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Effects of endophytic *Trichoderma asperellum* seed treatment and temperature on life history traits and population growth of *Trialeurodes vaporariorum* on tomato

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ABSTRACT

The greenhouse whitefly *Trialeurodes vaporariorum* (Westwood) (Hemiptera: Aleyrodidae) is a major pest of tomato production worldwide, causing direct feeding damage and indirectly transmitting economically important plant viruses. This study evaluated the effects of endophytic *Trichoderma asperellum* seed treatment on the development, survival, reproduction, and demographic performance of *T. vaporariorum* on two tomato cultivars (Kilele F1 and Riogrande) under three constant temperature regimes (20, 25, and 30 °C). Seeds were treated with *T. asperellum*, thiamethoxam (positive control), or sterile distilled water (negative control) in a factorial experiment with four replications per treatment combination. Endophytic colonization of tomato tissues by *T. asperellum* was confirmed through fungal re- isolation. Life- history traits were evaluated, and stage-specific fertility life tables were constructed to estimate net reproductive rate (R_0), the intrinsic rate of natural increase (r_m), mean generation time (T), finite rate of increase (λ), and doubling time (DT). Seed treatment with *T. asperellum* significantly prolonged immature development (up to 9 days), increased nymphal mortality, reduced adult longevity and fecundity, and suppressed population growth of *T. vaporariorum* across all temperatures ($p < 0.05$). Demographic parameters (R_0, r_m, and λ) were significantly lower in *T. asperellum*-treated plants ($p < 0.05$), whereas T and DT increased significantly ($p < 0.05$). Although less effective than thiamethoxam, *T. asperellum* increased mortality and reduced fecundity by up to 25% and 64%, respectively. These findings demonstrate the potential of endophytic *T. asperellum* as an environmentally sustainable component of integrated management strategies for *T. vaporariorum* in tomato production.

Keywords: *Trialeurodes vaporariorum, Trichoderma asperellum*, Endophytes, Life table traits, Temperature, Integrated pest management

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops worldwide because of its nutritional and socio-economic value (Deletre et al., 2022; Maurya et al., 2025) In Kenya, tomato production contributes substantially to food security and household incomes, but productivity remains constrained by insect pests and diseases (Murungi et al., 2023; AFA, 2024; Mumo et al., 2024).

The greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood) (Hemiptera: Aleyrodidae), is among the most damaging sap-sucking pests of tomato. Both nymphs and adults feed on phloem sap using specialized stylets, thereby reducing crop yield and quality (Albornoz et al., 2023). As they feed, they excrete honeydew, which promotes the growth of Ascomycete fungi on the leaves and fruits, reducing the plant's photosynthetic capacity and the aesthetic value of the fruits (Aiuchi et al., 2020). In addition, *T. vaporariorum* transmits economically important viruses, including *Criniviruses* such as tomato chlorosis virus (ToCV) and tomato infectious chlorosis virus (TICV), and torradoviruses such as tomato torrado virus, which cause 50-100% yield losses in tomato (Moodley et al., 2019). The global economic losses caused by *T. vaporariorum*, both directly and indirectly, exceed $1 billion annually (Dearlove et al., 2024).

Management of *T. vaporariorum* relies largely on synthetic insecticides, particularly neonicotinoids such as thiamethoxam, which provide effective control through systemic activity (Hilton et al., 2016). However, excessive dependence on these insecticides has raised concerns regarding environmental contamination, negative effects on beneficial organisms, and the development of insecticide resistance (Akutse et al., 2020; Li et al., 2023). Consequently, there is increasing interest in developing sustainable alternatives for incorporation into integrated pest management programmes. Endophytic fungi are increasingly recognised as promising biological

control agents because they colonize plant tissues without causing disease and can enhance plant resistance against arthropod pests and pathogens (Bamisile et al., 2018). Among these fungi, *Trichoderma asperellum* has demonstrated the ability to establish endophytic associations with crops, promote plant growth, and induce defence mechanisms through the production of bioactive metabolites and activation of systemic resistance pathways (Jaber and Ownley, 2018; Panwar and Szczepaniec, 2024). Seed treatment has been identified as an effective and economical method for establishing endophytic colonization and providing prolonged protection throughout crop development (Latz et al., 2018).

Temperature is a key determinant of insect development, survival, fecundity, and population growth (Gamarra et al., 2020). Under changing climatic conditions, temperature fluctuations are expected to influence both pest population dynamics and the efficacy of microbial biological control agents (Skendžić et al., 2021). Understanding these interactions is therefore essential for developing climate-resilient pest management strategies. Although endophytic fungi have shown potential to suppress sap-feeding insects, information on the effects of *T. asperellum* on the life-history traits and demographic performance of *T. vaporariorum* across varying temperature regimes remains limited. Most demographic studies and phenology models available have focused mainly on evaluating the life-history parameters of *T. vaporariorum* across different temperature ranges on untreated plants. Therefore, this study evaluated the effects of endophytic *Trichoderma asperellum* seed treatment on the development, survival, reproduction, and demographic performance of *T. vaporariorum* on two tomato cultivars under different temperature conditions. We hypothesized that endophytic colonization by *T. asperellum* would suppress whitefly population growth and that these effects would vary across temperature regimes.

Materials and methods

Experimental site

Laboratory experiments were conducted at Jomo Kenyatta University of Agriculture and Technology, Kenya (1.0913° S, 37.0143° E), from September to December 2024. An experiment was conducted to assess the effects of tomato seed treatment with *T. asperellum* on the life history parameters of *T. vaporariorum*.

Source and rearing of whiteflies

The starter colony of *T. vaporariorum* was obtained from the International Centre of Insect Physiology and Ecology (*icipe*), Duduville Campus, Nairobi, Kenya (1.2219°S, 36.8967°E). The whiteflies were reared for three generations on potted French beans (*Phaseolus vulgaris* L. cv. Goal) placed in fine mesh insect-proof cages (RestCloud®) (60 cm×60 cm×100 cm, L×W×H) in the greenhouse at 25 ± 2 °C, 65% ± 5 RH, and a 12 h:12 h L:D photoperiod, before use in the experiment. Healthy plants were regularly added to the cages to maintain the colonies.

Source of tomato seeds

Two tomato cultivars, the most widely cultivated in the country, namely Kilele F1 and Riogrande (Avedi, 2022), were used in this study. The tomato seeds were purchased from a local agrodealer in Thika town, Kenya.

Source of the seed inoculum and preparation

The treatments that were used in the experiment included thiamethoxam (3-(2-chloro-1, 3-thiazol-5-ylmethyl)-5-methyl-1, 3,5-oxadiazinan-4-ylidene(nitro)amine), (Apron Star® 42WS), a water-soluble powder, purchased from a local agrodealer in Thika, and *Trichoderma asperellum* (Tricoat®), which was obtained from Real IPM, Thika.

Tomato seeds of the Kilele F1 and Riogrande cultivars were first surface-sterilized to eliminate any potential epiphytic microbes and remove chemical residues that may have been applied during commercial storage. Briefly, the seeds were soaked in 70% ethanol for 2 minutes, soaked in 1.5% sodium hypochlorite for 3 minutes, and then rinsed three times with sterile distilled water. To confirm the effectiveness of the sterilization, the last rinse water was plated on potato dextrose agar (PDA), sealed with parafilm, and incubated at 25 °C in an incubator (DNP-9052 electric thermostatic incubator). The absence of microbial growth after 1 week of incubation confirmed the effectiveness of the surface sterilization procedure (Jaber et al., 2018). After surface sterilization, the seeds were subjected to three treatments. One bunch was soaked with *T. asperellum* (Tricoat®) conidial suspensions containing 1×10^8 conidia/ml. Another bunch of seeds was treated with thiamethoxam (Apron Star® 42WS) at a rate of 0.0025 g per 1 g of tomato seeds (positive control). The last bunch had seeds of the two tomato varieties soaked in sterile distilled water (negative control). The seeds were subjected to their respective treatments for 18 hours.

