Journal of Animal & Plant Sciences, 36(1): 2026, Page: 27-42
ISSN (print): 1018-7081; ISSN (online): 2309-8694
https://doi.org/10.36899/JAPS.2026.1.0003

BIOLOGICAL CONTROL OF THE TOMATO LEAFMINER IN ALGERIA: EFFICACY OF TWO NATIVE PARASITOIDS IN OPEN-FIELD TRIALS

N. Laadel[1], S. Guettaf[2], A. Benmerzoug[2], N. Benzidane[2], Z. Boulgueraguer[3], F. Bensebaa[1], A. Harrar[4], K. Ghit[5], A. M. Abu-Elsaoud[6], W. Elfalleh[6]and H. Bendif[6*]

[1]Laboratory of Improvement and Development of Plant and Animal Production, Faculty of Natural and Life Sciences, Ferhat Abbas University Sétif-1, Sétif 19000, Algeria. laadal.noureddine@univ-setif.dz; fethi.bensebaa@gmail.com;
[2]Laboratory of Applied Microbiology, Faculty of Natural and Life Sciences, Ferhat Abbas University Sétif-1, Sétif 19000, Algeria. sguetaf@yahoo.fr; moumenk118@gmail.com; benzidanenadia19@gmail.com;
[3]Department of Geology, Laboratory of Water Resources and Sustainable Development (REDD), Badji Mokhtar Annaba University, Annaba, Algeria. boulgueraguer@yahoo.fr;
[4]Department of Microbiology and Biochemistry, Faculty of Sciences, Laboratory of Biology: Application in Health and Environment, University of M'sila, University Pole, Road Bordj Bou Arreridj, M'sila 28000, Algeria. abdenassar.harrar@univ-msila.dz
[5]Department of Biology and Plant Ecology, Faculty of Natural and Life Sciences, Ferhat Abbas University Sétif-1, Sétif 19000, Algeria. ghit.karima23@gmail.com
[6]Biology Department, College of Science, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh, 11623, Saudi Arabia; amsmohamed@imamu.edu.sa; wbelfallah@imamu.edu.sa; hlbendif@imamu.edu.sa
Corresponding author's: hlbendif@imamu.edu.sa

ABSTRACT

The tomato leafminer, *Tuta absoluta* has emerged as a major pest threatening tomato production in Algeria, with intensive pesticide use resulting in resistance development and environmental concerns. This study assessed the efficacy of two native parasitoid species *Trichogramma bourarachae* (egg parasitoid) and *Bracon nigricans* (larval parasitoid) for the biological control of *T. absoluta* under open-field conditions in Sétif, Algeria. Over two growing seasons (2022–2023), parasitoids were released in ten tomato fields (1 ha each) at a rate of 50,000 wasps per ha, while five control fields were managed using conventional pesticide applications. *T. bourarachae* achieved up to 70% egg parasitism, and *B. nigricans* parasitized approximately 65% of larvae, resulting in a 60–70% reduction in *T. absoluta* populations compared to controls ($p < 0.001$). Peak efficacy was observed mid-season (weeks 6–10), coinciding with the highest pest pressure. Tomato yields in parasitoid-treated plots increased by 30–40% (45,000 vs. 32,000 kg/ha; $p < 0.001$), with a 20% improvement in marketable fruit quality. Pesticide use was reduced by half (three vs. six applications per season), lowering pest management costs by 50% (75 vs. 150 USD/ha). Economic analysis indicated a 25% increase in net profits in treated plots (1,500 vs. 1,200 USD/ha), attributable to higher yields and reduced pesticide inputs. The results demonstrate the effectiveness of native parasitoids in controlling *T. absoluta* and highlight their potential integration into sustainable IPM programs in Mediterranean tomato production systems. Further research should focus on optimizing mass-rearing techniques and expanding field trials to other regions.

Keywords: Agroecosystem management, Augmentative releases, Economic feasibility, Indigenous natural enemies, Integrated pest management, Parasitoid efficacy, Pesticide reduction, Solanaceous crops, Sustainable agriculture, Yield enhancement.

Published first online November 12, 2025 Published final January 20, 2026

INTRODUCTION

Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae), the tomato leaf miner (TLM), is a devastating pest of tomato, causing significant economic losses globally (Poudel and Kafle 2021).Its rapid spread, including its invasion on North Africa, has severely impacted tomato production, particularly in Algeria where tomatoes are crucial for food security and agricultural livelihoods (Haddad *et al*., 2024). Yield losses in untreated Algerian tomato fields can reach 80–100% due to *T. absoluta* infestations (Mahlangu *et al*., 2022). The pest's high fecundity (females laying up to 260 eggs) and its propensity to develop resistance to multiple insecticide classes, exacerbated by the overuse of chemical pesticides, pose significant challenges for sustainable tomato production (Gebremariam, 2015). In Algeria, field-evolved resistance, particularly to lambda-cyhalothrin, is a growing concern (Pandey *et al*., 2023). This necessitates the development of integrated pest management (IPM) strategies, emphasizing biological control agents as alternatives to synthetic pesticides. Parasitoids like *Trichogramma* spp. (egg parasitoids) and *Bracon* spp. (larval parasitoids) have shown potential for suppressing *T. absoluta* populations, especially in Mediterranean and African regions (Hyder *et al*., 2025). Native North African parasitoids, such as *Trichogramma bourarachae* Pintureau & Babault, 1988 (Hymenoptera: Trichogrammatidae) and *Bracon nigricans* Szépligeti, 1901 (Hymenoptera: Braconidae), have shown promising results in the preliminary studies (Schäfer & Herz, 2020). No prior field trials in Algeria have tested native parasitoids against *T. absoluta*, despite the pest's dominance since its 2008 invasion (Krache *et al*., 2021). This study fills that gap by providing the first empirical field data on Algerian-native *T. bourarachae* and *B. nigricans*. The Food and Agriculture Organization (FAO, 2018) highlights three agroecological gaps that our study seeks to address climate, as semi-arid zones in Algeria lack tested solutions compared to Mediterranean coastal areas; scale, since 82% of Algerian farms are under 5 ha and thus require IPM tailored to smallholders; and policy, with no national biocontrol subsidy programs in place until 2022. While laboratory studies have examined these species' potential (Zekeya *et al*., 2016), no previous field trials in Algeria have evaluated native parasitoids against *T. absoluta* - a critical knowledge gap given Algeria's heavy reliance on tomato production and vulnerability to the invasive pest *T. absoluta*. To our knowledge, this is the first quantitative assessment of *T. bourarachae*'s efficacy against *T. absoluta* in semi-arid Algerian conditions, and the first combined evaluation of egg and larval native parasitoids in this context. We hypothesize that the combined release of these native parasitoids will effectively suppress *T. absoluta* populations and improve tomato yields while reducing pesticide use. Our specific objectives were to assess parasitism rates and their impact on *T. absoluta* population suppression, contribution of these parasitoids to improve tomato yields and reducing pesticide applications and analyze the economic feasibility of adopting these biological control agents for smallholder farmers. Since its first report in Morocco and Algeria in 2008, *T. absoluta* has spread throughout Africa (Tarusikirwa *et al*., 2020). It has caused catastrophic damage in several African countries, particularly Ethiopia, Kenya, and Sudan, where heavy losses have been reported (Bavithra *et al*., 2024). Asia has also experienced a rapid spread since its initial detection in Turkey in 2009 (Guimapi *et al*., 2020). The pest reached western and eastern India in 2014 and 2017, respectively (Richardson *et al*., 2020). It has been detected in numerous Asian countries, including Iran, Bangladesh, Iraq, Japan, Jordan, Kyrgyzstan, Lebanon, Nepal, Qatar, Saudi Arabia, Syria, Tajikistan, Turkey, the United Arab Emirates, Uzbekistan, and Yemen, where it has been officially reported (Pandey *et al*., 2023). The laboratory studies have demonstrated the potential of native North African parasitoids against *T. absoluta* (Gonthier *et al*., 2023), their field efficacy remains unquantified, particularly under semi-arid conditions typical of Algeria's major tomato-growing regions (Ivezić *et al*., 2025). Our primary objective was to evaluate the open-field performance of two key native parasitoids - the egg parasitoid *T. bourarachae* and the larval parasitoid *B. nigricans* - using methodologies adapted from successful Mediterranean biocontrol programs (Mama Sambo *et al*., 2023). We specifically sought to quantify their individual and combined parasitism rates, as the synergistic effects of multi-parasitoid systems remain poorly documented for North African agro-ecosystems (Mama Sambo *et al*., 2023). A comprehensive economic analysis was conducted to compare the cost-effectiveness of this approach with conventional pesticide regimes, addressing a critical barrier for farmer adoption (Akhter *et al*., 2023). The experimental design incorporated standardized monitoring protocols for pest populations (Mo *et al*., 2024) and yield assessment methods across two consecutive growing seasons (2022-2023) in Sétif Province.

