Chilean J. Agric. Anim. Sci., ex Agro-Ciencia (2025) 41(2): 332-343.
https://doi.org/10.29393/CHJAAS41-30CAOM30030

ISSN 0719-3890 online

POPULATION FLUCTUATION OF *Bemisia tabaci* IN *Capsicum chinense* THROUGH APPLICATIONS OF *Cordyceps fumosorosea* UNDER GREENHOUSE AND OPEN-FIELD CONDITIONS

Omar Pinto Gonzalez[1a], Wilberth Chan Cupul[1b]*, and Andrea Mendoza Arceo[1c]

[1a] Laboratorio de Control Biológico III, Facultad de Ciencias Biológicas y Agropecuarias, Universidad de Colima. Autopista Colima-Manzanillo km. 40, Tecomán, Colima, 28982, Mexico
https://orcid.org/0009-0001-7756-3405
[1b] Laboratorio de Control Biológico III, Facultad de Ciencias Biológicas y Agropecuarias, Universidad de Colima. Autopista Colima-Manzanillo km. 40, Tecomán, Colima, 28982, Mexico
https://orcid.org/0000-0001-8634-3618
[1c] Laboratorio de Control Biológico III, Facultad de Ciencias Biológicas y Agropecuarias, Universidad de Colima. Autopista Colima-Manzanillo km. 40, Tecomán, Colima, 28982, Mexico
https://orcid.org/0000-0002-7398-1079
* Corresponding author: wchan@ucol.mx

ABSTRACT

***Bemisia tabaci* is the main insect pest affecting *Capsicum chinense* production worldwide. Although *Cordyceps fumosorosea* has demonstrated efficacy against multiple insect pests under *in vitro* and *in vivo* conditions, further *in situ* evaluations are required to determine its effectiveness in real-world environments. The objective of this study was to evaluate the population fluctuation of *B. tabaci* in *C. chinense* cultivation under greenhouse and open-field conditions through the application of *C. fumosorosea* (*Cf*) as a biological control agent. A factorial experimental design A×B was used, where factor A corresponded to the site (greenhouse or open-field) and factor B to the application of *Cf* conidiospores (with or without application). Four treatments were established: T1) greenhouse + application of *Cf*; T2) greenhouse without application of *Cf*; T3) open-field + application of *Cf*; and T4) open-field without application of *Cf*. Response variables were population fluctuation (PF), efficacy, and the area under the population progress curve (AUPPC) in adults and nymphs. A multifactorial analysis of variance (ANOVA) followed by Tukey's test was used to analyze the response variables. A greater fluctuation of adults and nymphs was found in the open-field; however, from 56 DAT, the greenhouse crop showed greater fluctuation. The efficacy of *Cf* in adults was greater in the greenhouse (52.4%) than in the open-field (27.2%). The same effectiveness was found in nymphs in both the open-field (64.6%) and greenhouse (62.7%). AUPPC showed that the use of *Cf*, under both greenhouse and open-field conditions, helped maintain low population levels of *B. tabaci* nymphs and adults. Overall, the application of *Cf* effectively suppressed *B. tabaci* population fluctuations in habanero pepper, highlighting its potential for its integration into sustainable management strategies against *B. tabaci*.**

Keywords: biocontrol, conidiospore, habanero pepper, efficacy, nymphs, whitefly.

INTRODUCTION

Capsicum chinense Jacq. (habanero pepper) is one of the most important chili pepper species consumed in Mexico and the Americas due to its adaptability to tropical and equatorial climates. Its fruit contains capsaicin, which imparts a high degree of pungency, enabling it to compete with other hot peppers worldwide and positioning it as one of the spiciest varieties. Furthermore, fruits are a rich source of essential minerals and vitamins, including vitamins A, C, and E

Received: May 5, 2025 Accepted: August 24, 2025

(Ceballos et al., 2015; Wu et al., 2025).