Media preparation and establishment of treated seeds

Plastic containers of 500 g capacity were filled with cocopeat media, leveled, and moistened uniformly. Seeds treated with *T asperellum*, thiamethoxam, and the negative control were subsequently sown at a uniform depth of approximately 0.5 cm. Five seeds were sown in each container. After sowing, the containers were placed in fine-mesh insect-proof cages (RestCloud®) (100 cm × 60 cm × 60 cm, L×W×H) and placed in the greenhouse under natural environmental conditions at 25 ± 2 °C, 65% ± 5 RH, and a photoperiod of 12 h: 12 h L: D. After emergence, the seedlings were thinned to 3 per container and then transferred to the laboratory.

Experimental design

Laboratory experiments were laid out in a completely randomized design (CRD) with a 3×2×3 factorial arrangement and replicated four times. The main effect was temperature at three levels (20 °C, 25 °C, and 30 °C); the sub-effect was varieties at two levels (Kilele F1 and Riogrande); and the sub-sub-effect was treatments at three levels (*Trichoderma asperellum*, Thiamethoxam, and control).

Effects of seed treatment on the development and survival of *T. vaporariorum* immatures

At the four true leaf stage, the tomato plants were placed in plastic cages covered with fine muslin mesh (0.1 µm) for ventilation. Each cage represented a treatment and had four containers, each having three tomato plants. Each container served as a replicate. The cages were placed in three temperature-controlled incubators (BIOBASE BJPX-A400II) set at different temperatures: 20, 25, and 30 °C. The choice of these temperatures was based on average temperature ranges in tomato-growing regions of Kenya (Mwangi et al., 2020). The relative humidity in the three incubation chambers was 70 ± 2%, and the photoperiod was maintained at 12 h:12 h L: D. The plants were watered on a need basis, and water-soluble nutrients containing N:P:K, (19:19:19) (Goldchance®) (Greenlife Crop Protection Africa) were applied once a week.

To assess the effects of seed treatment on the development and survival of greenhouse whitefly immatures, two- to three-day-old adults (100 individuals with a sex ratio of 1:1) were transferred from the rearing cage using an aspirator. The whiteflies were introduced to four true-leaf tomato plants in cages placed in the incubators. The adults were left in the cage for 12 h to oviposit, and recovered using an aspirator and collection vials. The number of eggs laid was counted with the aid of a digital microscope (model G1600) and a tally counter. A total of 50 eggs per plant were used for the nymphal development and survival experiments, and excess eggs were brushed off the plant using a fine camel brush. Upon hatching, the first instar nymphs (crawlers) were counted,

and the positions where the crawlers settled were marked by placing a small black dot next to the crawlers using a black fine-tipped nontoxic marker pen for observation of the subsequent development stages (Naranjo and Ellsworth, 2017). Daily observations were done to determine nymphal development, survival, and adult emergence.

The first-instar nymphs were identified by their small size, oval shape, and translucent color. The second- and third-instar nymphs were distinguished by their relative shapes and sizes. Each transition between nymphal instars is marked by a molt, followed by noticeable changes in size and shape (Capinera, 2008). The fourth-instar nymphs ('pupa') were identified by the presence of long, erect waxy filaments and visible eyes (Gamarra et al., 2017). The number of emerged adults was determined by counting the empty pupal cases.

Sex ratio

Adults emerging from the fourth nymphal instar (puparium) were randomly aspirated from each cage and their sex determined based on the body size, with the males being slightly smaller than the females (Perring et al., 2018). Forty adults were selected from each treatment, and the numbers of males and females were recorded to determine the sex ratio.

Adult longevity and fecundity

Pairs of newly emerged *T. vaporariorum* were confined on the underside of the leaves of both the *T. asperellum* and thiamethoxam-treated plants and on the control plants of both cultivars. They were confined using styrofoam clip cages (height 2.4 cm and inner diameter 3.4 cm). The plants were placed in incubation chambers set at constant temperatures of 20, 25, and 30 °C. Every 24 hours, the clip cages with the whiteflies were moved to new leaflets, and the number of eggs laid per female was counted under a digital microscope (model G1600) and recorded until all the

female whiteflies had died. Data on fecundity and longevity were collected and recorded daily. The data analysis did not include females that did not produce eggs and those that died within the first 24 hours (Aregbesola et al., 2020).

Colonization assessment

To determine the colonization of tomatoes by endophytic *T. asperellum*, the tomatoes were carefully uprooted from the planting containers after all the whiteflies had died. The plant roots were washed using tap water to remove the cocopeat media attached to the roots. The plants were cut into roots, stems, and leaves sections using a sterile scalpel, then surface-sterilized using 70% ethanol for 2 minutes, followed by 1.5% sodium hypochlorite for 3 minutes, then rinsed three times using sterile distilled water (Akutse et al., 2013). The different plant parts were cut into 1×1 cm pieces under the laminar flow hood. The pieces were placed onto PDA plates supplemented with 0.05% antibiotics (chloramphenicol at 1.25g/L) to suppress bacterial contamination, sealed with parafilm, and incubated at 25 °C in an incubator (DNP-9052 electric thermostatic incubator) for 10 days. The last rinse water was also plated out to assess the effectiveness of the surface sterilization procedure as described earlier (Bamisile et al., 2020). The colonization of the different plant parts was determined based on the morphological and microscopic similarity to the fungal structures of the mother plates according to Koch's postulates (Petrini and Fisher, 1986).

Data analyses

The data were analyzed using R software version 4.5.2 (R Core Team, 2024). The Shapiro-Wilk and Levene tests were performed to check for normality and homogeneity of variance, respectively, using the "stats" and "car" packages (Shapiro and Wilk, 1965). Where assumptions were violated, the data were transformed using either square root, log, or log(X+1). Data on

percentage nymphal mortality were analyzed using generalized linear model (GLM) with binomial error distribution and logit link function using "stats" package. Data on development duration, the total fecundity, adult longevity, and oviposition rate were analysed using analysis of variance (ANOVA), and mean separation was done using Tukey's honestly significant difference (HSD) test at $p \leq 0.05$ using the "agricolae" package. Adult survival was assessed using log- rank (Mantel-Cox) test. Survival curves were generated using the Kaplan-Meier estimator method and visualised using the "Survival" and "Survminer" packages in R (Kaplan and Meier, 1958). Age-specific fertility life tables were constructed following Andrewartha & Birch (1954). The age of individuals was expressed as (x), the age-specific survival (l_x), the proportion of individuals surviving at age x, while the age-specific fecundity (m_x) was the mean number of female offspring produced by females at age x. From these data, the following demographic parameters were estimated: The net reproductive rate ($R_0 = \Sigma\, l_x m_x$), the mean generation time ($T = \Sigma\, x l_x m_x / \Sigma\, l_x m_x$), the intrinsic rate of natural increase (r_m), the finite rate of increase ($\lambda = e^{rm}$), and doubling time ($DT = \ln(2)/r_m$). The intrinsic rate of increase (r_m) was estimated using the Euler-Lotka equation ($\Sigma\, e^{-rmx} l_x m_x = 1$). The Jackknife resampling technique was used to estimate means and standard errors of the demographic parameters (Meyer et al., 1986). Differences among the seed treatments at each temperature were determined using one-way ANOVA followed by Tukey's HSD post hoc test at $p < 0.05$, using the "agricolae" and "multicompView" packages

Results

Morphological identification of re- isolated *T. asperellum*

The re-isolated fungus had a dark-green colony with whitish margins. Microscopic observations showed branched hyphae and conidiophores along the main axis with ampulliform phialides. The conidia were globose and ovoid, with smooth margins, and were green in colour **(Fig. 1A- D).** The

morphology of *T. asperellum* observed in this study is similar to that reported previously by Rahman et al. (2021)