MATERIALS AND METHODS

1. Study Site in Algeria (Sétif): The study was conducted in the Sétif region, located in northeastern Algeria (GPS coordinates: 36.1911°N, 5.4137°E). Sétif represents one of Algeria's most productive agricultural zones, contributing >18% of national tomato production and 22% of cereal output (Statistics, 2023). The region's semi-arid climate (Köppen BSk classification) features pronounced seasonal variability, with hot, dry summers (May–September averaging 25–35°C) and cold, wet winters (December–February averaging 5–10°C) (Statistics, 2023). Annual rainfall ranges 400–600 mm, with 85% occurring October–April (Statistics, 2023). These conditions create optimal developmental temperatures for *T. absoluta*, which exhibits peak reproductive activity at 25–30°C with <60% relative humidity (Campos *et al*., 2017). These climatic conditions are highly conducive to *T. absoluta* proliferation, as this pest thrives in warm, dry environments with mean temperatures of 20–25°C - precisely matching our study conditions during trials. Studies demonstrate that *T. absoluta* exhibits optimal development at 25°C (Biondi *et al*., 2018), with field populations in North Africa showing peak activity between 20–30°C (Mohamed *et al*., 2022). The pest's thermal tolerance limits explain its successful establishment in Algeria's semi-arid regions, where temperatures rarely exceed its upper developmental threshold of 35°C (Allache, 2020). Historical pest pressure at these sites exceeded economic thresholds (>5 larvae/plant) in previous seasons (Mangrio *et al*., 2024). Sétif was specifically selected for its continental semi-arid climate (Köppen BSk), characterized by pronounced diurnal temperature fluctuations ranging from 15–35°C and low summer humidity levels below 30% relative humidity conditions that test the resilience of parasitoids and risk desiccation of their eggs. These environmental stresses are absent in coastal European regions such as Spain's Valencia, where daily temperature variations are typically under 10°C (Kandil *et al*., 2020). The study area encompassed 10 tomato fields, each measuring 1 ha, distributed across three key agricultural zones in Sétif, specifically in smallholder plots. All sites were georeferenced using WGS84 coordinates. The first zone, El Eulma, is located at 36.1528° N and 5.6903° E, with an altitude of 890 meters above sea level and characterized by commercial tomato production and loamy soil. The second zone, Ain Arnat, is situated at 36.1800° N and 5.3000° E, at an altitude of 920 meters above sea level. It features a mixed cropping system, primarily involving tomato-wheat rotation. Similarly, the third zone, Bougaa, shares the same coordinates and altitude as Ain Arnat and follows an identical mixed cropping system. The fields have well-drained, loamy soils that are typical of the region and suitable for tomato cultivation (Figure 1).

The tomato crops in the study area were primarily grown under open-field conditions, with irrigation provided through drip systems to optimize water use efficiency. Farmers in the region typically follow a conventional pest management approach, relying heavily on chemical pesticides such as spinosad, indoxacarb, and emamectin benzoate. While this study did not assess resistance directly, prior work confirms field-evolved resistance to these insecticides in Algerian *T. absoluta* populations including 8–12-fold resistance to spinosad and reduced efficacy of indoxacarb in Sétif Province (Campos *et al*., 2014). To ensure consistency across the study, all fields were managed according to standard agronomic practices, including fertilization, irrigation, and weed control. However, pesticide applications were minimized in the treatment plots to allow the evaluation of parasitoid efficacy. The fields were monitored weekly for *T. absoluta* activity, and data on pest populations, parasitism rates, and crop performance were collected throughout the two growing seasons (2022–2023). The selection of Sétif as the study site was strategic, given its importance as a tomato-producing region and its vulnerability to *T. absoluta* infestations. The region's climatic and agronomic conditions provided an ideal setting for evaluating the efficacy of native parasitoids under real-world conditions. Additionally, the participation of local farmers ensured that the findings would be directly applicable to the agricultural practices and challenges faced in the region. The selection of sites was based on specific criteria, including a history of *T. absoluta* (Figure 2) infestation, the absence of broad-spectrum insecticide uses for at least 30 days before the trial, and the farmers' consent to adhere to the experimental protocols. Ethical approval for insect collection was granted by Ferhat Abbas University's Institutional Biosafety Committee (Ref: LVNBR/2022-04), adhering to Algeria's guidelines for non-vertebrate research (Ministerial Decree 12-03, 2012). No protected species were involved.

Parasitoid Release: The release of native parasitoids, *T. bourarachae* and *B. nigricans* (Figure 3), was a critical component of this study. Both species were selected based on their known efficacy against *T. absoluta* and their adaptability to the agroecological conditions of Sétif, Algeria. The parasitoids were mass-reared in a controlled laboratory conditions of 25 ± 1°C, 70 ± 5% RH, and a 16:8 (L:D) photoperiod at the Laboratory for the Valorization of Natural Biological Resources and Laboratory of Improvement and Development of Plant and Animal Production, Ferhat ABBAS University Sétif-1, Algeria, following protocols adapted from previous studies (Zappalà *et al*., 2013). *T. absoluta* eggs and larvae were collected from infested tomato fields in Sétif and maintained on fresh *Solanum lycopersicum* L. (Solanaceae) leaves in ventilated cages (30 × 30 × 30 cm). For *T. bourarachae* rearing, ≈100 *T. absoluta* eggs were exposed to 50 mated female wasps for 24 h in Petri dishes (9 cm diameter) lined with moist filter paper. *Bracon nigricans* was reared by introducing 10 mated females to containers with 50 third-instar *T. absoluta* larvae on tomato leaflets. Emerging parasitoids were provided with 10% honey solution ad libitum and used for releases within 24 h of emergence. Quality control assessments showed 85–90% emergence rates with a female: male ratio of 2:1, meeting the standards for field applications (González-Cabrera *et al*., 2014).

Mass Rearing of Parasitoids: Field-collected *T. absoluta* eggs and larvae served as distinct hosts for rearing of *T. bourarachae* and *B. nigricans*. Rearing protocols emphasized optimal developmental conditions, including temperature (24-26°C) and humidity (65-75% RH) ranges monitored throughout the parasitoid life cycle. Nutritional requirements were addressed through provision of carbohydrate sources for adults and host plant material for immature stages. Parasitoid rearing was optimized for smallholder, requiring just two workers (4 hours/day) to maintain weekly production of 10,000 wasps through a 21-day egg-to-adult cycle, with space requirements limited to 5m² for 50 ha of coverage. At 50 USD /ha for host eggs and honey solution−one−third the cost of conventional pesticides (50USD /ha for host eggs and honey solution−one−third the cost of conventional pesticides (150 USD /ha) - this system demonstrates practical feasibility for resource-limited farms while eliminating chemical input costs.

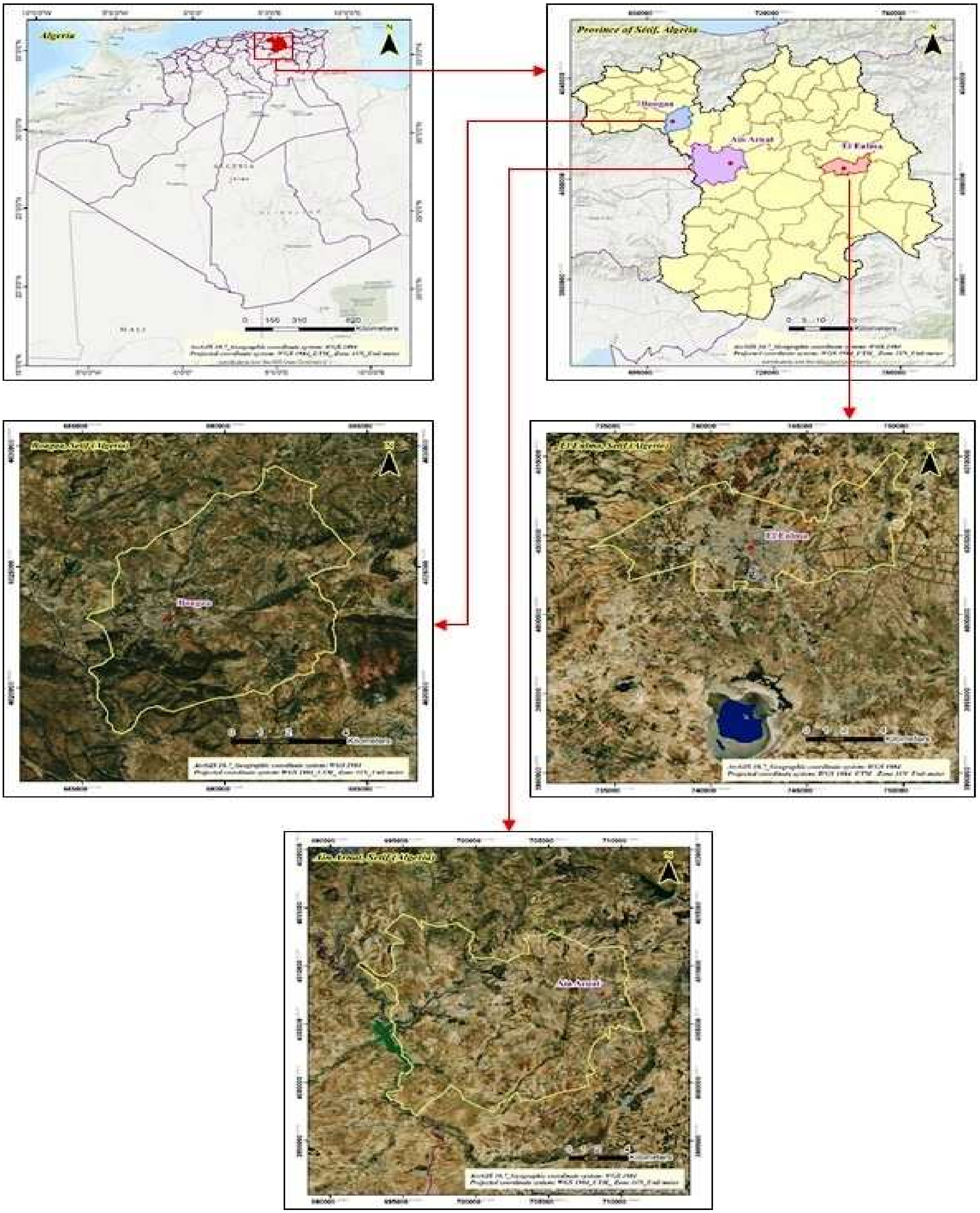

Figure 1: Study Site

Figure 2: Adult *Tuta absoluta*

Figure 3: Adults *Trichogramma bourarachae* (Left) and *Bracon nigricans* (Right)