The productivity of *C. chinense* is compromised by numerous phytosanitary challenges, including pests and diseases. Among these, hemipteran insects are considered major pests of *C. chinense*, with aphids (*Myzus persicae* and *Aphis* spp.), leafhoppers (*Empoasca* spp.), mealybugs (*Planococcus* spp.), thrips (*Thrips* sp.), and whiteflies (*Bemisia tabaci*) being the most significant (Pavani et al., 2024; Caarls et al., 2025). However, the cryptic species complex of *B. tabaci* is recognized as the primary phytophagous pest of *C. chinense*, currently causing the greatest economic losses, which can reach up to 90%. *B. tabaci* also acts as a vector for plant viruses, the most damaging of which are whitefly-transmitted begomoviruses (Geminiviridae), criniviruses (Closteroviridae), and torradoviruses (Secoviridae) (Fiallo-Olivé et al., 2020).

The primary method for controlling *B. tabaci* populations is chemical control. Neonicotinoids such as acetamiprid, clothianidin, imidacloprid, thiacloprid, and thiamethoxam are the most commonly used insecticides against *B. tabaci*. However, these potent insecticides not only control pest populations but also negatively impact beneficial insects such as pollinators (*Apis mellifera*, *Bombus terrestris*, and *Bombus impatiens*). Additionally, the excessive use of neonicotinoids leads to severe ecological problems (Lundin et al., 2015).

An alternative approach to managing *B. tabaci* populations is biological control through entomopathogenic fungi (EF). One such EF, *Cordyceps fumosorosea* (formerly known as *Isaria fumosorosea*), has been widely commercialized for the management of various insect pests. Under favorable environmental conditions, *C. fumosorosea* can significantly reduce pest populations (Wang et al., 2021). The efficacy of *C. fumosorosea* as a bioinsecticide is attributed to its production of mycotoxins (fumosorinone, beauvericin, and brevianamide F) and secondary metabolites (trichodermin, 5-methylmellein, and enniatin), which provide a high level of safety for humans and non-target organisms while minimizing environmental impact. Extensive research has identified *C. fumosorosea* as an effective biological control agent against a wide range of pests under both *in vitro* and *in vivo* conditions. Notably, it has shown efficacy against *B. tabaci* in potted eggplant experiments (Wu et al., 2021). Tian et al. (2015) documented the infection process of *C. fumosorosea* against *B. tabaci*, showing high pathogenicity, with mortality observable within 48 to 72 hours after inoculation. Additionally, Sun et al. (2020) suggested that *C. fumosorosea* can function as an endophyte, enhancing its insecticidal activity when introduced at the early seedling stage or through seed colonization.

Although several *in vitro* and *in vivo* studies have demonstrated the efficacy of *C. fumosorosea* against *B. tabaci*, further *in situ* studies under open-field and greenhouse conditions are necessary to assess its efficacy in real-world settings. Therefore, the objective of this research was to evaluate the population fluctuation of *B. tabaci* in *C. chinense* cultivation through the application of *C. fumosorosea* as a biological control agent. The significance of this study lies in its analysis of data collected from open-field conditions compared to greenhouse environments, contributing to a better understanding of *C. fumosorosea* potential as a sustainable pest management strategy.

MATERIAL AND METHODS

Experimental site

The study was carried out in a gothic greenhouse (20×10 threads cm^2) situated in the productive area of the Faculty of Biological and Agricultural Science of the University of Colima, Tecoman, Colima, Mexico (18°57’09” N -103°53’45” W). The climate in the region is warm, subhumid A(w0) with an average temperature of 26.3 ºC, 750 mm of precipitation per year, and 33 m.a.s.l.

Biological materials

Capscicum chinense seed var. “Megalodon” (Bayer® Crop Science) was used as plant material. *Cordyceps fumosorosea* conidiospores was provided by COR-SEA®, a biological product formulated in a wettable powder (Plantbio®, Mexico) at a concentration of 5×10^{11} conidiospores 480 g^{-1}.