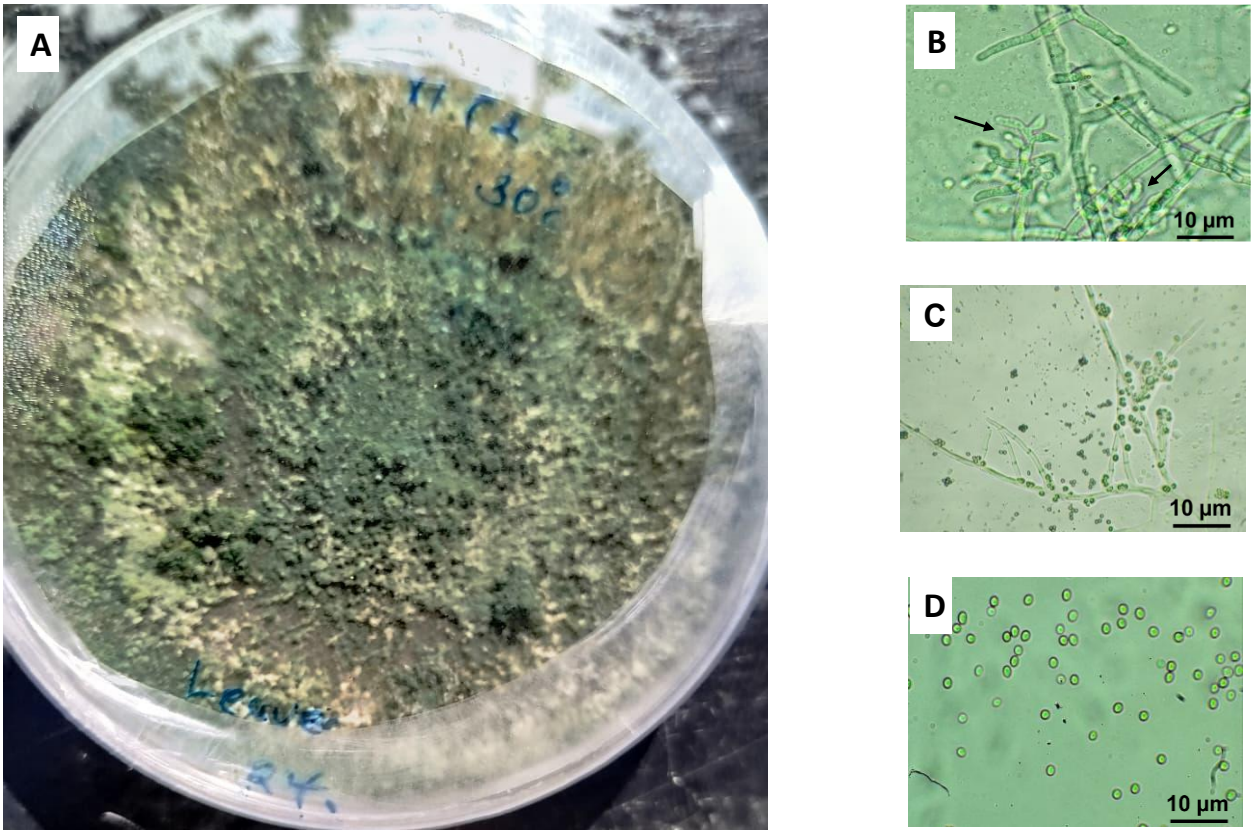


Fig. 1 Morphological and microscopic morphology of *T. asperellum* re- isolated from tomato **(A)** colony morphology on PDA medium **(B)** phialides (black arrows) and branched hyphae **(C)** branched conidiophores and mass of conidia **(D)** conidia

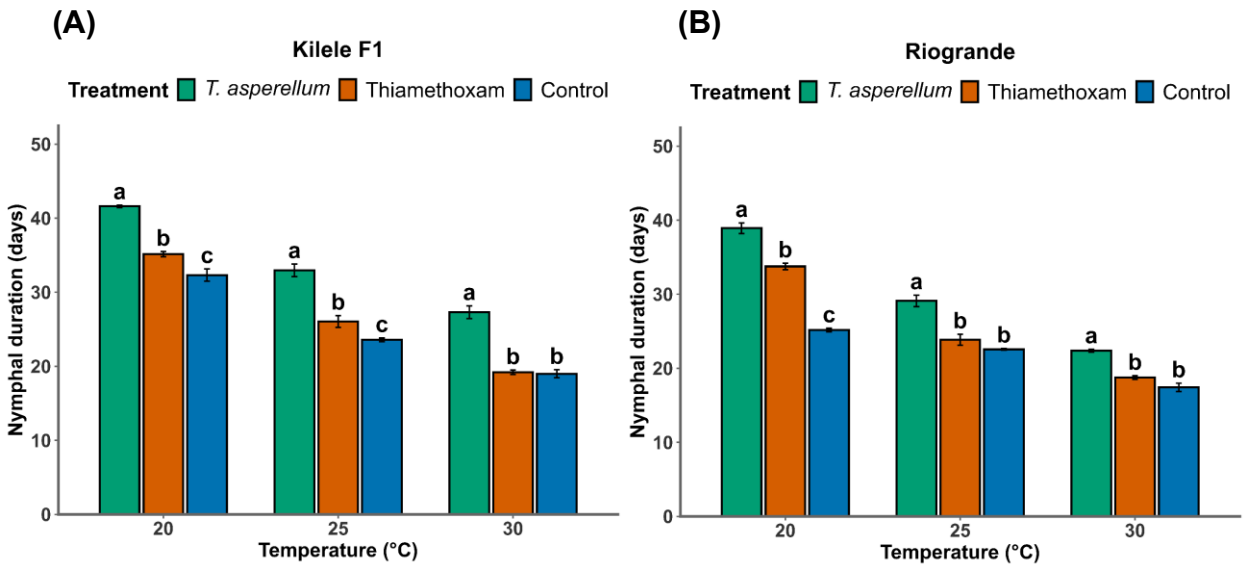
Effects of seed treatments on the development time and mortality of *T. vaporariorum* immatures

Development time

Stage-specific development duration analysis showed that *T. asperellum* significantly prolonged the duration across most stages at 20, 25, and 30 °C in both cultivars **(Table 1 and 2)**. There were

234 less differences between thiamethoxam and control. Among the individual development stages,
235 the egg stage generally recorded the longest duration across all the seed treatments and
236 temperatures in both cultivars.

237 The total immature development duration declined with increase in temperature across all
238 treatments on both cultivars. On Kilele F1, temperature ($F_{2, 27}$ = 169.43, $p < 0.001$) and seed
239 treatments ($F_{2, 27}$ = 60.17, $p < 0.001$) had highly significant effects on the development duration
240 **(Table 1)**. On Riogrande, the interaction between temperature and seed treatment was highly
241 significant ($F_{4, 27}$ =25.85, $p = < 0.001$) **(Table 2)**. The development duration ranged from 41.6-
242 27.3 days on Kilele F1 and 38.9-22.4 days on Riogrande plants treated with *T. asperellum* at 20
243 and 30 °C. The development duration on thiamethoxam-treated Kilele F1 plants ranged from 35.1
244 to 19.2 days and from 33.8 to 18.8 days on Riogrande while the development time on control plants
245 ranged from 32.3 to 19.0 on Kilele F1 and from 25.2 to 17.4 on Riogrande **(Fig. 2).**



246

247 **Fig. 2** Effect of tomato seed treatment on the development duration of *T. vaporariorum* nymphs

248 on **(A)** Kilele F1 and **(B)** Riogrande tomato cultivars at different temperatures. Bars represent mean

249 ± SE values. Different letters indicate significant differences at $p < 0.05$

250

Table 1. Stage-specific duration (± S.E) of *Trialeurodes vaporariorum* on Kilele F1 tomato cultivar subjected to three treatments and at three constant temperatures