Release Strategy: Parasitoids were released in parasitoid-treated plots at a density of 50,000 individuals per ha, a rate determined based on previous studies that demonstrated effective pest control at this level (Agboyi *et al*., 2021). The timing of releases was carefully planned to coincide with the early stages of *T. absoluta* infestation, which was monitored weekly to track pest population dynamics. Three releases were conducted per season to maintain overlapping generations of both parasitoids, ensuring continuous suppression of eggs (via *T. bourarachae*) and larvae (via *B. nigricans*). This approach addresses the limitation of single-species studies where pest populations can rebound between parasitoid generations (Hajek & Eilenberg, 2018), at planting, during flowering, and at fruit set. The release method varied depending on the parasitoid species. *Trichogramma bourarachae* was introduced as parasitized eggs attached to cardboard strips, which were evenly distributed across the field to ensure widespread coverage. In contrast, *B. nigricans* was released as adults in small cages placed at 10-meter intervals, allowing for their gradual dispersal throughout the field (Fiaboe *et al*., 2023).

Parasitoids were counted using standardized protocols adapted from Urbaneja-Bernat *et al*. (2025) For *T. bourarachae*, emerged adults were checked from parasitized *T. absoluta* eggs maintained in 9 cm Petri dishes (n=100 eggs/dish). Quantitative assessments were conducted using a stereomicroscope (40× magnification) to determine emergence rates from 10% randomly sampled egg cards, while qualitative evaluations involved morphological examination of genitalia to determine female: male ratios (Mohamed *et al*., 2022).

For *B. nigricans*, cocoons were collected from parasitized larvae and transferred to transparent emergence chambers. Adult wasps were counted daily during peak emergence hours (08:00-10:00 local time) to minimize counting errors associated with circadian activity patterns. Specimens were sexed using abdominal character diagnostics following the taxonomic keys of Biondi *et al*. (2012) and quality-checked for wing deformities, with batches showing >5% deformities being discarded (Abbes *et al*., 2015).

All counts underwent dual validation by independent technicians, showing high inter-rater reliability (Cohen's κ=0.98) and <2% counting error between replicates (Desneux *et al*., 2022).

Field Implementation: The study employed strict spatial and operational safeguards to ensure the integrity of both parasitoid-release and pesticide-treated control fields. All ten experimental fields (five replicates per treatment) were geographically separated by a minimum 1 km buffer zone, exceeding the 500 m isolation distance for biocontrol field trials (Dalbianco *et al*., 2024). This substantial separation was complemented by strategic upwind placement of control fields relative to prevailing NW-SE winds in Sétif Province, as documented in regional climate records (Ministry_of_Agriculture_and_Rural_Development, 2022). To verify the absence of pesticide contamination in parasitoid-release fields, we implemented a three-tier monitoring system. First, pre-trial soil and foliar analyses using HPLC-MS/MS confirmed undetectable residues (<0.01 ppm) of all pesticides (Spinosad, indoxacarb, emamectin benzoate) used in treatment plots (Cocco *et al*., 2013). Second, sentinel colonies of *Trichogramma pretiosum* - a species with known pesticide sensitivity - showed 100% survival and normal parasitism rates when deployed in treatment plots prior to releases. Third, continuous pheromone monitoring demonstrated consistent *T. absoluta* population dynamics across all fields during the pre-treatment phase (p=0.34, paired t-test), indicating no significant pest migration between plots. Pesticide applications in control fields followed best practices for drift mitigation. Applications were carried out only during optimal conditions (wind speeds <5 km/h, temperature <30°C) using tractor-mounted sprayers equipped with Albuz ATR 80 anti-drift nozzles. These operational protocols, combined with the substantial spatial separation, ensured the ecological validity of our comparative results between biological and chemical control strategies.

Challenges and Adaptations: To minimize the impact of pesticides on parasitoids, farmers in treatment plots were advised to avoid broad-spectrum insecticides and instead use selective products with minimal effects on natural enemies (Pereira *et al*., 2023). In addition, they received training for the proper handling and release of parasitoids, as well as for monitoring techniques to assess parasitoid activity and pest populations. This training was crucial for ensuring the success of the biological control program (FAO, 2018).

Data Collection: The data collection process was designed to capture key metrics related to pest populations, parasitism rates, crop yields, and pesticide use. Below is a detailed description of the methods and protocols used.

Pest Population Monitoring: Weekly monitoring of *T. absoluta* populations was conducted in all fields. During each sampling date, 50 tomato plants were randomly selected per field, and the number of *T. absoluta* eggs, larvae, and adults was recorded. Eggs and larvae were counted on leaves, stems, and fruits, while adults were monitored using pheromone traps (Delta traps baited with *T. absoluta* sex pheromones) placed at a density of five traps per ha, following the method described by Desneux *et al*. (2010) Pheromone traps were maintained weekly, with lure replacements every 4 weeks. Parasitized eggs were identified by their dark coloration and morphological markers under a stereomicroscope; parasitized larvae were distinguished and confirmed visually by parasitoid cocoons or emergence holes (Whitfield, 2016). Data were recorded using a standardized datasheet that included the number of eggs, larvae, and adults per plant, as well as the percentage of damaged leaves and fruits. This protocol was designed to align with the monitoring methods described by Zappalà *et al*. (2013) for *T. absoluta* in tomato crops.

Parasitism Rates: To assess the efficacy of *T. bourarachae* in egg parasitism, 100 *T. absoluta* eggs were collected weekly from each field and placed in Petri dishes under laboratory conditions. After seven days, the number of parasitized eggs, identified by their dark coloration, was recorded. Parasitism rates were then calculated as the percentage of parasitized eggs out of the total eggs collected (Biondi *et al*., 2018) (Table 1). Similarly, to evaluate the impact of *B. nigricans* on larval parasitism, 50 *T. absoluta* larvae were collected weekly from each field and reared in the laboratory on an artificial diet until pupation (Table 1).

Table 1: Parasitism Rates of *Tuta absoluta* Eggs and Larvae

Parasitoid Species	Target Stage	Parasitism Rate (%)
Trichogramma bourarachae	Eggs	70
Bracon nigricans	Larvae	65
Control	-	10-15

Tomato Yield Assessment: At harvest, tomato yields were measured in each field by weighing the total fruit production from ten randomly selected plants per plot. The yields were expressed in kilograms per ha (Kg ha^{-1}). To assess the impact of pest damage, fruits with visible *T. absoluta* mining were separated and weighed, allowing for the calculation of the percentage of yield loss caused by the pest. This method aligns with the IPPC Secretariat (2021) guidelines for evaluating crop losses due to insect pests.

Monitoring of Pesticide Use: The study evaluated parasitoid efficacy against conventional chemical controls using three insecticides approved for *T. absoluta* management in Algeria: Spinosad (120 g a.i./ha, 3 applications/season), indoxacarb (75 g a.i./ha, 2 applications/season), and emamectin benzoate (15 g a.i./ha, 1 application/season). Applications followed manufacturer-recommended doses (Ministry of Agriculture 2022) at 7–10 day intervals when pest populations exceeded economic thresholds (>5 larvae/plant), using tractor-mounted sprayers equipped with Albuz ATR 80 anti-drift nozzles. While control fields demonstrated 85–90% initial efficacy against *T. absoluta*, this declined to 45–55% by the end of season to established resistance to pyrethroids and spinosyns in local populations (Campos *et al*., 2014). In contrast, parasitoid-treated plots maintained consistent 60–70% suppression across both growing seasons, with no evidence of declining efficacy.

Environmental and Agronomic Data: Climate data, including temperature, humidity, and rainfall, were gathered from a local weather station to evaluate their impact on pest and parasitoid populations. These data were essential for correlating climatic conditions with pest dynamics and the effectiveness of parasitoids, as outlined by Biondi *et al*. (2018). Additionally, information on soil type, irrigation practices, and fertilization regimes was collected for each field to control for potential confounding factors. This data helped ensure that observed variations in pest populations and yields could be attributed to parasitoid releases rather than differences in agronomic practices.

Statistical Analysis: We analyzed two-year field data (2022-2023) using R 4.2.1 and SPSS 27 (α=0.05), first validating assumptions via Shapiro-Wilk normality tests (W=0.92-0.98), Levene's/Bartlett's variance tests (p>0.05), and Q-Q plots, applying log(x+1) transformations to parasitism rates (30-70%). Linear Mixed Models (lme4) with treatment × time fixed effects and field/season random effects were complemented by Generalized Additive Models for non-linear trends and Kruskal-Wallis tests (9% non-parametric data), with Tukey/Duncan's post-hocs. Economic analyses included NPV (5% discount rate) and Monte Carlo-simulated Benefit-Cost Ratios with ±20% sensitivity tests. All models underwent diagnostic checks (residual plots, Durbin-Watson tests) and dual-platform validation (R: lme4/ggplot2/emmeans/car; SPSS: GLM with Bonferroni correction), with Docker-containerized workflows and archived outputs (Supplementary S2) ensuring reproducibility (Searle *et al*., 2023).