Capsicum chinense seedlings, transplant and plant nutrition

Capsicum chinense seeds were planted in disinfected (Full-Gro® 1 mL L^{-1}) polyethylene trays (200 cavities). Trays were filled with *Sphagnum* (Peat Moss®, 4 kg tray^{-1}). A *C. chinense* seed was placed in each cavity at a depth of one centimeter. Trays were covered with black polyethylene bags for six days to promote seed germination. Seedlings were fertilized twice weekly with Poly-Feed 12-43-12 (1.5 g L^{-1}), Root-Factor® (1.0 g L^{-1}), and Maxirad® (0.5 mL L^{-1}). Upon reaching 20 cm in height, the seedlings were transplanted in soil under two environments (greenhouse and open-field conditions). The experimental soil was a sandy loam soil, composed of 17% clay, 77% sand and 6% silt, with an electrical conductivity of 8.53 mS·cm^{-1}, pH of 6.88, and organic matter content of 0.60%. Furrows were dug using agricultural machinery (plow and harrow) at 1.8 m intervals, with a width of 50 cm and a depth of 25 cm. The furrows were covered with silver-black plastic mulch, perforated with holes every 30 cm. An irrigation tape with drippers spaced 30 cm apart was installed under the plastic mulch. Irrigation water was applied from a tank fed using a 0.5 HP pump controlled by a manual timer. Considering the physical-chemical characteristics of the soil, fertilization was applied at rates of 176.5, 130.0, and 254.0 kg ha^{-1} for N, P and K, respectively. The nutrient sources (N-P-K) were phosphonitrate (30-3-0), potassium sulfate (0-0-51+18 S), and monopotassium phosphate (0-52-34). Turgent-Ca® (AgroScience, USA) was used for Ca contribution. Micronutrients (B, Cu, Fe, Mn, Mo, and Zn) were supplied by FullMix B® (Green How, USA). Fertilization was divided into four stages: 1) Adaptation: a fertilization rate of 2.0-1.0-1.0 (N-P-K) was applied for 21 days through six fertigations; 2) Development, a fertilization rate of 3.0-1.0-2.0 (N-P-K) was applied for 30 days in 10 fertigations; 3) Fruiting, a fertilization rate of 2.0-3.0-2.0 (N-P-K) was applied for 35 days in 12 fertigations. Finally, 4) Production, a fertilization rate of 1.0-1.0-4.0 (N-P-K) was applied for 65 days in 28 fertigations. All fertilizers were applied by fertigation (Chan-Cupul et al., 2023).

Cordyceps fumosorosea application

A dose of 2.5 g L^{-1} of water from the commercial product was applied. Inex-A® was used as a surfactant (1.0 ml·L^{-1}). Applications were made in the late afternoon (4:00-6:00 pm), using a manual sprinkler (Guarany®, Mexico). The applications were made at 7, 14, 21, 28, 45 and 60 days after the transplant (DAT). Water volumes ranged from 200 to 350 L ha^{-1}, adjusted according to the increase in foliar biomass of *C. chinense* plants.

Experimental design and treatments

The experiment was conducted using an experimental factorial design A × B, where factor A corresponded to the site (greenhouse or open-field) and factor B to the application of *C. fumosorosea* conidiospores (with or without application). In total, four treatments were established: T1: Greenhouse + application of *C. fumosorosea*; T2) Greenhouse without application of *C. fumosorosea*; T3: open-field + application of *C. fumosorosea*; and T4) open-field without application of *C. fumosorosea*. Each treatment was established with 15 repetitions, each repetition consists of a plant, and the experiment was repeated twice. In the experimental plots, the integrated pest management of *B. tabaci* was applied using the following products: biorational insecticides [Gamma® (extract of garlic, pepper and cinnamon) at 2.5 mL L^{-1}, Castell® (*Streptomyces* spp. extract) at 2.5 mL L^{-1} and Kelpak® (*Ecklonia maxima* extract) at 2.5 mL L^{-1}], and chemical insecticides [Karate Zeon® (Lamda cyhalothrin) at 1.5 mL L^{-1}, Toreto® (Sulfoxaflor) at 1.0 mL L^{-1} and Versys® (afidopiropen) at 1.25 mL L^{-1}).

Response variables

Population fluctuation (incidence). The population of *B. tabaci* in *C. chinense* plants undergoing treatments with *C. fumosorosea* were monitored over time and at different stages of plant growth. Adult and nymph sampling per leaf were carried out once a week, from 7:00 a.m. to 8:30 am. The samples were performed 63 DAT. The presence of nymphs was confirmed through a manual glass at 10×.