Temperature °C	Treatment	Egg stage (d)	1st Instar (d)	2nd instar (d)	3rd Instar (d)	4th Instar (d)	Egg - Adult (d)
20	*T. asperellum*	13.8 ± 0.34 a	7.4 ± 0.29 a	6.0 ± 0.20 a	6.5 ± 0.19 a	8.0 ± 0.20 a	41.6 ± 0.17 a
	Thiamethoxam	11.3 ± 0.39 b	5.8 ± 0.14 b	5.0 ± 0.11 b	6.6 ± 0.32 a	6.5 ± 0.29 b	35.1 ± 0.35 b
	Control	10.2 ± 0.34 b	5.7 ± 0.52 b	5.6 ± 0.05 a	5.1 ± 0.26 b	5.8 ± 0.20 b	32.3 ± 0.83 c
	F	26.58	6.989	14.84	10.15	12.77	80.94
	df	2,9	2,9	2,9	2,9	2,9	2,9
	p	< 0.001	0.015	0.001	0.005	0.002	< 0.001
25	*T. asperellum*	11.2 ± 0.18 a	3.9 ± 0.34 a	4.8 ± 0.21 a	5.0 ± 0.35 a	6.4 ± 0.50 a	33.0 ± 0.85 a
	Thiamethoxam	8.2 ± 0.33 b	5.6 ± 0.24 b	3.9 ± 0.50 b	4.9 ± 0.46 a	5.1 ± 0.27 a	26.1 ± 0.80 b
	Control	8.3 ± 0.17 b	3.7 ± 0.46 b	3.8 ± 0.27 b	4.0 ± 0.34 a	3.8 ± 0.35 b	23.6 ± 0.26 c
	F	37.24	6.78	2.52	2.35	11.3	49.69
	df	2,9	2,9	2,9	2,9	2,9	2,9
	p	< 0.001	0.016	0.136	0.151	0.003	< 0.001
30	*T. asperellum*	8.5 ± 0.23 a	4.8 ± 0.22 a	4.2 ± 0.55 a	4.6 ± 0.32 a	5.2 ± 0.43 a	27.3 ± 0.86 a
	Thiamethoxam	5.6 ± 0.19 b	3.4 ± 0.26 b	3.4 ± 0.13 a	3.3 ± 0.27 a	3.5 ± 0.40 b	19.2 ± 0.29 b
	Control	5.7 ± 0.52 b	3.6 ± 0.46 b	3.4 ± 0.13 a	3.2 ± 0.23 a	3.2 ± 0.08 b	19.0 ± 0.55 b
	F	56.78	4.43	1.76	7.53	10.12	59.69
	df	2,9	2,9	2,9	2,9	2,9	2,9
	p	< 0.001	0.046	0.227	0.012	0.005	< 0.001

Within the same temperature, means followed by the same letter within a column are not significantly different at $p \leq 0.05$, Tukey's honest significant difference (HSD) test

Table 2. Stage-specific duration (± S.E) of *Trialeurodes vaporariorum* on Riogrande tomato subjected to three treatments at three constant temperatures

Temperature °C	Treatment	Egg stage (d)	1st Instar (d)	2nd instar (d)	3rd Instar (d)	4th Instar (d)	Egg - Adult (d)
20	*T. asperellum*	12.1 ± 0.28 a	7.1 ± 0.30 a	6.1 ± 0.58 a	6.4 ± 0.46 a	7.2 ± 0.27 a	38.9 ± 0.71 a
	Thiamethoxam	9.8 ± 0.17 b	5.7 ± 0.18 b	6.2 ± 0.51 a	5.6 ± 0.11 a	6.6 ± 0.12 a	33.8 ± 0.43 b
	Control	7.6 ± 0.28 c	4.7 ± 0.21 c	4.5 ± 0.25 a	4.4 ± 0.46 a	4.0 ± 0.23 a	25.2 ± 0.25 c
	F	76.11	25.63	4.25	7.48	111.7	250.1
	df	2,9	2,9	2,9	2,9	2,9	2,9
	p	< 0.001	< 0.001	0.05	0.012	< 0.001	< 0.001
25	T. asperellum	10.3 ± 0.45 a	4.9 ± 0.43 a	5.1 ± 0.35 a	4.5 ± 0.21 a	4.4 ± 0.41 a	29.1 ± 0.77 a
	Thiamethoxam	8.2 ± 0.50 b	4.3 ± 0.26 a	3.6 ± 0.31 b	3.8 ± 0.35 a	4.1 ± 0.16 a	23.9 ± 0.75 b
	Control	6.2 ± 0.34 c	4.5 ± 0.30 a	4.3 ± 0.35 a	3.8 ± 0.16 a	3.8 ± 0.17 a	22.6 ± 0.12 b
	F	21.18	0.823	5.78	2.24	1.3	29.5
	df	2,9	2,9	2,9	2,9	2,9	2,9
	p	< 0.001	0.47	0.024	0.162	0.319	< 0.001
30	*T. asperellum*	7.7 ± 0.19 a	4.0 ± 0.20 a	3.3 ± 0.38 a	3.2 ± 0.31 a	4.2 ± 0.20 a	22.4 ± 0.19 a
	Thiamethoxam	5.8 ± 0.12 b	3.3 ± 0.20 a	3.3 ± 0.37 a	3.2 ± 0.19 a	3.3 ± 0.17 b	18.8 ± 0.24 b
	Control	5.2 ± 0.13 c	3.1 ± 0.29 a	3.0 ± 0.21 a	3.1 ± 0.09 a	3.0 ± 0.07 b	17.4 ± 0.56 b
	F	73.5	3.3	0.18	0.1	16.37	43.82
	df	2,9	2,9	2,9	2,9	2,9	2,9
	p	<0.001	0.084	0.84	0.909	0.001	< 0.001

Within the same temperature, means followed by the same letter within a column are not significantly different at $p \leq 0.05$, Tukey's honestly significant difference (HSD) test

251

252 ***Mortality***

253 The mortality rate in all stages was highest in thiamethoxam-treated plants, followed by *T.*
254 *asperellum*. The lowest mortality was in control plants in Kilele F1 **(Table 3)** and Riogrande
255 **(Table 4).** Cumulative mortality in Kilele F1 was 60, 37, and 16% in thiamethoxam, *T. asperellum*,
256 and control at 20 °C; 70, 48, and 26.5% at 25 °C; and 80.5, 59.5, and 34.4% at 30 °C, respectively.
257 In Riogrande, the cumulative mortality was 57.5, 34.5, and 14.5 % at 20 °C, 67, 46, and 26 % at
258 25 °C, and 79, 55.5, and 34.5 % at 30 °C in thiametoxam, *T. asperellum*, and control, respectively.

259 Temperature (x^2 = 12.01, df = 2, p = 0.02) and seed treatments (x^2 = 108.595, df = 2, p = < 0.001)
260 had highly significant effects on the cumulative mortality of *T. vaporariorum* immatures **(Fig. 3).**

261

Table 3. Stage-specific percentage mortality (± S.E) of *Trialeurodes vaporariorum* on Kilele F1 tomato subjected to three treatments at three constant temperatures

Temperature °C	Treatment	Egg stage	1st Instar	2nd instar	3rd Instar	4th Instar	Egg - Adult
20	*T. asperellum*	14.5 ± 2.49 b	7.6 ± 2.03 a	5.6 ± 1.84 b	6.7 ± 2.05 b	9.4 ± 2.37 b	37.0 ± 3.41 b
	Thiamethoxam	28.5 ± 1.80 a	10.5 ± 2.56 a	12.5 ± 2.92 a	12.5 ± 3.13 a	18.4 ± 3.91 a	60.0 ± 3.46 a
	Control	7.0 ± 3.19 c	2.7 ± 1.19 b	2.2 ± 1.09 c	1.7 ± 0.97 c	3.5 ± 1.38 c	16.0 ± 2.59 c
	x^2	34.6	9.15	13.43	14.61	16.71	86.24
	df	2, 9	2, 9	2, 9	2, 9	2, 9	2, 9
	p	< 0.001	0.01	0.001	0.001	< 0.001	< 0.001
25	*T. asperellum*	22.0 ± 2.93 b	9.0 ± 2.29 a	7.8 ± 2.24 b	16.0 ± 3.78 b	11.9 ± 2.98 b	48.0 ± 3.53 b
	Thiamethoxam	36.0 ± 3.39 a	13.3 ± 2.30 a	15.3 ± 3.42 a	9.9 ± 2.61 a	24.1 ± 4.80 a	70.0 ± 3.24 a
	Control	11.0 ± 2.21 c	4.5 ± 1.55 b	4.7 ± 1.62 c	4.9 ± 1.70 c	4.5 ± 1.68 c	26.5 ± 3.12 c
	x^2	36.4	7.67	9.28	8.55	18.94	78.4
	df	2, 9	2, 9	2, 9	2, 9	2, 9	2, 9
	p	< 0.001	0.022	0.01	0.014	< 0.001	< 0.001
30	*T. asperellum*	27.0 ± 3.14 b	10.3 ± 2.51 a	12.2 ± 2.86 b	13.9 ± 3.23 b	18.2 ± 3.88 b	59.5 ± 3.47 b
	Thiamethoxam	40.5 ± 3.47 a	16.8 ± 3.43 a	20.2 ± 4.04 a	24.1 ± 4.81 a	35.0 ± 6.16 a	80.5 ± 2.80 a
	Control	15.0 ± 2.52 c	5.3 ± 1.72 b	5.6 ± 1.81 c	7.2 ± 2.10 c	7.1 ± 2.16 c	34.5 ± 3.36 c
	x^2	33.42	10.17	12.92	12.33	23.32	90.63
	df	2, 9	2, 9	2, 9	2, 9	2, 9	2, 9
	p	< 0.001	0.006	0.002	0.002	< 0.001	< 0.001