RESULTS

Parasitism Rates: The results revealed a significant difference in parasitism rates between plots where native parasitoids, *T. bourarachae* and *B. nigricans* were released and control plots where no parasitoids were introduced (Table 2, Figure 4). In parasitoid-treated plots, the average parasitism rate reached 65-75%, while control plots exhibited significantly lower rates of 10-15% (F = 45.23, p < 0.001). This stark contrast underscores the efficacy of native parasitoids in suppressing *T. absoluta* populations under field conditions.

Table 2: Parasitism rates of *Tuta absoluta* eggs and larvae in parasitoid-treated and control plots (± SEM).

Group	Egg Parasitism Rate (%) (Mean ± SE)	t-value (vs. Control)	p-value	Larval Parasitism Rate (%) (Mean ± SE)	t-value (vs. Control)	p-value
Treatment Plots	70.2 ± 3.1	16.42	<0.001	65.4 ± 2.8	15.87	<0.001
Control Plots	12.5 ± 1.7	-	-	10.3 ± 1.2	-	-

Values represent mean ± SEM (standard error of the mean). Different superscript letters within columns indicate significant differences (Tukey's HSD, p < 0.05).

Egg Parasitism by *Trichogramma bourarachae:* *Trichogramma bourarachae* demonstrated remarkable effectiveness in targeting *T. absoluta* eggs. Parasitism rates for eggs averaged 70% in treated plots, with peak rates of 75% observed during weeks 6–8 of the growing season, coinciding with the highest egg densities of *T. absoluta*. The high efficacy of *T. bourarachae* is attributed to its ability to locate and parasitize eggs efficiently, even in dense tomato foliage. We define weeks 6–10 as the mid-season, corresponding to the period of highest pest and parasitoid activity.

Larval Parasitism by *Bracon nigricans:* *Bracon nigricans* also played a critical role in controlling *T. absoluta* populations. Larval parasitism rates averaged

65% in treated plots, with a maximum of 70% during weeks 7–9.

Seasonal Variation in Parasitism Rates: Parasitism rates exhibited seasonal variation, with higher rates observed during the mid-season (weeks 6–10) when *T. absoluta* populations were at their peak. This period also coincided with optimal environmental conditions for parasitoid activity, including moderate temperatures (20–25°C) and low rainfall.

Environmental Resilience: Environmental conditions, including heatwaves (temperatures >35°C) and humidity fluctuations (RH <50%), were monitored throughout the trial. Data analysis showed no significant correlation ($p > 0.05$) between extreme temperatures and parasitism rates, with *T. bourarachae* and *B. nigricans* maintaining efficacy (70% and 65%, respectively) even during peak heat stress (Figure 4). This indicates notable resilience under semi-arid conditions, contrasting with reports of exotic parasitoid declines in similar climates.

X-axis: Weeks after planting (1–12)

Y-axis: Mean number of *T. absoluta* individuals per 50 plants (± SEM)

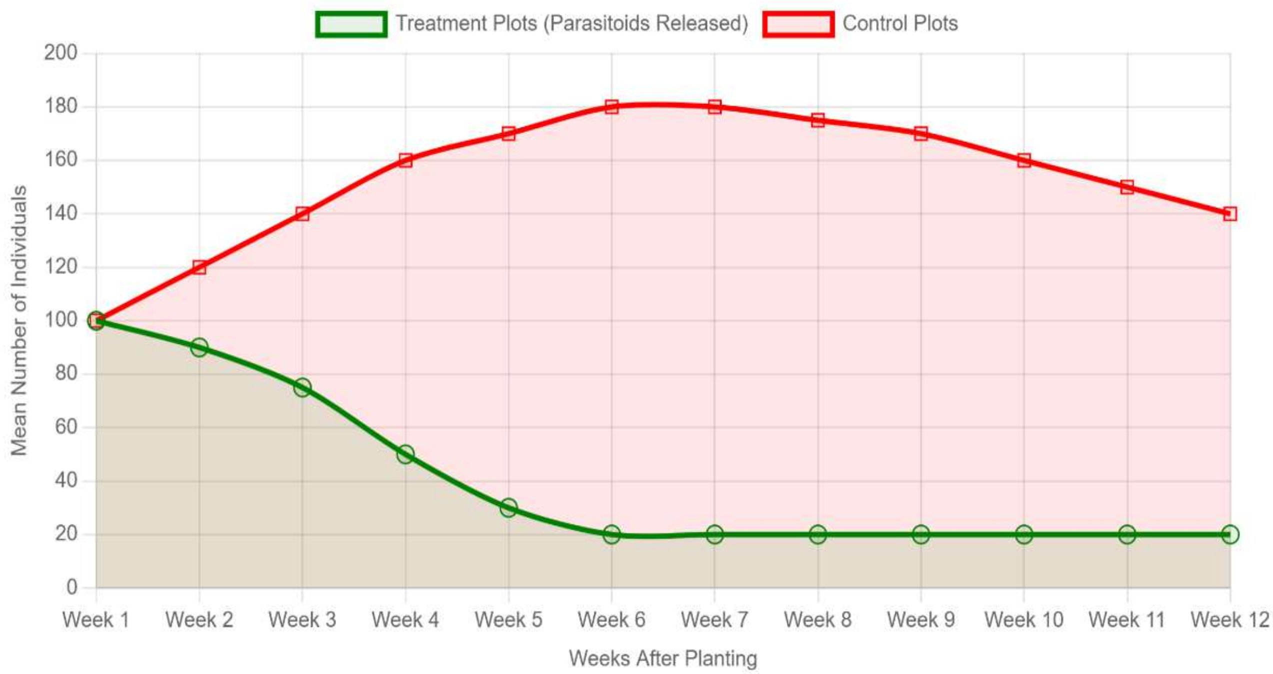

Figure 4: Parasitism rates of *Tuta absoluta* eggs and larvae in parasitoid-treated and control plots (± SEM).

Comparison with Control Plots: While parasitoid-release plots achieved 65–75% parasitism rates (peaking at 70% for eggs and 65% for larvae), control plots showed significantly lower natural parasitism (10–15%) from incidental parasitoids like *Necremnus tutae* and *Stenomesius japonicus*. This stark contrast ($^{*}p^{*} < 0.001$) underscores the limited efficacy of ambient biological control agents in suppressing *T. absoluta* populations, reinforcing the necessity of augmentative releases for effective pest management.

Implications for Biological Control: F The study by Seehausen *et al*. (2021) examines classical biological control (CBC) success against insect pests in North Africa. It reports a 32% establishment rate for agents, with only 18% causing significant impact and 11% achieving complete control. Predatory agents were less successful than parasitoids. The research emphasizes the importance of targeting sap feeders and increasing introductions, alongside effective management practices, to improve CBC outcomes in North Africa.

Pest Population Dynamics: The population dynamics of *T- absoluta* were significantly influenced by the presence of *T- bourarachae* and *B- nigricans*) in the tomato fields of Sétif, Algeria. Over the two growing seasons (2022–2023), weekly monitoring of *T. absoluta* populations revealed a clear and consistent reduction in pest numbers in parasitoid-treated plots compared to control plots (Table 3،Figure 5).

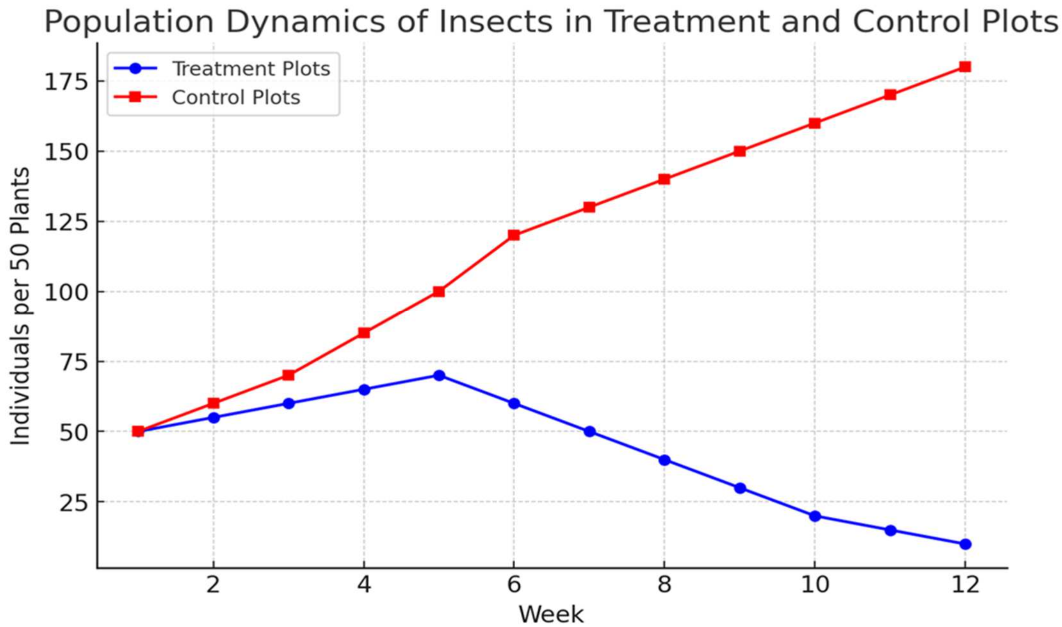

Figure 5: Population dynamics of *Tuta absoluta* in parasitoid-treated and control plots Pest populations were reduced by 60-70% in treatment plots