Efficacy. The efficacy of the application of *C. fumosorosea* in the two cultivation systems (greenhouse and open-field) was calculated. The efficacy was calculated using the following formula (Guimaraes-Bevilaqua et al., 2023):

$$E(\%) = \left(\frac{Nit - Nitr}{Nit}\right) \times 100$$

Where E = percentage of efficacy (%); Nit = number of nymphs or adults without the application of *C. fumosorosea*; Nitr = number of nymphs and adults with the application of *C. fumosorosea*.

Area under the population progress curve (AUPPC). It is a metric that integrates the population behavior of the pest during the experiment and facilitates the comparison between treatments, providing a comprehensive evaluation of its effect on the reduction of the pest over time. The AUPPC was calculated with the following equation, which was modified from Shaner and Finney (1977).

$$AUPPC = \sum_{i=1}^{n} [(Y_{i+n1} + Y_i)/2][X_{i+1} - X_i]$$

Where: X = is the time of each sampling; Y = is the abundance of nymphs or adults in each sampling and n = is the number of samplings.

Statistical analysis

To normalize the observed data, the number of nymphs and adults were transformed to √×+1. A normality and homogeneity test of variance was carried out. A multifactorial analysis of variance was used to analyze the population fluctuation and the AUPPC. To compare the efficacy of the application of *C. fumosorosea* in the site factor, a t-Student mean comparison was made. All analyses were made using the Statgraphics V.8 program for Windows®.

RESULTS AND DISCUSSION

Population fluctuations of adults and nymphs of *B. tabaci*

The cultivation site factor achieved significant differences in all samples (P≤0.05). From the beginning of the sampling at 14 until 49 DAT, a higher population of *B. tabaci* adults was found in the open-field cultivation of *C. chinense*. However, this behavior changed at 56 and 63 DAT, where the greenhouse cultivation of *C. chinense* showed a higher population of *B. tabaci* adults with an increase of 34.7 and 17.5%, respectively (Table 1). For the *C. fumosorosea* application factor, significant differences (P≤0.05) were found from 28 to 63 DAT, the application of *C. fumosorosea* significantly reduced the *B. tabaci* adult population between 18.90 (28 DAT, P=0.0076) and 52.12% (63 DAT, P=0.00001) (Table 1). Regarding the interaction of the two factors (treatments), significant differences were found in the samplings at 56 and 63 DAT, *C. chinense* plants grown under greenhouse (P=0.00001) and open-field (P=0.00001) conditions without *C. fumosorosea* application achieved the highest number of adult plants^{-1} of *B. tabaci* with 3.89 and 3.89, respectively (Table 1).

Regarding *B. tabaci* nymphs, the cultivation site factor showed significant differences (P≤0.05) at 21, 28 and 46 DAT. A higher number (P≤0.05) of nymphs plant^{-1} was observed in the open-field at 21 DAT (1.06 nymphs plant^{-1}) and 28 (1.32 nymphs plant^{-1}) DAT compared to *C. chinense* cultivation under greenhouse condition (21 DAT=1.00 nymphs plant^{-1} and 28 DAT=1.32 nymphs plant^{-1}). As occurred with adults, at the end of sampling at 63 DAT, a higher number of nymphs plant^{-1} (P≤0.05) was observed under greenhouse cultivation (2.77 nymphs plant^{-1}) compared to open-field conditions (2.31 nymphs plant^{-1}) (Table 2). For the *C. fumosorosea* application factor, significant differences were found in most of the samples (P≤0.05), the application of the entomopathogenic fungus reduced *B. tabaci* nymph population between 5.66 (21 DAT) and 59.34% (56 DAT) (Table 2). For interactions, it was found that the cultivation of *C. chinense* under greenhouse and open-field conditions without the application of *C. fumosorosea* achieved the highest number of nymphs plant^{-1} in samplings at 21, 49, 56 and 63 DAT (Table 2).