Within the same temperature, means followed by the same letter within a column are not significantly different at $p < 0.05$, Tukey's honestly significant difference (HSD) test

Table 4. Stage-specific percentage mortality (± S.E) of *Trialeurodes vaporariorum* on Riogrande tomato subjected to three treatments at three constant temperatures

Temperature °C	Treatment	Egg stage	1st Instar	2nd instar	3rd Instar	4th Instar	Egg - Adult
20	*T. asperellum*	18.0 ± 2.72 b	6.7 ± 1.95 b	5.2 ± 1.80 b	4.8 ± 1.78 b	5.1 ± 1.87 b	34.5 ± 3.36 b
	Thiamethoxam	28.0 ± 3.17 a	10.4 ± 2.55 a	10.1 ± 2.65 a	13.8 ± 3.20 a	15.0 ± 3.57 a	57.5 ± 3.49 a
	Control	6.0 ± 1.68 c	2.1 ± 1.05 c	2.2 ± 1.08 c	2.2 ± 1.20 b	2.8 ± 1.25 b	14.5 ± 2.49 c
	x^2	36.83	10.83	9.26	15.62	14.23	84.55
	df	2, 9	2, 9	2, 9	2, 9	2, 9	2, 9
	p	< 0.001	0.004	0.01	< 0.001	0.001	< 0.001
25	*T. asperellum*	24.5 ± 3.04 b	7.8 ± 2.20 b	7.9 ± 2.29 b	7.0 ± 2.26 b	9.2 ± 2.66 b	46.0 ± 3.52 b
	Thiamethoxam	32.5 ± 3.31 a	13.3 ± 2.93 a	12.8 ± 3.09 a	16.7 ± 3.69 a	22.4 ± 4.52 a	67.0 ± 3.32 a
	Control	10.0 ± 2.12 c	4.4 ± 1.54 c	4.7 ± 1.61 c	4.9 ± 1.68 b	5.1 ± 1.77 b	26.0 ± 3.10 c
	x^2	32.34	8.04	6.22	10.59	15.95	69.68
	df	2, 9	2, 9	2, 9	2, 9	2, 9	2, 9
	p	< 0.001	0.018	0.045	0.005	< 0.001	< 0.001
30	*T. asperellum*	25.5 ± 3.08 b	10.1 ± 2.47 b	11.2 ± 2.72 b	12.6 ± 3.04 b	14.4 ± 3.45 b	55.5 ± 3.51 b
	Thiamethoxam	36.5 ± 3.40 a	18.9 ± 3.47 a	20.4 ± 3.97 a	25.6 ± 4.82 a	31.2 ± 5.93 a	79.0 ± 2.88 a
	Control	14.5 ± 2.49 c	5.9 ± 1.79 c	6.2 ± 1.90 c	6.0 ± 1.93 b	7.8 ± 2.24 b	34.5 ± 3.36 c
	x^2	26.14	12.45	11.91	17.44	16.98	83.99
	df	2, 9	2, 9	2, 9	2, 9	2, 9	2, 9
	p	< 0.001	0.002	0.003	< 0.001	< 0.001	< 0.001

Within the same temperature, means followed by the same letter within a column are not significantly different at $p < 0.05$, Tukey's honestly significant difference (HSD) test

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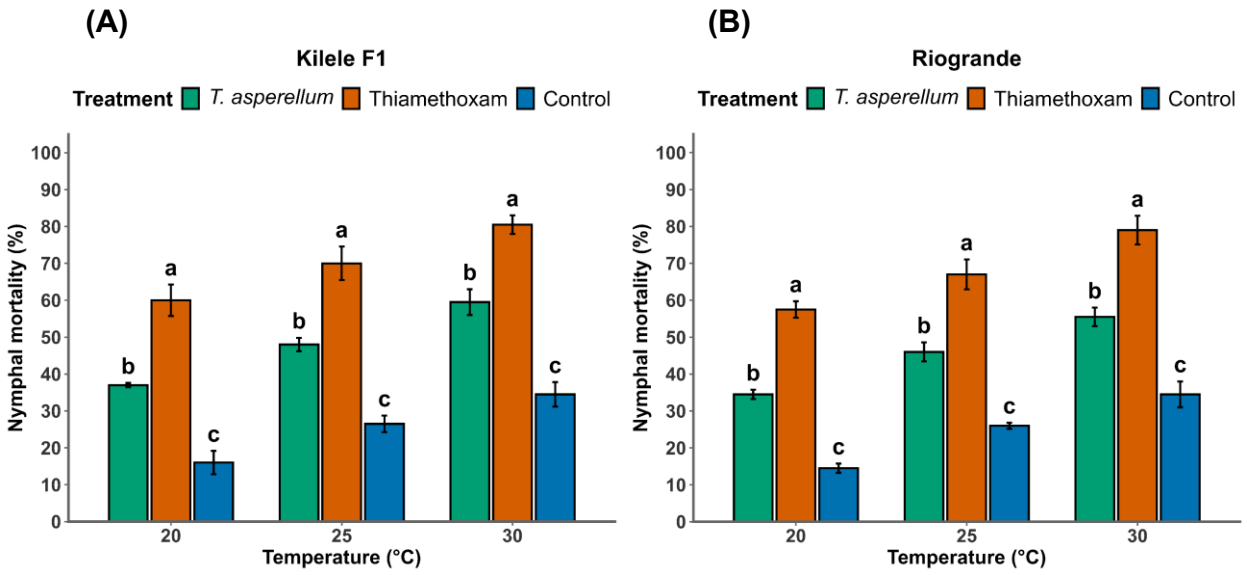


Fig. 3 Effect of tomato seed treatment on *T. vaporariorum* nymphal mortality on **(A)** Kilele F1 and **(B)** Riogrande tomato cultivars at different temperatures. Bars represent mean ± SE values. Different letters indicate significant differences at $p < 0.05$

Effects of seed treatments on the sex ratio, longevity, and reproduction rate of *T. vaporariorum* female adults

Sex ratio

In both cultivars across the three seed treatments, the proportion of females ranged from 52.5-55% at 20 and 25 °C. However, there was a slight decline in the proportion at 30 °C, reaching 47.5% in Kilele F1 and 47.5-52.5% in Riogrande **(Table 5 and 6).** Temperature, seed treatment and the temperature × seed treatment combinations did not have significant effects on the sex ratio of *T. vaporariorum* in both Kilele F1 and Riogrande ($p > 0.05$).