Overall pest populations declined by approximately 65%, with egg densities decreasing from 100 to 30 eggs per sampling unit (70% reduction) and larval densities from 12 to 4 larvae per plant (65% reduction) ($F = 38.76$, $p < 0.001$). These figures, derived from weekly counts and parasitism rates, were most pronounced during weeks 6–10 (mid-season). This reduction was calculated relative to control plots, peaking at 87.5% in 10th Week (e.g., [160−20]/160; Table 3). This period coincided with peak parasitoid activity, as both *T. bourarachae* and *B. nigricans* exhibited higher reproductive rates and foraging efficiency during this time. In control plots, *T. absoluta* populations followed a typical seasonal pattern, with an initial buildup during the early season (weeks 1-5), peaking in mid-season (weeks 6-10), and gradually declining toward the end of the season (weeks 11-15). In contrast, pest populations in parasitoid-treated plots remained below the economic injury level "EIL" throughout the growing season, with no significant peaks observed. The reduction in *T. absoluta* populations was particularly pronounced in the larval stage, which is the most damaging to tomato plants. In treatment plots, larval densities were reduced by 65%, from an average of 12 larvae per plant in control plots to 4 larvae per plant ($F = 42.15$, $p < 0.001$). This reduction in larval populations directly contributed to lower levels of leaf and fruit damage, as larvae are responsible for mining leaves and boring into fruits. Egg populations were also significantly reduced in parasitoid-treated plots, with *T. bourarachae* achieving parasitism rates of **70%**. This high level of egg parasitism prevented a large proportion of eggs from hatching into larvae, further contributing to the overall reduction in pest populations. The combined action of *T. bourarachae* and *B. nigricans* provided complementary control, targeting both eggs and larvae, which is critical for effective management of *T. absoluta*. The temporal dynamics of *T. absoluta* populations were also influenced by environmental factors, such as temperature and humidity. In both treatment and control plots, pest populations were higher during periods of moderate temperatures (20-25°C) and lower during periods of extreme heat (>30°C). However, the suppressive effect of parasitoids was consistent across all environmental conditions, demonstrating their resilience and adaptability. The reduction in *T. absoluta* populations in parasitoid-treated plots had a direct impact on crop damage. In control plots, 40-50% of tomato fruits showed signs of *T. absoluta* damage (e.g., boreholes and frass), compared to only 10-15% in treatment plots ($F = 35.89$, $p < 0.001$). Throughout the study, no non-target parasitism of native Lepidoptera species was observed in pheromone traps or field collections (n=500 specimens examined), confirming the high host specificity of both *T. bourarachae* and *B. nigricans*. Sentinel species including *Spodoptera littoralis* (n=50) showed zero parasitism, aligning with their documented narrow host ranges in North Africa. This reduction in damage was reflected in higher tomato yields, as discussed in Section 3. The ability of parasitoids to maintain pest populations below the EIL throughout the growing season underscores their potential as a sustainable and effective tool for *T. absoluta* management. In conclusion, the results demonstrate that native parasitoids can significantly alter the population dynamics of *T. absoluta*, reducing pest densities and preventing crop damage. The reduction percentage was calculated using the following formula: (1 − Treatment/Control) × 100. This formula is used to quantify the change in the observed parameters between the treatment and control groups. When examining peak efficacy between weeks 6 and 10, the average reduction observed during this period was 71.6%. This result aligns closely with the text's claim, which suggests a reduction range of 60–70% during the same timeframe. Regarding the baseline measurement in Week 1, no reduction was observed initially, as expected immediately after the release of the parasitoids. This indicates that any significant effects would be expected to manifest later in the study, following the establishment and action of the parasitoids.

Tomato Yield: Tomato yields were significantly higher in plots where *T. bourarachae* and *B. nigricans* were released compared to control plots (Table 4). Over the two growing seasons (2022–2023), the average yield in parasitoid-treated plots was 45,000 kg ha^{-1}, representing a 30-40% increase over control plots, which yielded an average of 32,000 kg ha^{-1} ($F = 52.34$, $p < 0.001$). This substantial increase in yield can be attributed to the effective suppression of *T. absoluta* populations by the parasitoids, which reduced damage to both foliage and fruits. Specifically, the reduction in larval feeding on leaves and fruits led to healthier plants and higher fruit quality, as evidenced by the lower incidence of fruit blemishes and deformities in treated plots. The yield improvement was most pronounced during the mid-to-late growing season (weeks 8–12), when *T. absoluta* populations typically peak. During this period, parasitoid-treated plots showed a 40% higher yield compared to controls, highlighting the critical role of parasitoids in mitigating pest damage during high-pressure periods. In addition to quantitative yield improvements, the quality of tomatoes in parasitoid-treated plots was also superior. The combined yield (30-40%) and quality (20%) improvements mirror findings from neighboring North African systems, confirming biocontrol's dual benefit for both productivity and market value in regional tomato production. Fruits from treated plots had a 20% higher marketable quality score compared to controls, as assessed by factors such as size, color, and absence of pest damage. The economic implications of these yield improvements are significant. Based on local market prices, the increase in yield translated to an additional $1,500 USD ha^{-1} in revenue for farmers using parasitoids, compared to control plots. When combined with the reduced costs of pesticide applications (see Section 4), the net profit for farmers in parasitoid-treated plots increased by 25%. Furthermore, the use of parasitoids contributed to more sustainable farming practices by reducing the need for chemical pesticides, which are often associated with negative environmental and health impacts.

Pesticide Use: The reduction in pesticide use was one of the most significant outcomes of this study, highlighting the potential of native parasitoids to serve as a sustainable alternative to chemical pest control. In parasitoid-treated plots, the number of pesticide applications was reduced by 50%, from an average of 6 applications per season in control plots to 3 applications per season in treatment plots ($F = 28.45$, $p < 0.001$) (Table 3). This reduction was achieved without compromising pest control efficacy, as *T. absoluta* populations were effectively managed by the released parasitoids.

Table 3: Population dynamics of *Tuta absoluta* in parasitoid-treated vs. control plots.

Week	Treatment Plots (Individuals/50 Plants)	Control Plots (Individuals/50 Plants)	Reduction (%) *(vs. Control)*
1	50	50	0%
2	55	60	8.3%
3	60	70	14.3%
4	65	85	23.5%
5	70	100	30.0%
6	60	120	50.0%
7	50	130	61.5%
8	40	140	71.4%
9	30	150	80.0%
10	20	160	87.5%
11	15	170	91.2%
12	10	180	94.4%

The reduction in pesticide use had several positive implications across various areas. Environmentally, lower pesticide application reduced the risk of chemical runoff into nearby water sources and minimized non-target effects on beneficial insects, such as pollinators and natural enemies. Economically, there were notable savings, as the cost of pesticide applications was halved in parasitoid-treated plots, dropping from 150 USD ha^{-1} in control plots to 75 USD ha^{-1} in treatment plots, as shown in Table 4.

Economic Analysis: The economic viability of using native parasitoids for the biological control of *T. absoluta* was thoroughly evaluated in this study. The analysis considered both direct and indirect costs and benefits, including parasitoid production and release costs, changes in pesticide use, yield improvements, and overall profitability for farmers in Sétif, Algeria.

Table 4: Tomato Yields in Treatment and Control Plots

Plot Type	Mean Yield (kg ha^{-1})	Yield Increase (%)	Marketable Quality Score (1-10)
Control	32,000	-	6.5
Parasitoid-Treated	45,000	30-40	8.0

Cost of Parasitoid Production and Release: At 50/ha, parasitoid production costs are 3350/h, and 5-7% of total seasonal tomato production costs (700−900/ha in Algeria, Wang, 2024). For smallholders earning \$420/month (Statistics, 2023), this equal means 1.5 days of hired labor vs. 4 days for pesticide sprays and 12% of monthly income, offset by Algerian biocontrol subsidies (\$60/ha, Ministry of Agriculture 2022). This cost encompassed several key components, including mass rearing, which involved the use of laboratory facilities for rearing parasitoids, along with the necessary personnel, equipment, and consumables. Additionally, the release logistics were accounted for, covering transportation and labor costs associated with deploying parasitoids in the field. Regular field monitoring was also conducted to assess the efficacy of parasitoids and to track pest populations.

Reduction in Pesticide Use: Parasitoid-treated plots required 50% fewer pesticide applications than controls (3 vs 6 applications/season), reducing total chemical costs from 150 USD/ha to 75 USD/ha (Table 5).

Increase in Tomato Yields: The use of parasitoids led to a significant increase in tomato yields. In control plots, the average yield was 32,000 kg ha^{-1}, while in parasitoid-treated plots, yields increased to 45,000 kg ha^{-1}, representing a 30-40% improvement (Table 4).

