sand for dry season and cherry rose for rainy season). Median and interquartile values followed by the same letter are not statistically different at the significance level considered (α = 0.05), according to the Dunn post-hoc pairwise comparisons test.

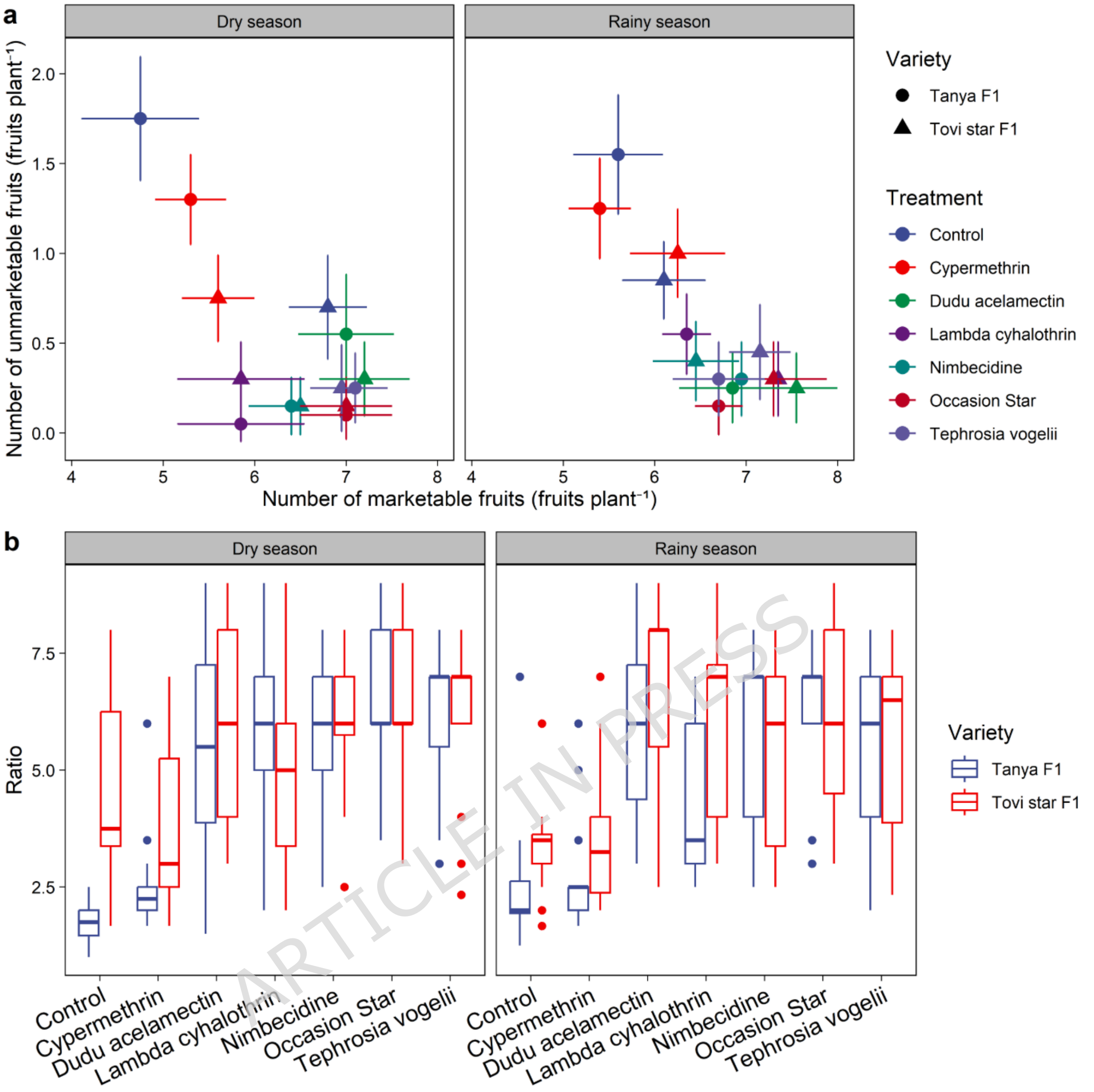

Figure 4. Differential effects of *Tuta absoluta* control on marketable fruit yield in the two cropping seasons. **a:** Comparison of tomato marketability (marketable and unmarketable fruits) across treatment efficacy for the two varieties. **b:** Efficacy ratios calculated as the number of marketable fruits divided by the number of unmarketable fruits plus one for each treatment and variety.