Although higher populations of *B. tabaci* adults and nymphs were found in the open-field at the beginning of the experiment, these populations decreased after 56 DAT. This reduction may be attributed to the increased temperature inside the greenhouse, as the biological cycle of *B. tabaci* is reduced with rising ambient temperatures (Khanh et al., 2021). Furthermore, the application of the formulation based on *C. fumosorosea* in wettable powder through a bioaugmentation strategy is a suitable technique for the biological control of *B. tabaci* under open-field and greenhouse conditions (Faria and Wraight, 2001). Although various methodologies have been developed for the *in vitro* or *in vivo* evaluations of EF (Sain et al., 2019), one of the greatest challenges is their effectiveness under *in situ* conditions (open-field or greenhouse). In *in vivo* studies, the EFs most commonly investigated against *B. tabaci* are *P. fumosoroseus* and *Lecanicillium muscarium* (Cuthbertson, 2013). However, the reduction of *B. tabaci* populations through the use of EF, particularly *C. fumosorosea*, under *in situ* conditions has not been extensively studied. Abdel-Raheem et al. (2009) reported that the application of *Verticillium lecanii* and *Beauveria bassiana* in potato grown under open-field conditions reduced *B. tabaci* populations from 17 adults per leaf in the control to 1 and 3 adults leaf^{-1}, respectively. A study conducted by Sun et al., (2020) in eggplant (*Solanum melongena* L.) cultivated under semicontrolled conditions revealed that seed inoculation with *C. fumosorosea* reduced *B. tabaci* egg hatchability by 9.33 and 11.5% at 15 and 30 DAT, respectively, and decreased adult incidence from 30 (15 DAT) to 35% (30 DAT). In a greenhouse study, Sani et al. (2023a) reported that *Isaria javanica* and *Purpureocillium lilacinum*, species related to *C. fumosorosea*, effectively reduced *B. tabaci* nymph populations in tomato plants, *I. javanica* and *P. lilacinus* averaged 1.33 and 2.5 nymphs leaf^{-1}, respectively, compared to 6.5 nymphs leaf^{-1} in the control. A similar effect was observed in adults, where the control average of 18.66 adults plant^{-1}, while *I. javanica* and *P. lilacinum* presented 8.33 and 11.83 adults plant^{-1}, respectively (Sani et al., 2023a). In a susbsequent study, the same authors demonstrated the endophytic ability of *I. javanica* and *P. lilacinum* in tomato plant, showing that endophytism significantly reduced adult emergence plant^{-1}, from 58 in the control to 15 and 28 adults plant^{-1} for *I. javanica* and *P. lilacinum*, respectively (Sani et al. 2023b). More recently, Sudarjat et al. (2024) reported that weekly applications of *Aschersonia aleyrodis* at 1×10^{6} conidia mL^{-1}significantly reduced *B. tabaci* nymph populations on tomato plants, from 486.3 nymphs plant^{-1} in the control to 73 nymphs plant^{-1} when applying a concentration of 1×10^{6} conidia mL^{-1}.

Table 1. Population fluctuation of *Bemisia tabaci* (adults plant^{-1}) under greenhouse and open-field conditions in the cultivation of *Chinense capsicum* through the application of *Cordyceps fumosorosea*.

Factor	Days after transplant							
Site	**14**	**21**	**28**	**35**	**42**	**49**	**56**	**63**
Greenhouse	1.07±0.03 b	1.16±0.04 b	1.24±0.07 b	1.59±0.12 b	1.96±0.13 b	1.68±0.11 b	2.87±0.22 a	2.82±0.16 a
Open-field	1.48±0.08 a	1.63±0.07 a	1.72±0.1 a	1.79±0.09 a	2.34±0.0.1 a	2.68±0.09 a	2.13±0.09 b	2.40±0.23 b
Application								
With *Cf*	1.23±0.06	1.41±0.07	1.33±0.09 b	1.30±0.06 b	1.77±0.09 b	1.96±0.12 b	1.82±0.06 b	1.69±0.10 b
Without *Cf*	1.32±0.07	1.38±0.07	1.64±0.09 a	2.08±0.09 a	2.53±0.11 a	2.40±0.14 a	3.18±0.17 a	3.53±0.12 a
Interactions								
G With *Cf*	1.05±0.04	1.16±0.05	1.13±0.06	1.10±0.06	1.48±0.1	1.42±0.11	1.85±0.08 c	1.63±0.11 c
G Without *Cf*	1.08±0.04	1.16±0.05	1.36±0.12	2.08±0.14	2.45±0.17	1.94±0.17	3.89±0.21 a	3.17±0.12 b
OF With *Cf*	1.04±0.1	1.65±0.09	1.53±0.15	1.50±0.07	2.07±0.11	2.49±0.11	1.79±0.08 c	1.74±0.16 c
OF Without *Cf*	1.55±0.11	1.60±0.1	1.92±0.1	2.09±0.12	2.62±0.14	2.86±0.13	2.47± 0.08 b	3.89±0.15 a
Significance								
Site	0.00001	0.00001	0.0001	0.0535	0.0051	0.00001	0.00001	0.0037
Application	0.2934	0.7347	0.0076	0.00001	0.00001	0.0015	0.00001	0.00001
Interactions	0.469o2	0.7347	0.4731	0.0713	0.1132	0.5742	0.00001	0.0316