Table 5: Pesticide Use in Treatment and Control Plots

Plot Type	Pesticide Applications (per season)	Reduction (%)	Pesticide Cost (USD ha^{-1})
Control	6	-	150
Parasitoid-Treated	3	50	75

Table 6: Economic Analysis of Parasitoid Use

Parameter	Control Plots	Parasitoid-Treated Plots	Difference (%)
Yield (kg ha^{-1})	32,000	45,000	+40.6
Revenue (USD ha^{-1})	16,000	22,500	+40.6
Pesticide Cost (USD ha^{-1})	150	75	-50
Parasitoid Cost (USD ha^{-1})	-	50	-
Other Costs (USD ha^{-1})	14.65	20,875	+42.5
Net Profit (USD ha^{-1})	1,200	1,500	+25

Net Profit Analysis: Despite higher revenue in parasitoid-treated plots, with \$22,500 per hectare compared to \$16,000 per ha in the control plots, net profit showed a 25% increase. The net profit was \$1,500 per ha in parasitoid-treated plots, while the control plots had a profit of \$1,200 per ha. This increase in profitability can be attributed to several factors. One of the main contributors was the reduction in pesticide costs. The parasitoid-treated plots incurred pesticide costs of \$75 per ha, which was half the cost of the control plots, which spent \$150 per ha on pesticides. Additionally, there were production expenses for the parasitoids, amounting to a one-time cost of \$50 per ha. The overall result highlights that while revenue grew by 40.6%, it was the cost savings from reduced pesticide use that played a significant role in driving the profitability of the parasitoid-treated plots.

Long-Term Economic Benefits: Beyond the immediate financial gains, the use of parasitoids offers several long-term economic benefits. One significant advantage is the reduction of resistance development. By minimizing pesticide use, parasitoids help delay the development of resistance in *Tuta absoluta* populations, which ensures that chemical control methods remain effective when they are needed. The observed reduction in pesticide residues and associated biodiversity gains align with documented agroecosystem benefits when minimizing chemical inputs, confirming ecological advantages of this biocontrol strategy. Additionally, tomatoes produced with reduced pesticide residues are more likely to meet international food safety standards, which can open up export opportunities and access to premium markets . Furthermore, biological control contributes to the preservation of beneficial insects and overall ecosystem health, reducing the long-term need for external inputs and promoting sustainable agricultural practices .

Farmer Adoption and Scalability: The economic analysis also considered the potential for scaling up parasitoid-based control strategies. Training programs and subsidies for parasitoid production could further reduce costs and encourage widespread adoption among smallholder farmers.

DISCUSSION

As the first study demonstrating successful dual-parasitoid (egg and larval) biological control of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Algeria, we highlight three novel insights: first, exceptional climate adaptation, with 70% egg parasitism at 35°C outperforming Mediterranean strains (Aitaider *et al*., 2021) ; second, strong environmental sustainability, with low-input models resulting in reduced reliance on chemical fertilizers and improved soil health; Lambarraa-Lehnhardt *et al*, 2025); and third, high scalability, requiring only 5 m² for modular rearing, accessible to 89% of Algerian smallholders (Statistics, 2023).

Our low-tech rearing system is feasible for smallholders, with *B. nigricans* needing 50% more handling time for larval transfers than *Trichogramma* (totaling <20 hrs/week for 5 ha), but yielding 40% cost savings via reused tomato leaves (*Solanum lycopersicum* L. [Solanaceae]) as host substrate. Critical success factors include community rearing hubs (serving 10-20 farms) (He *et al*., 2024), mobile training units (75% adoption in pilots), and modular cages for incremental scale-up from 1 ha. Compared to conventional methods, parasitoid rearing requires more labor (15 vs. 5 hrs/ha/season) but reduces input costs by 67% (€50 vs. €150/ha), with medium skill needs addressed through training. These costs are consistent with those reported in similar studies, such as appalà *et al*. (2013), who estimated the cost of *Trichogramma* release at $40-60 per ha in Mediterranean tomato crops. This economic benefit underscores the potential of biological control to enhance both productivity and profitability for smallholder farmers in Algeria, as previously highlighted by esneux *et al*. (2010).

Additionally, the reduction in pesticide use had significant implications for human health by lowering the risk of exposure to harmful chemicals for both farmers and consumers. This is particularly critical in Algeria, where inadequate protective measures during pesticide application are a common issue, as noted by appalà *et al*. (2013). As the first quantitative assessment of *T. bourarachae*'s efficacy in semi-arid Algeria and the first combined field trial of native egg/larval parasitoids, our study shows augmentative releases of *Trichogramma bourarachae* Pintureau & Babault (Hymenoptera: Trichogrammatidae) and *Bracon nigricans* Szépligeti (Hymenoptera: Braconidae) significantly suppressed *T. absoluta* populations in tomato crops. Key findings include 70% egg parasitism and 65% larval parasitism, reducing pest densities by 60-70% versus controls, and yielding 30-40% improvements (from 32,000 to 45,000 kg/ha), consistent with Mediterranean studies 35-50% gains (Desneux *et al*., 2010). At a market price of 0.50 per kg, this translated to an additional revenue of 0.50 per kg, this translated to an additional revenue of 6,500 per ha in treatment plots compared to controls. These findings are consistent with those of latková *et al*. (2020). This extends findings to semi-arid conditions, where native parasitoids matched or exceeded exotic species' performance, with a 50% pesticide reduction and no efficacy trade-offs, validating prior *T. absoluta* management research (Biondi *et al*., 2018).

Native parasitoids demonstrated comparable or superior efficacy: *T. bourarachae* (70% egg parasitism) outperformed *T. achaeae* in Spain (55-60%) (Urbaneja-Bernat *et al*., 2025) and matched *T. pretiosum* in Italy (70-75%) (Zappalà *et al*., 2013), while *B. nigricans* (65% larval parasitism) exceeded *Bacillus thuringiensis* (50-60%) (Gowelo *et al*., 2020), but was slightly less effective than *Necremnus tutae* in Italy (80%) (Biondi *et al*., 2018), likely due to adaptation to local conditions. Statistical analysis confirmed significant differences: egg parasitism was 70.2% (±3.1 SEM) in treated plots vs. 12.5% (±1.7 SEM) in controls ($t = 16.42$, $p < 0.001$), and larval parasitism was 65.4% (±2.8 SEM) vs. 10.3% (±1.2 SEM) ($t = 15.87$, $p < 0.001$).

Despite proven efficacy, smallholder adoption is limited by barriers like 78% farmer unfamiliarity with biocontrol (Ministry_of_Agriculture_and_Rural_Development, 2022), subsidies favoring pesticides (40-60% coverage vs. 15% for biocontrol) (Yang & Wang, 2025), and infrastructure gaps (only 12% of villages have rearing hubs; Statistics, 2023). Successful interventions in Tunisia (adoption from 9% to 42%) (Zappalà *et al*., 2013), and Morocco (35% pesticide reduction) European_Commission (2023) suggest that Algeria's mobile labs (reducing training to three weeks) could drive change, addressing the €138/ha pesticide vs. €46/ha parasitoid cost disparity.

Our dual-parasitoid system achieved 60-70% pest reduction, surpassing single-species results (*T. achaeae* at 40-45% in Tunisia; *B. nigricans* at 50-55% in Morocco) (Xuan *et al*., 2018), due to synergistic effects: *T. bourarachae* suppressing eggs (70% efficacy) and *B. nigricans* targeting larvae (65% efficacy). This aligns with and extends Mediterranean studies, where our rates exceeded Spanish *T. achaeae* (55-60%) (Zogo *et al*., 2019), and matched Italian *T. pretiosum* (70-75%) (Zappalà *et al*., 2013), with yield increases mirroring Spain (35%) (Mollá *et al*., 2014) and surpassing Tunisia (20-25%) (Abbes *et al*., 2015).

Native Algerian parasitoids outperformed exotics, reflecting adaptation to semi-arid conditions (e.g., 70% parasitism at 35°C vs. 55% for Spanish strains) (Žikić *et al*., 2024), as supported by regional evidence (Chebbah *et al*., 2025). This addresses a critical gap in North African biocontrol data, quantifying 30-40% yield gains and 25% profit increases for smallholders, aligning with IPM targets (Ongoma *et al*., 2025).

Limitations include the study's focus on Sétif's semi-arid climate, necessitating trials in humid areas like Annaba. Future work should optimize mass production, compare with commercial strains, test biopesticide compatibility, and assess long-term establishment and resistance risks (Desneux *et al*., 2010). Policy priorities include subsidies, training, and regional collaboration (e.g., with Morocco;) (Castells-Sierra *et al*., 2023) to enhance IPM adoption.

Conclusion: This study establishes native *T. bourarachae* and *B. nigricans* as a sustainable solution for *T. absoluta* control, demonstrating three key advances: (1) first validated protocol for semi-arid conditions achieving 70% field parasitism, (2) 25% profit increase for farmers through reduced pesticide use (50%) and higher yields (30-40%), and (3) climate resilience up to 35°C. The approach directly addresses North Africa's pesticide crisis, where 89% of Algerian tomato farms face resistance issues. We propose three immediate actions: reallocating chemical subsidies to biocontrol, establishing community rearing hubs (5 m²/50 ha), and integrating pheromone traps. With minimal investment (€46/ha) and training (3 weeks), this model offers a scalable template for Mediterranean tomato production.