Longevity

In Kilele F1, the longevity of *T. vaporariorum* was significantly influenced by temperature ($F_{2, 27}$ = 3.33, p = 0.05) and seed treatment ($F_{2, 27}$ = 22.41, p < 0.001). Longevity was highest in control plants and decreased with an increase in temperature, averaging 17, 13, and 12 days at 20, 25, and 30 °C, respectively. Similarly, in Riogrande, longevity was significantly influenced by temperature ($F_{2, 27}$ = 4.71, p = 0.018) and seed treatment ($F_{2, 27}$ = 30.10, p < 0.001). Longevity was highest in control plants, averaging 19, 14, and 13 days at 20, 25, and 30 °C, respectively **(Table 5 and 6).**

Total fecundity

Total fecundity of *T. vaporariorum* on Kilele F1 was significantly influenced by temperature ($F_{2, 27}$ = 11.16, p < 0.001), and seed treatment ($F_{2, 27}$ = 29.57, p < 0.001). Similarly, in Riogrande, total fecundity was significantly affected by temperature ($F_{2, 27}$ = 14.22, p < 0.001) and seed treatments ($F_{2, 27}$ = 57.93, p < 0.001). Across both cultivars, significant differences were observed among the seed treatments at 20, 25, and 30 °C. In Kilele F1, the highest fecundity was on control plants with mean egg production of 61, 69.3, and 39.8 eggs per female at 20, 25, and 30 °C, respectively. Similarly, in Riogrande, control plants supported the highest fecundity with mean egg production of 70.8, 77.8, and 48.3 eggs per female at 20, 25, and 30 °C, respectively. The highest fecundity was observed at 25 °C across the seed treatments **(Table 5 and 6).**

Oviposition rate

In Kilele F1, the oviposition rate of *T. vaporariorum* was significantly affected by temperature ($F_{2, 27}$ = 6.88, p = 0.004). The seed treatments did not have a significant effect on oviposition rate ($F_{2, 27}$ = 2.03, p = 0.151). However, a significant temperature × seed treatment was observed ($F_{4, 27}$ = 2.870, p = 0.042). In Riogrande, the oviposition rate was only significantly affected by temperature ($F_{2, 27}$ = 9.78, p < 0.001). The highest oviposition rate was on control plants (4.53, 6.53, and 4.78

298 eggs/female/ day) at 20 °C, 25 °C, and 30 °C, respectively. Across the three seed treatments, the
299 highest oviposition rates were recorded at 25 °C in both cultivars. In Kilele F1, oviposition rates
300 at 25 °C were 5.9, 4.4, and 4.2 eggs/female/day on control, thiamethoxam- and *T. asperellum*-
301 treated plants. Similarly, in Riogrande, oviposition rates at 25 °C were 6.5, 4.5, and 4.5
302 eggs/female/day on control, thiamethoxam, and *T. asperellum*-treated plants, respectively **(Table**
303 **5 and 6).**

Table 5. Effect of different treatments on the sex ratio, longevity, and reproduction rate of *T. vaporariorum* on cultivar Kilele F1 at different temperatures

Temperature (°C)	Treatment	Sex ratio (% of ♀)	Female longevity (d)	Reproductive rate	
				Total fecundity (eggs/female)	Oviposition rate (eggs/female/day)
20	*T. asperellum*	52.5 ns	9.8 ± 0.63 b	34.5 ± 1.55 b	3.8 ± 0.25 a
	Thiamethoxam	55.0 ns	7.0 ± 0.41 a	23.3 ± 1.55 a	3.4 ± 0.09 a
	Control	55.0 ns	16.5 ± 1.71 c	61.0 ± 1.58 c	4.2 ± 0.35 b
25	*T. asperellum*	52.5 ns	8.8 ± 0.63 b	36.3 ± 2.43 b	4.4 ± 0.37 a
	Thiamethoxam	52.5 ns	6.5 ± 0.50 a	25.8 ± 2.02 a	4.2 ± 0.39 a
	Control	52.5 ns	13.0 ± 0.91 c	69.3 ± 2.17 c	5.9 ± 0.32 b
30	*T. asperellum*	47.5 ns	5.8 ± 0.85 b	14.3 ± 1.80 b	2.9 ± 0.07 a
	Thiamethoxam	47.5 ns	4.3 ± 0.48 a	9.8 ± 1.60 a	2.3 ± 0.17 a
	Control	47.5 ns	12.0 ± 0.91 c	39.8 ± 3.68 c	4.6 ± 0.39 b

Means followed by different letters within columns are significantly different at $p < 0.05$

% of ♀ = (♀/ (♂+♀) × 100.

304

Table 6. Effect of different treatments on the sex ratio, longevity, and reproduction rate of *T. vaporariorum* on cultivar Riogrande at different temperatures

Temperature (°C)	Treatment	Sex ratio (% of ♀)	Female longevity (d)	Reproductive rate	
				Total fecundity (eggs/female)	Oviposition rate (eggs/female/day)
20	*T. asperellum*	52.0 ns	9.5 ± 0.65 b	37.5 ± 1.85 b	4.0 ± 0.27 a
	Thiamethoxam	55.0 ns	7.3 ± 0.63 a	25.5 ± 0.87 a	3.6 ± 0.23 a
	Control	55.0 ns	19.0 ± 1.08 c	70.8 ± 3.09 c	4.5 ± 0.19 b
25	*T. asperellum*	52.5 ns	8.8 ± 0.85 b	38.8 ± 1.70 b	4.5 ± 0.31 a
	Thiamethoxam	55.0 ns	6.5 ± 0.65 a	28.5 ± 1.85 a	4.5 ± 0.26 a
	Control	55.0 ns	14.0 ± 0.71 c	77.8 ± 1.49 c	6.5 ± 0.52 b
30	*T. asperellum*	47.5 ns	6.0 ± 0.71 b	18.3 ± 1.75 b	3.3 ± 0.27 a
	Thiamethoxam	52.5 ns	5.3 ± 0.85 a	13.5 ± 1.85 a	2.8 ± 0.10 a
	Control	47.5 ns	13.3 ± 0.63 c	48.3 ± 1.89 c	4.8 ± 0.25 b

Means followed by different letters within columns are significantly different at $p < 0.05$

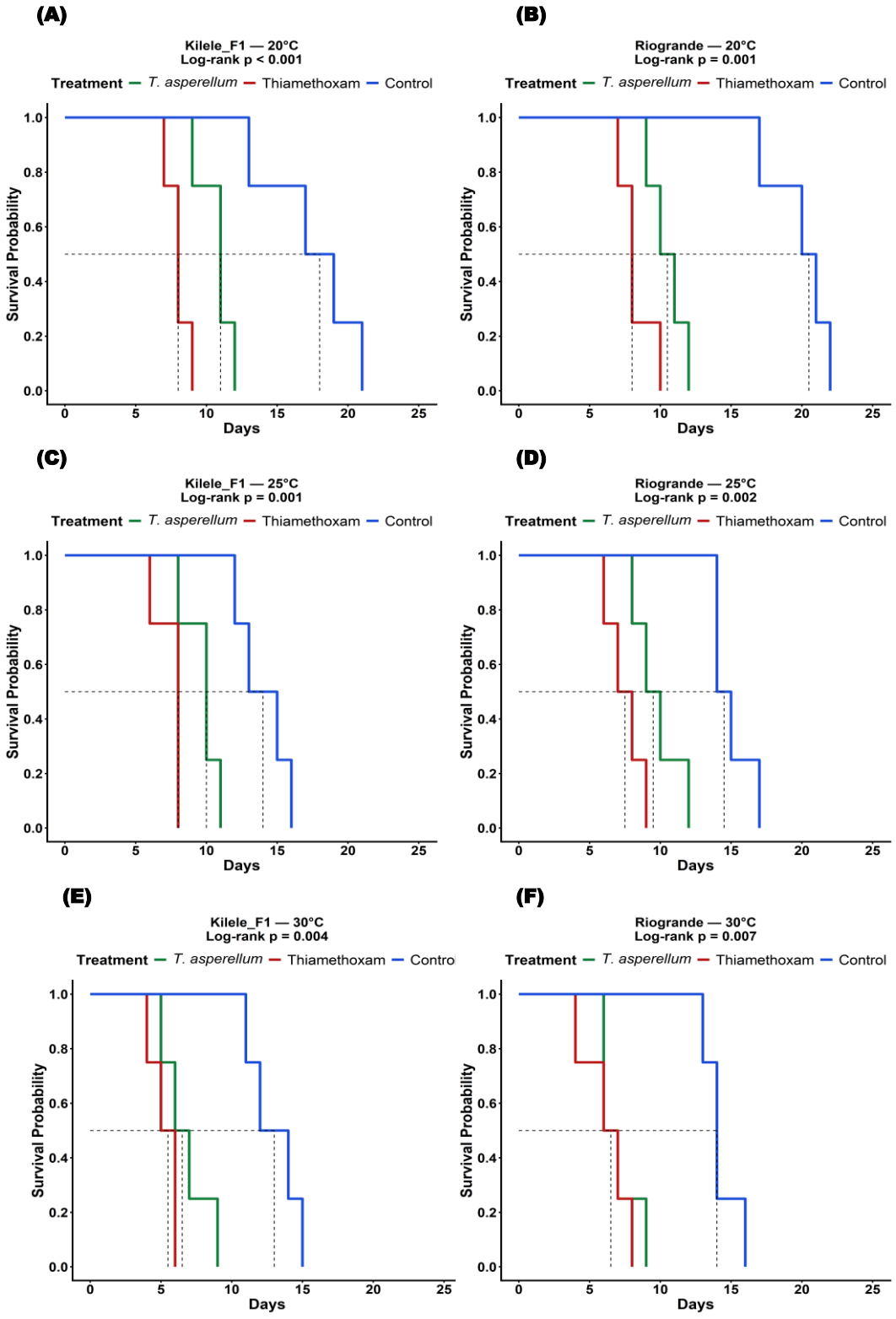
% of ♀ = (♀/ (♂+♀) × 100.