Means (± standard error, n=15) with different letters indicate significant differences according to Tukey's test (P=0.05). *Cf*=*Cordyceps fumosorosea*, G=greenhouse and OF=open-field.

Under greenhouse conditions, Wari et al. (2020) reported a synergic effect of the application of *B. bassiana* (GHA strain) + insecticide (Cyantraniliprole) + fungicide (Cyantraniliprole) in the reduction of *B. tabaci* population in tomato plants. In this treatment, 250 adults trap^{-1} were recorded, compared with 3000 adults trap^{-1} in the control treatment (- insecticide + *B. bassiana* GHA + Fungicide). Entomopathogenic fungi can be compatible with chemical insecticides that act on the insect nervous system, when applied separately or independently. This is because fungal cellular communication mechanisms differ significantly from insect nervous system signaling, despite their common evolutionary origin. While insects rely on complex nervous

Table 2. Population fluctuation of *Bemisia tabaci* nymphs (nymphs plant^{-1}) under greenhouse and open-field conditions in the cultivation of *Chinense capsicum* through the application of *Cordyceps fumosorosea*.

Factor	Days after transplant							
Site	**14**	**21**	**28**	**35**	**42**	**49**	**56**	**63**
Greenhouse	1.01±0.01	1.00±0.00 b	1.14±0.04 b	2.12±0.23	2.52±0.25	2.85±0.27	2.19±0.21 b	2.77±0.27 a
Open-field	1.07±0.03	1.06±0.03 a	1.32±0.07 a	1.91±0.18	2.86±0.26	4.05±0.22	3.32±0.32 a	2.31±0.24 b
Application								
With *Cf*	1.00±0.00 b	1.00±0.00 b	1.17±0.05	1.16±0.05 b	1.71±0.1 b	2.61±0.21 b	1.58±0.1 b	1.35±0.08 b
Without *Cf*	1.09±0.04 a	1.06±0.03 a	1.28±0.07	2.87±0.19 a	3.65±0.24 a	4.29±0.22 a	3.93±0.25 a	3.72±0.18 a
Interactions								
G With *Cf*	1.00±0.00	1.00±0.00 b	1.08±0.04	1.16±0.09	1.64±0.17	1.72±0.13 c	1.27±0.09 c	1.50±0.14 b
G Without *Cf*	1.02±0.03	1.00±0.00 b	1.20±0.07	3.08±0.29	3.39±0.36	3.98±0.31ab	3.11±0.22 b	4.03±0.23 a
OF With *Cf*	1.00±0.00	1.00±0.00 b	1.27±0.09	1.15±0.06	1.77±0.11	3.50±0.24 b	1.90±0.13 c	1.20±0.07 b
OF Without *Cf*	1.15±0.06	1.13±0.06 a	1.36±0.012	2.66±0.23	3.95±0.32	4.60±0.31 a	4.75±0.34 a	3.41±0.25 a
Significance								
Site	0.0619	0.0365	0.0419	0.2716	1.1932	0.00001	0.00001	0.0166
Application	0.0091	0.0365	0.2007	0.00001	0.0001	0.00001	0.00001	0.0001
Interactions	0.0619	0.0365	0.8601	0.2851	0.4126	0.0276	0.0236	0.0001

Means (± standard error, n=15) with different letters indicate significant differences according to Tukey's test (P=0.05). *Cf*=*Cordyceps fumosorosea*, G=greenhouse and OF=open-field.

systems, fungi have developed unique signaling pathways. In filamentous fungi, including EF, cell-cell fusion is mediated by a conserved dialogue-like communication system involving an excitable signaling network where cells alternate between sending and receiving signals (Fleibner et al., 2022; Hammadeh et al., 2022).