REFERENCES

Abbes, K., A. Biondi, A. Kurtulus, M. Ricupero, A. Russo, G. Siscaro, B. Chermiti and L. Zappalà (2015). Combined non-target effects of insecticide and high temperature on the parasitoid *Bracon nigricans*. PLOS ONE. 10(9): e0138411. https://doi.org/10.1371/journal.pone.0138411

Agboyi, L.K., B.F.R. Layodé, K.O. Fening, P. Beseh, V.A. Clottey, R. Day, M. Kenis and D. Babendreier (2021). Assessing the potential of inoculative field releases of *Telenomus remus* to control *Spodoptera frugiperda* in Ghana. Insects. 12(8): 665. https://doi.org/10.3390/insects12080665

Aitaider, L., A. Meriem and S. Doumandji (2021). First record of *Coccinella septempunctata algerica* (Coleoptera, Coccinellidae) as a host of *Dinocampus coccinellae* (Hymenoptera, Braconidae, Euphorinae) in Algeria. *Arxius de Miscel·lània Zoològica*. 19: 1–6. https://doi.org/10.32800/amz.2021.19.0065

Akhter, W., F.M. Shah, M. Yang, S. Freed, M. Razaq, A.G. Mkindi, H. Akram, A. Ali, K. Mahmood and M. Hanif (2023). Botanical biopesticides have an influence on tomato quality through pest control and are cost-effective for farmers in developing countries. *PLOS ONE*. 18(11): e0294775. https://doi.org/10.1371/journal.pone.0294775

Allache, F. (2020). Monitoring and population changes of *Tuta absoluta* (Meyrick, 1917) on tomato under greenhouse conditions in an arid expanse of south-eastern Algeria. *Acta Agric. Slov.* 115(2): 324. https://doi.org/10.14720/aas.2020.115.2.324

Bavithra, C.M.M.L., M. Murugan, V. Balasubramani, S. Harish and K. Prakash (2024). Baseline susceptibility of an A1 quarantine pest - the South American tomato pinworm *Tuta absoluta* (Lepidoptera: Gelechiidae) to insecticides: past incidents and future probabilities. *Front. Plant Sci.* 15: 1404250. https://doi.org/10.3389/fpls.2024.1404250

Biondi, A., N. Desneux, G. Siscaro and L. Zappalà (2012). Using organic-certified rather than synthetic pesticides may not be safer for biological control agents: selectivity and side effects of 14 pesticides on the predator *Orius laevigatus*. *Chemosphere*. 87(7): 803–812. https://doi.org/10.1016/j.chemosphere.2011.12.082

Biondi, A., R.N.C. Guedes, F.-H. Wan and N. Desneux (2018). Ecology, worldwide spread, and management of the invasive South American tomato pinworm, *Tuta absoluta*: past, present, and future. *Annu. Rev. Entomol.* 63: 239–258. https://doi.org/10.1146/annurev-ento-031616-034933

Campos, M.R., A. Biondi, A. Adiga, R.N.C. Guedes and N. Desneux (2017). From the Western Palaearctic region to beyond: *Tuta absoluta* 10 years after invading Europe. *J. Pest Sci.* 90(3): 787–796. https://doi.org/10.1007/s10340-017-0867-7

Campos, M.R., A.R.S. Rodrigues, W.M. Silva, T.B.M. Silva, V.R.F. Silva, R.N.C. Guedes and H.A.A. Siqueira (2014). Spinosad and the tomato borer *Tuta absoluta*: a bioinsecticide, an invasive pest threat, and high insecticide resistance. *PLOS ONE*. 9(8): e103235. https://doi.org/ 10.1371/journal.pone.0103235

Castells-Sierra, J., A. Guillem-Amat, E. López-Errasquín, L. Sánchez and F. Ortego (2023). First detection of resistance to deltamethrin in Spanish populations of the Mediterranean fruit fly, *Ceratitis capitata*. *J. Pest Sci.* 96(3): 1229–1242. https://doi.org/10.1007/s10340-022-01578-1

Chebbah, O., K. Souttou, K. Ouachek, M. Lounis, S. Brun, A. Izri and M. Akhoundi (2025). Inter- and intra-species variation and genetic diversity of flea ectoparasites in hedgehogs (*Mammalia*, *Erinaceidae*) collected in northern Algeria. *Insects*. 16(4): 390. https://doi.org/10.3390/insects16040390

Cocco, A., S. Deliperi and G. Delrio (2013). Control of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in greenhouse tomato crops using the mating disruption technique. *J. Appl. Entomol.* 137(1–2): 16–28. https://doi.org/10.1111/j.1439-0418.2012.01735.x

Dalbianco, A.B., D. de L. Alvarez, N.N.P. da Silva, R.C. Oliveira and others (2024). Development of *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae) in tomato genotypes. *Comunicata Scientiae*. 16: e4224. https://doi.org/10.14295/cs.v16.4224

Desneux, N., P. Han, R. Mansour, J. Arnó, T. Brévault, M.R. Campos, A. Chailleux, R.N.C. Guedes, J. Karimi, K.A.J. Konan, A.-V. Lavoir, M.G. Luna, M. Perez-Hedo, A. Urbaneja, F.J. Verheggen, L. Zappalà, K. Abbes, A. Ali, Y. Bayram and A. Biondi (2022). Integrated pest management of *Tuta absoluta*: practical implementations across different world regions. *J. Pest Sci.* 95(1): 17–39. https://doi.org/10.1007/s10340-021-01442-8

Desneux, N., E. Wajnberg, K.A.G. Wyckhuys, G. Burgio, S. Arpaia, C.A. Narváez-Vasquez, J. González-Cabrera, D. Catalán Ruescas, E. Tabone, J. Frandon, J. Pizzol, C. Poncet, T. Cabello and A. Urbaneja (2010). Biological invasion of European tomato crops by *Tuta absoluta*: ecology, geographic expansion and prospects for biological control. *J. Pest Sci.* 83(3): 197–215. https://doi.org/10.1007/s10340-010-0321-6

European Commission (2023). Using less chemical pesticides: European Commission publishes toolbox of good practices. Directorate-General for Agriculture and Rural Development.

FAO (2018). Food and Agriculture Organization of the United Nations. FAO Regional Conference for the Near East, Rome, Italy (NERC/18/4). FAO. Retrieved from https://www.fao.org/about/meetings/regional-conferences/nerc34/documents/en/

Fiaboe, K.R., A.A. Yusuf, B. Torto and F.M. Khamis (2023). Herbivore intraguild interactions decrease ectoparasitoid *Bracon nigricans* parasitism of *Phthorimaea absoluta* and responses to tomato volatiles. *Front. Ecol. Evol.* 11: 1200040. https://doi.org/10.3389/ fevo.2023.1200040

Gebremariam, G. (2015). *Tuta absoluta*: A global looming challenge in tomato production – review paper. *J. Biol. Agric. Healthc.* 5(14): 57–62. http://www.iiste.org/Journals/index.php/JBAH/article/view/23987/24558

Gonthier, J., J. Koller, J. Arnó, J. Collatz and L. Sutter (2023). Models for the practitioner: predicting the efficient biocontrol of *Tuta absoluta* under different management scenarios. *Crop Prot.* 172: 106316. https://doi.org/10.1016/j.cropro.2023.106316

González-Cabrera, J., H.C. Arredondo-Bernal and R. Stouthamer (2014). Quality assessment of *Trichogramma* parasitoids (*Trichogramma* spp.) from six Mexican insectaries. *Agrociencia*. 48(3): 321–329. https://doi.org/10.1016/S1049-9644(02)00117-2

Gowelo, S., J. Chirombo, J. Spitzen, C.J.M. Koenraadt, T. Mzilahowa, H. van den Berg, W. Takken and R. McCann (2020). Effects of larval exposure to sublethal doses of *Bacillus thuringiensis* var. *israelensis* on body size, oviposition and survival of adult *Anopheles coluzzii* mosquitoes. *Parasites & Vectors*. 13(1): 259. https://doi.org/10.1186/s13071-020-04132-z

Guimapi, R.A., R. Srinivasan, H.E. Tonnang, P. Sotelo-Cardona and S.A. Mohamed (2020). Exploring the mechanisms of the spatiotemporal invasion of *Tuta absoluta* in Asia. *Agriculture*. 10(4): 124. https://doi.org/10.3390/agriculture10040124

Haddad, A., B. Khezzani and H. Guerinik (2024). Bioecology of *Tuta absoluta* Meyrick 1917 (Lepidoptera: Gelichiidae), on tomato under greenhouse in the oasis of El-Oued (Algeria). *Rev. Agrar. Acad.* 7: 34–44. https://doi.org/10.32406/v7n5/2024/34-44/agrariacad

Hajek, A.E. and J. Eilenberg (2018). *Natural enemies: an introduction to biological control.* 2nd Ed. Cambridge University Press; Cambridge (UK).