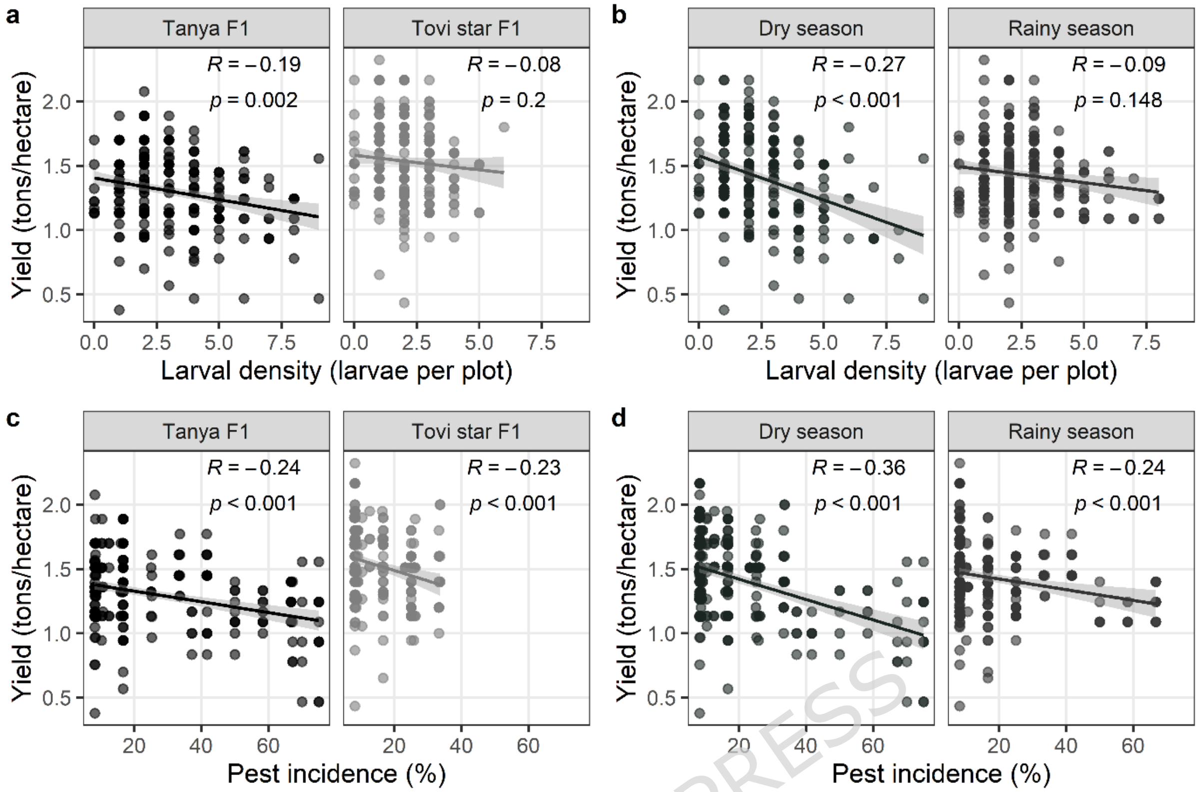

Figure 5. Scatter plot illustrating the effects of larval density and *Tuta absoluta* incidence on tomato yield. **a:** Varietal differences in yield response to increasing number of larvae; **b:** Season-specific yield losses associated with the number of larvae; **c:** Varietal differences in yield response to increasing incidence; **d:** Season-specific yield losses associated with the incidence of the pest. R in each plot represents the Spearman's rho coefficient.