Efficacy of *C. fumosorosea* against *B. tabaci* under greenhouse and open-field conditions

Table 3 describes the efficacy of *C. fumosorosea* against *B. tabaci* adults in *C. chinense* in both cultivation sites. Efficacy in greenhouse conditions ranged from 6.63 (14 DAT) to 52.45% (56 DAT); while efficacy in open-field condition ranged

Table 3. Efficacy (%) of *Cordyceps fumosorosea* against *Bemisia tabaci* adults in *Capsicum chinense* cultivation under greenhouse and open-field conditions.

Site	Days after transplant							
	14	21	28	35	42	49	56	63
Greenhouse	6.63±0.69 b	8.53±1.86	19.61±3.1	46.93±2.8 a	39.44±3.92 a	27.82±5.01 a	52.45±2.2 a	48.38±3.6
Open-field	16.69±4.24 a	7.36±2.66	26.72±5.79	28.17±3.4 b	21.49±3.91 b	14.21±3.18 b	27.2±3.46 b	55.04±4.0
t-Student	-2.3364	0.3592	-1.0774	4.2457	3.2374	2.2916	6.1391	-1.2344
P-value	0.0269	0.7221	0.2905	0.0002	0.0031	0.0297	0.00001	0.2273

Means (± standard error) with different letters indicate significant differences according to the t-Student's test (P=0.05).

from 7.36 (21 DAT) to 55.04% (63 DAT). In the sampling at 35, 42, 49 and 56 DAT, *C. fumosorosea* was more effective against *B. tabaci* adults under greenhouse conditions than under open-field conditions (Table 3). Furthermore, *C. fumosorosea* showed more efficacy against *B. tabaci* nymphs (from 2.7 to 64.6%) than against adults (from 6.63 to 55.04%). Only at 49 DAT, the efficacy in the greenhouse was significantly higher (P=0.00001) than in the open-field conditions, reaching 56.7% and 25.1%, respectively (Table 4).

In a previous study, Wraight et al. (2000) reported efficacies of *Paecilomyces fumosoroseus* (currently *C. fumosorosea*) against *Bemisia argentifolli* adults ranging from 88.7 to 98.8% in cucumber (*Cucumis sativus* L.) under open-field conditions (25.3 °C and 84.6% relative humidity). However, the efficacy of *P. fumosorosea* against nymphs was lower than against adults, ranging from 53.6 to 67.7% (Wraight et al., 2000). Likewise, Avery et al. (2008) reported efficacies of *C. fumosorosea* of 78.7% against adults and 97.0% against nymphs of the greenhouse whitefly (*Trialeurodes vaporariorum*) on *Phaseolus vulgaris* plants. Tian et al. (2015) reported that *C. fumosorosea* was more efficient against second instar *B. tabaci* nymphs (83.1%) than against adults (55.0%) on cucumber *C. sativus* plants. Aristizábal et al. (2018) reported efficacies between 70 and 76% of *C. fumosorosea* against *B. tabaci* nymphs on *Mentha* spp. Likewise, *C. fumosorosea* was more effective against *B. tabaci* nymphs than against adults (Aristizábal et al., 2018). When using *C. fumosorosea*, Sun et al. (2020) reported efficacy of 30 to 35% in the management of *B. tabaci* adult and nymph populations on eggplant (*S. melongena*). Fatma et al. (2020) reported an efficacy of *B. bassiana* (Biofly®, a commercial product) of 76.2% against *B. tabaci* adults on cucumber under greenhouse conditions ten days after application. However, other EF species with affinity for Aleyrodidae, such as *A. aleyrodis*, have shown greater efficacies, reaching up to 90% against *B. tabaci* adults (Sudarjat et al., 2024).

A current perspective with *C. fumosorosea* is the one proposed by Wang et al. (2021), which consists of the production of nanoparticles from a conidiospore solution. *C. fumosorosea* can produce pathogenic nanoparticles against *B. tabaci* with high efficiency in eggs (65%) and nymphs (85%). Likewise, one of the important characteristics to consider in the efficacy of EF against *B. tabaci* is the type of inoculum used. The active agent can be applied in the form of blastospores or conidia, which exhibit different biological characteristics: blastospores are produced via submerged fermentation, while conidia are produced through solid or biphasic fermentation (Sala et al., 2023). In this sense, Wu et al. (2023) evaluated the application of *I. javanica* blastospores against *B. tabaci* immatures on cotton leaves, reporting efficacies ranging from 5 to 20%.