305

306 **Survival probability of *T. vaporariorum* adults**

307 Survival time was defined as the number of days from adult emergence to death. Kaplan-Meier
308 survival analysis revealed significant differences in the survival of *T. vaporariorum* adults among
309 the three seed treatments on both tomato cultivars (Kilele F1 and Riogrande) across the three
310 temperature settings (20, 25, and 30 °C). In Kilele F1, both *T. asperellum* and thiamethoxam
311 significantly reduced adult survival compared with the control (proximate log-rank test: $x^2 = 15.29$,
312 df = 2, $p < 0.001$ at 20 °C, $x^2 = 13.33$, df = 2, $p = 0.001$ at 25 °C, $x^2 = 11.25$, df= 2, $p = 0.00$, and
313 at 30 °C. Similarly, significant treatment effects were observed in Riogrande (proximate log-rank
314 test $x^2 = 13.23$, df = 2, $p = 0.001$ at 20 °C, $x^2 = 12.91$, df = 2, $p = 0.002$ at 25 °C, and $x^2 = 9.85$, df

315 = 2, $p = 0.007$ at 30 °C **(Fig 4)**. In both cultivars and across the three temperature settings, control
316 plants consistently maintained higher survival probabilities and longer survival durations of *T.*
317 *vaporariorum* adults compared with *T. asperellum* and thiamethoxam-treated plants.



318

319 **Fig. 4** Kaplan-Meier survival curves of *T. vaporariorum* adults on Kilele F1 and Riogrande tomato
320 cultivars treated with *T. asperellum*, thiamethoxam, and control at 20, 25, and 30 °C.

Effects of seed treatments on the demographic parameters of *T. vaporariorum*

Seed treatment significantly affected all life table parameters of *T. vaporariorum* across all temperatures in Kilele F1 and Riogrande tomato cultivars ($p < 0.05$). Seed treatment with *T. asperellum* and thiamethoxam significantly suppressed the population growth potential of *T. vaporariorum* compared to untreated plants (**Table 7 and 8**). The net reproductive rate (R_0) differed significantly among treatments at all temperatures in both cultivars ($p < 0.001$), with *T. asperellum* reducing R_0 by 61.6-77.4% relative to control across all temperatures in both cultivars. The intrinsic rate of natural increase (r_m) was also significantly affected by seed treatments at all temperatures ($p < 0.001$). The *T. asperellum* seed treatment reduced r_m by 36-59% relative to control. The mean generation time (T) was significantly affected by the seed treatments at all temperatures in both cultivars ($p < 0.05$) and declined with increasing temperature. The longest generation time of *T. vaporariorum* was observed in *T. asperellum*-treated Kilele F1 and Riogrande. No significant differences in T were observed between thiamethoxam-treated and control plants. Similarly, doubling time (DT) differed significantly among treatments at all temperatures. At 20 and 25 °C, *T. asperellum* did not differ significantly from thiamethoxam but differed significantly from the control. The finite rate of increase (λ) was also significantly affected by seed treatments at all temperatures in both cultivars ($p < 0.001$). The *T. asperellum* seed treatment reduced λ by 4.3 – 7.9 % relative to the control across all temperatures in both cultivars.

340

Table 7. Effects of seed treatments on the life table parameters of *Trialeurodes vaporariorum* on Kilele F1 at three constant temperatures

Temperature (°C)	Treatment	Parameters				
		R_0	r_m	T	DT	λ
20	*T. asperellum*	19. 68 ± 0.70 b	0.064 ± 0.001 b	46.93 ± 0.17 a	10.89 ± 0.11 a	1.058 ± 0.001 b
	Thiamethoxam	9.30 ± 1.16 c	0.056 ± 0.003 b	39.33 ± 0.63 b	12.45 ± 0.64 a	1.066 ± 0.003 b
	Control	51.31 ± 2.80 a	0.100 ± 0.003 a	40.14 ± 1.25 b	6.96 ± 0.25 b	1.105 ± 0.004 a
25	*T. asperellum*	18.25 ± 0.90 b	0.078 ± 0.002 b	37.26 ± 0.57 a	8.88 ± 0.25 a	1.081 ± 0.002 b
	Thiamethoxam	7.66 ± 1.22 c	0.068 ± 0.007 b	29.76 ± 0.95 b	10.49 ± 0.91 a	1.070 ± 0.007 b
	Control	51.07 ± 1.94 a	0.134 ± 0.001 a	30.07 ± 0.47 b	5.19 ± 0.05 b	1.143 ± 0.001 a
30	*T. asperellum*	5.94 ± 1.11 b	0.056 ± 0.006 b	30.33 ± 1.22 a	12.90 ± 1.60 b	1.058 ± 0.006 b
	Thiamethoxam	1.8 ± 0.16 c	0.027 ± 0.004 c	21.59 ± 0.36 b	28.21 ± 4.93 a	1.027 ± 0.004 c
	Control	26.24 ± 3.46 a	0.138 ± 0.007 a	23.89 ± 1.04 b	5.05 ± 0.27 b	1.149 ± 0.008 a

The values are jackknife estimates ± standard errors. For each parameter at a specific temperature, means within a column followed by the same letter are not significantly different (Tukey's HSD test, $p < 0.05$).

Parameters: R_0 Net reproductive rate; r_m Intrinsic rate of natural increase; T Mean generation time (days); DT, Doubling time (days); and λ, Finite rate of increase

341

Table 8. Effects of seed treatments on the life table parameters of *Trialeurodes vaporariorum* on Riogrande at three constant temperatures

Temperature (°C)	Treatment	Parameters				
		R_0	r_m	T	DT	λ
20	*T. asperellum*	24.39 ± 1.13 b	0.072 ± 0.002 b	44.26 ± 0.57 a	9.58 ± 0.25 a	1.075 ± 0.002 b
	Thiamethoxam	10.83 ± 0.61 c	0.064 ± 0.002 c	37.32 ± 0.31 b	10.88 ± 0.33 a	1.066 ± 0.002 c
	Control	60.58 ± 3.29 a	0.127 ± 0.002 a	33.31 ± 0.20 b	5.48 ± 0.07 b	1.135 ± 0.002 a
25	*T. asperellum*	20.85 ± 0.93 b	0.090 ± 0.003 b	34.03 ± 0.93 a	7.73 ± 0.24 a	1.094 ± 0.003 b
	Thiamethoxam	9.51 ± 1.47 c	0.081 ± 0.007 b	27.56 ± 0.69 b	8.83 ± 0.90 a	1.084 ± 0.008 b
	Control	57.55 ± 1.42 a	0.144 ± 0.002 a	28.95 ± 0.60 b	4.83 ± 0.08 b	1.154 ± 0.003 a
30	*T. asperellum*	8.09 ± 0.76 b	0.080 ± 0.003 b	26.08 ± 0.61 a	8.74 ± 0.39 b	1.083 ± 0.004 b
	Thiamethoxam	2.78 ± 0.57 c	0.043 ± 0.009 c	21.95 ± 0.45 b	18.54 ± 4.18 a	1.044 ± 0.009 c
	Control	31.62 ± 2.07 a	0.153 ± 0.003 a	23.04 ± 0.71 b	4.52 ± 0.08 b	1.166 ± 0.003 a

The values are jackknife estimates ± standard errors. For each parameter at a specific temperature, means within a column followed by the same letter are not significantly different (Tukey's HSD test, $p < 0.05$).