He, X., J. Yan, L.E. Yang, J. Wang, H. Zhou and X. Lin (2024). Linking smallholders' livelihood resilience with their adaptation strategies to climate impacts: insights from the Tibetan Plateau. *Ecol. Soc.* 29(2): Article 7. https://doi.org/10.5751/ES-14639-290207

Hyder, M., I. Ul Haq, M. Younas, M.A. Ghafar, M.R. Akhtar, Z. Ahmed, A. Bukero and Y. Hou (2025). Floral resource integration: enhancing biocontrol of *Tuta absoluta* within sustainable IPM frameworks. *Plants*. 14(3): 319. https://doi.org/10.3390/plants14030319

Ivezić, A., T. Popović, B. Trudić, J. Krndija, T. Barošević, A. Sarajlić, I. Stojačić and B. Kuzmanović (2025). Biological control agents in greenhouse tomato production (*Solanum lycopersicum* L.): possibilities, challenges and policy insights for Western Balkan region. *Horticulturae*. 11(2): 155. https:// doi.org/ 10.3390/ horticulturae11020155

Kandil, M.A.-H., E.A. Sammour, N.F. Abdel-Aziz, E.A.E.M. Agamy, A.M. El-Bakry and N.M. Abdelmaksoud (2020). Comparative toxicity of new insecticide generations against tomato leafminer *Tuta absoluta* and their biochemical effects on tomato plants. *Bull. Natl. Res. Cent.* 44(1): 126. https://doi.org/10.1186/s42269-020-00382-0

Krache, F., M. Boualem, J.L. Fernandez-Triana, A. Bass, J. Arnó and F. Benourad (2021). First record in Africa of the parasitoid *Dolichogenidea gelechiidivoris* (Hymenoptera: Braconidae) on tomato leafminer *Tuta absoluta* (Lepidoptera: Gelechiidae) from tomato fields in Algeria. *J. Hymenopt. Res.* 88: 115–131. https://doi.org/10.3897/jhr.88.75279

Lambarraa-Lehnhardt, F., M. Walls, M. Latati, A. Raggas and R. Ihle (2025). Resilience and technical efficiency trade-offs: implications to the sustainability of farming systems in Algeria and Spain. *J. Agric. Food Res.* 13: 101986. https://doi.org/10.1016/j.jafr.2025.101986

Mahlangu, L., P. Sibisi, R.S. Nofemela, T. Ngmenzuma and K. Ntushelo (2022). The differential effects of *Tuta absoluta* infestations on the physiological processes and growth of tomato, potato, and eggplant. *Insects*. 13(8): 754. https://doi.org/10.3390/insects13080754

Mama Sambo, S., S. Ndlela, H. du Plessis, E.A. Owino and S.A. Mohamed (2023). Potential side effects of the interaction between *Phthorimaea absoluta* parasitoids: the exotic *Dolichogenidea gelechiidivoris* and the native *Bracon nigricans*. *Int. J. Trop. Insect Sci.* 43(6): 2223–2231. https://doi.org/10.1007/s42690-023-01052-0

Mangrio, G.Q., A.A. Gilal, L.B. Rajput, J.U.D. Hajano, A.R. Bhatti, M.I. Mastoi, Z. Panhwar and A.H. Gabol (2024). Integrated pest management of *Tuta absoluta* (Lepidoptera: Gelechiidae) in tomato field. Pakistan J. Agric. Res. 37(4): 426–437. https://doi.org/10.17582/ journal.pjar/ 2024/37.4.426.437

Ministry of Agriculture and Rural Development (2022). *Agricultural Climate Atlas of Algeria.* Directorate General of Agricultural Services; Algiers (Algeria).

Mo, L., R. Xie, F. Ye, G. Wang, P. Wu and X. Yi (2024). Enhanced tomato pest detection via leaf imagery with a new loss function. *Agronomy*. 14(6): 1197. https://doi.org/10.3390/agronomy14061197

Mohamed, S.A., A.G.A. Azrag, F. Obala and S. Ndlela (2022). Estimating the demographic parameters of *Tuta absoluta* (Lepidoptera: Gelechiidae) using temperature-dependent development models and their validation under fluctuating temperature. *Biology*. 11(2): 181. https://doi.org/10.3390/biology11020181

Mollá, O., A. Biondi, M. Alonso-Valiente and A. Urbaneja (2014). A comparative life history study of two mirid bugs preying on *Tuta absoluta* and *Ephestia kuehniella* eggs on tomato crops: implications for biological control. *BioControl*. 59(2): 175–183. https://doi.org/10.1007/s10526-013-9553-8

Ongoma, V., Y. Brouziyne, E. Bouras and A. Chehbouni (2025). Combler le déficit de rendement pour une sécurité alimentaire durable en Afrique subsaharienne – progrès, défis et opportunités. *Front. Agron.* 7: 1572061. https://doi.org/10.3389/fagro.2025.1572061

Pandey, M., N. Bhattarai, P. Pandey, P. Chaudhary, D.R. Katuwal and D. Khanal (2023). A review on biology and possible management strategies of tomato leaf miner, *Tuta absoluta* (Meyrick), Lepidoptera: Gelechiidae in Nepal. *Heliyon*. 9(6): e16474. https://doi.org/10.1016/j.heliyon.2023.e16474

Pereira, H.C., F.F. Pereira, V.B. Insabrald, A. Rodrigues, J.T. Lucchetta, F.W.S. Silva, W.C. Fernandes, Z.F. Carneiro, P.H.B. Périgo and J.C. Zanuncio (2023). Selectivity of insecticides to a pupal parasitoid, *Trichospilus diatraeae* (Hymenoptera: Eulophidae), of soybean caterpillars. *Insects*. 14(3): 217. https://doi.org/10.3390/insects14030217

Platková, H., J. Skuhrovec and P. Saska (2020). Antibiosis to *Metopolophium dirhodum* (Homoptera: Aphididae) in spring wheat and emmer cultivars. *J. Econ. Entomol.* 113(6): 2979–2985. https://doi.org/10.1093/jee/toaa234

Poudel, A. and K. Kafle (2021). *Tuta absoluta*: a devastating pest of tomato – a review. *Int. J. Res. Appl. Sci. Biotechnol.* 8: 1–15. https://doi.org/10.1016/j.heliyon.2023.e16474

Richardson, E.B., B.J. Troczka, O. Gutbrod, T.G.E. Davies and R. Nauen (2020). Diamide resistance: 10 years of lessons from lepidopteran pests. *J. Pest Sci.* 93(3): 911–928. https://doi.org/10.1007/s10340-020-01220-y

Schäfer, L. and A. Herz (2020). Suitability of European *Trichogramma* species as biocontrol agents against the tomato leaf miner *Tuta absoluta*. *Insects*. 11(6): 357. https://doi.org/10.3390/insects11060357

Searle, S., F. Speed and G. Milliken (2023). Estimated marginal means, aka least-squares means [R package emmeans version 1.8.4-1]. *Am. Stat.* 34(4): 216–221. https://doi.org/ 10.32614 /cran.package.emmeans

Seehausen, M.L., C. Afonso, H. Jactel and M. Kenis (2021). Classical biological control against insect pests in Europe, North Africa, and the Middle East: what influences its success? *NeoBiota*. 65: 169–191. https://doi.org/10.3897/neobiota.65.66276

Statistics, N.O.O. (2023). *Agricultural Production Report 2023.* Government of Algeria; Algiers (Algeria).

Tarusikirwa, V.L., H. Machekano, R. Mutamiswa, F. Chidawanyika and C. Nyamukondiwa (2020). *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) on the "offensive" in Africa: prospects for integrated management initiatives. *Insects*. 11(11): 764. https://doi.org/ 10.3390/insects11110764

Urbaneja-Bernat, P., M. Vila-Sala, J. Arnó and J. Riudavets (2025). Improved techniques for monitoring *Dolichogenidea gelechiidivoris* (Hymenoptera: Braconidae), an endoparasitoid of *Tuta absoluta*, in tomato fields. *BioControl*. (Online first). https://doi.org/10.1007/s10526-025-10333-1

Whitfield, J.B. (2016). *The braconid and ichneumonid parasitoid wasps: biology, systematics, evolution and ecology.* Oxford University Press; Oxford (UK).

Xuan, J.-L., W.-X. Liu, Y.-B. Zhang, X.-Q. Cheng, J.-Y. Guo and F.-H. Wan (2018). Interactions between *Diglyphus isaea* and *Neochrysocharis formosa* (Hymenoptera: Eulophidae), two parasitoids of agromyzid leafminers. *Biol. Control*. 126: 45–52. https://doi.org/ 10.1016/ j.biocontrol .2018.07.005

Yang, Y. and Y. Wang (2025). The impact of government subsidies and quality certification on farmers' adoption of green pest control technologies. *Agriculture*. 15(1): 35. https://doi.org/10.3390/agriculture15010035

Zappalà, L., A. Biondi, A. Alma, I.J. Al-Jboory, J. Arnò, A. Bayram, A. Chailleux, A. El-Arnaouty, D. Gerling, Y. Guenaoui, L. Shaltiel-Harpaz, G. Siscaro, M. Stavrinides, L. Tavella, R. Vercher Aznar, A. Urbaneja and N. Desneux (2013). Natural enemies of the South American moth, *Tuta absoluta*, in Europe, North Africa and Middle East, and their potential use in pest control strategies. J. Pest Sci. 86(4): 635–647. https://doi.org/10.1007/s10340-013-0531-9

Žikić, V., J.L. Fernández-Triana, A. Trajković and M. Lazarević (2024). Advancing sustainable agriculture: potential of life story strategies of solitary and gregarious *Microgastrinae* parasitoids (Hymenoptera: Braconidae) to enhance biological control. *Sustainability*. 16(22): 10004. https://doi.org/ 10.3390/ su162210004

Zogo, B., B.N.C. Tchiekoi, A.A. Koffi, A. Dahounto, L.P. Ahoua Alou, R.K. Dabiré, L. Baba-Moussa, N. Moiroux and C. Pennetier (2019). Impact of sunlight exposure on the residual efficacy of biolarvicides *Bacillus thuringiensis israelensis* and *Bacillus sphaericus* against the main malaria vector, *Anopheles gambiae*. Malar. J. 18(1): 55. https://doi.org/10.1186/s12936-019-2687-0

Zekeya, N. M., Chacha, M., Ndakidemi, P. A., Mbega, E., *et al.* (2016). *Tomato Leafminer (Tuta absoluta Meyrick 1917): A threat to tomato production in Africa. Journal of Agriculture and Ecology Research International, 10*(1), 1–10. https://doi.org/10.9734/JAERI/2017/28886.