Parameters: R_0 Net reproductive rate; r_m Intrinsic rate of natural increase; T Mean generation time (days); DT, Doubling time (days); and λ, Finite rate of increase

342

Discussion

The present study evaluated the effectiveness of seed treatment with *T. asperellum* for the management of *T. vaporariorum* on tomato at different temperatures. Temperature and Tomato seed treatment with *T. asperellum* and thiamethoxam affected life-history and demographic parameters of *T. vaporariorum*. From the findings of the present study, thiamethoxam seed treatment was slightly better than *T. asperellum* in reducing fecundity and survival and suppressing whitefly populations. Although thiamethoxam was slightly more effective, *T. asperellum* prolonged the development of immatures, increased mortality, and reduced the survival, fecundity, and population growth of *T. vaporariorum* in both cultivars (Kilele F1 and Riogrande at 20, 25, and 30 °C. It is therefore a potential, environmentally friendly alternative that can be incorporated into integrated pest management programmes.

The time taken for *T. vaporariorum* to complete development from egg to adult stage was longest for whitefly immatures feeding on plants treated with *T. asperellum* across the three temperature regimes, compared with those that fed on plants treated with thiamethoxam and control plants. Similar results were observed by Akello & Sikora. (2012), who reported that endophytic colonization of on fava bean (*Vicia faba* L.) with *T. asperellum* and other endophytes slowed development and onset of reproduction in aphids, *Acyrthosiphon pisum* (Harris) (Homoptera: Aphidae). Endophytic *Trichoderma* induce plant defense responses by activating jasmonic acid and salicylic acid signaling pathways, leading to production of secondary metabolites such as phenolics, phytoalexins, terpenoids, and proteinase inhibitors, which have unfavourable effects on insect pests, including slowing nymphal development, reducing survival and oviposition, and deterring feeding (Jaber et al., 2018; Agbessenou et al., 2020; Panwar and Szczepaniec, 2024).

Moreover, there was a significant increase in mortality of *T. vaporariorum* nymphs and a reduction in reproduction and survival of the adults on treated plants across the three temperature settings. In the present study, *T. asperellum* increased the cumulative mortality by upto 20% and reduced fecundity by more than 40 % relative to untreated plants. Similar trends were reported fava beans endophytically colonized by *T. asperellum* M2RT4 and other endophytes were negatively affected (Akello and Sikora, 2012), *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) on *T. asperellum* M2RT4 endophytically colonized maize (Kinyungu et al., 2023), and *Spoladea recurvalis* on amaranth (Nyamamba et al., 2025). These effects are most likely due to modifications in the nutritional quality of phloem sap, making the host plants less suitable for feeding and oviposition (Akello and Sikora, 2012). Additionally, Nyamamba et al. (2025) previously reported that the reduction of eggs laid by *Spoladea recurvalis* could be a result of the production of volatile organic compounds by *T. asperellum* endophytically treated plants. From the study, a slight increase in the proportion of males was observed at 30 °C. This is likely due to arrhenotokous parthenogenesis in *T. vaporariorum,* in which high temperatures reduce the fertilization ability of females, which makes unfertilized eggs develop into males (Gamarra et al., 2017; Bondy and Hunter, 2019). However, contrasting results were reported by Manzano & Lenteren (2009), who found a strongly male-biased sex ratio on bean cultivars at 19, 22, and 26 °C.

In the present study, temperature had significant effects on the life-history traits of *T. vaporariorum,* with higher temperatures leading to faster development. The reduction in development duration with increase in temperature is in line with previous studies indicating that whiteflies have a faster growth rate when temperatures are favourable due to improved metabolic activity (Samih et al., 2014). Higher temperature, however, increased mortality and reduced

fecundity, especially at 30 °C, implying that whitefly fitness is negatively affected when temperatures are close to the upper thermal threshold. This could be attributed to the fact that whiteflies are ectotherms and are highly sensitive to changes in environmental temperature (Gamarra et al., 2020). The results from the current study concur with those of Xie et al. (2011), who reported that the optimal development, survival, and fecundity of *T. vaporariorum* is favored at temperatures not exceeding 24 °C, unlike in *Bemisia tabaci* whose development and survival are not adversely affected at higher temperatures. This is due to the ability of *B. tabaci* to upregulate heat shock proteins (HSPs) in response to thermal stress, which is an adaptation that is important in ensuring normal functioning of the cells even at high temperatures (Barman et al., 2023). In contrast, *T. vaporariorum* have weaker HSP responses, which affects their tolerance to extreme temperatures (Cui et al., 2008).

Host plant-endophyte-pest interactions that are influenced by temperature are increasingly gaining importance in relation to climate change (Ahmad et al., 2026). The rising temperatures as a result of climate change are expected to alter pest phenology, abundance, and geographical distribution, thereby increasing the risk of whitefly outbreaks in tropical production systems (Aregbesola et al., 2019). At the same time, climate variability may influence the establishment and persistence of microbial biological control agents (Suryanarayanan and Shaanker, 2021). The consistent suppressive effects of *T. asperellum* on *T. vaporariorum* reproduction and survival observed in this study suggest that endophytic fungi could contribute to the development of climate-resilient pest management strategies that maintain efficacy even under changing environmental conditions.

Life-table analyses provided further evidence of the adverse effects of *T. asperellum* on whitefly population dynamics. Plants colonized by *T. asperellum* exhibited lower net reproductive rates, intrinsic rates of increase, and finite rates of increase, along with longer generation times and

411 increased doubling times. These demographic responses indicate that endophytic colonization not
412 only affects individual performance but also substantially limits the capacity of whitefly
413 populations to increase over successive generations. Similar demographic effects have been
414 reported among insects exposed to resistant hosts or biological control agents and have been shown
415 to be reliable indicators of long-term pest suppression (Andrewartha and Birch, 1954).

416 Although thiamethoxam is effective in managing whiteflies, its overuse has adverse effects on
417 pollinators, non-target organisms, and the environment (Li et al., 2023; Yang et al., 2026). In
418 contrast, *T. asperellum* offers additional benefits beyond pest control, including enhancing plant
419 growth, nutrient uptake, and tolerance to biotic and abiotic stress (Natsiopoulos et al., 2024).

420 **Conclusion**

421 Seed treatment with *T. asperellum* significantly affected the development, survival, reproduction,
422 and population growth of *T. vaporariorum* under varying temperatures. Therefore, *T. asperellum*
423 can be integrated into environmentally sustainable and climate-resilient pest management
424 programmes. However, despite these promising findings, the present study was done under
425 controlled conditions in the laboratory, which may not reflect the reality in the greenhouse and
426 field environments. In addition, the colonization assessment was done using fungal re-isolation
427 and identification of morphological and microscopic features. Molecular approaches were not used
428 for fungal identification. Therefore, future studies are necessary in order to investigate the
429 persistence of endophytic colonization under greenhouse and field conditions, to evaluate the
430 impact of endophytic *T. asperellum* on the transmission of plant viruses by *T. vaporariorum*, and
431 elucidate the biochemical and molecular mechanisms underlying induced resistance in tomato
432 plants.

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Author Contributions

Conceptualization, design, and methodology: BJC, LKM, NNM, and DA. Data collection, curation, and analysis: BJC and LKM. Validation: BJC, LKM, NNM, and DA. Supervision: LKM, NNM, and DA. Project administration: LKM. Funding acquisition: LKM

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Data availability: All the data from this research is available upon request from the corresponding author

Consent for publication

Declarations

Competing interests

The authors declare no conflict of interest, whether financial or non-financial

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