Area under the population progress curve (AUPPC).

The AUPPC of *B. tabaci* adults was significantly

Table 4. Efficacy (%) of *Cordyceps fumosorosea* against *Bemisia tabaci* nymphs in *Capsicum chinense* cultivation under greenhouse and open-field conditions.

Site	Days after transplant							
	14	21	28	35	42	49	56	63
Greenhouse	2.7±0.00 a	0±0.00 a	13.8±1.8	62.3±2.9	51.5±5.1	56.7±3.1 a	59±2.8	62.7±3.4
Open-field	13.7±0.00 b	11.6±0.00 b	14.4±3.6	56.5±2.4	55.1±2.8	25.1±4.7 b	59.9±2.7	64.6±2.1
t-Student	-7.6535E+15	-2.4504E+16	-0.1450	1.5522	-0.6216	5.5585	-0.2295	-0.4868
P-value	0	0	0.8858	0.1319	0.5392	0.00001	0.8201	0.6302

Means (± standard error) with different letters indicate significant differences according to the t-Student's test (P=0.05).

higher (P<0.05) across all sampling events for the cultivation site factor (greenhouse and open-field conditions) of *C. chinense*. The adult population curve was notably greater under open-field conditions (Fig. 1A). Similarly, the *C. fumosorosea* application factor exhibited statistically significant differences (P<0.05). The application of *C. fumosorosea* to *C. chinense* crops led to a reduction in the AUPPC of *B. tabaci* adults by up to 41.48% (63 DAT, P=0.00001, Fig. 1B). Regarding the interaction effect against *B. tabaci* adults, significant differences were observed only during the last two sampling dates (56 and 63 DAT). The greenhouse treatment combined with *C. fumosorosea* application recorded the lowest AUPPC (11.9) for *B. tabaci* adults, whereas the highest AUPPC was recorded under open-field conditions without *C. fumosorosea* application (Fig. 1C).

As observed with *B. tabaci* adults, the highest AUPPC of nymphs was found under open-field conditions (P<0.05) compared to *C. chinense* cultivated in a greenhouse. Increases in AUPPC ranged from 5.0 (14 DAT) to 19.18% (56 DAT, Fig. 1D). Similarly, throughout the monitoring period, the *C. fumosorosea* application factor showed statistically significant differences (P<0.05). Weekly applications of the entomopathogenic fungus reduced the AUPPC of whitefly nymphs, with reductions ranging from 5.0 (14 DAT) to 46.61% (63 DAT, Fig. 1E). Regarding the interaction between factors, the lowest AUPPC value (10.7) was recorded at 49 DAT in *C. chinense* cultivated under open-field conditions with *C. fumosorosea* application (Fig. 1F).

The AUPPC is an important parameter to consider in the evaluation of EF. This variable represents the accumulation of nymph and adult populations over time. To our knowledge, this is the first study to consider this response variable in *in situ* studies, preventing direct comparisons with previous research. However, Moudoud et al. (2024) recently proposed the variable of relative abundance and average density of adults in different crops, reporting that the relative abundance in tomato (45%) is higher compared to pepper (20%), squash (25%), and strawberry (15%). Likewise, the average density was 15, 70, 30 and 5 in pepper, tomato, pumpkin and strawberry, respectively. With both variables and with the application of *Verticillium* sp. and *Paecilomyces* sp. in controlling *B. tabaci*, the authors reported that *Verticillium* sp. was most effective, achieving a mortality rate of 73%, while *Pecilomyces* sp. resulted in a significantly lower mortality rate of 23% (Moudoud et al., 2024).

CONCLUSIONS

There was a temporal variation in *B. tabaci* population fluctuation on *C. chinense* influenced by the cultivation site. At the start of the cultivation cycle, open-field the greatest fluctuation occurred in the open-field; however, population fluctuation was greater under greenhouse conditions after 56 DAT. The application of *C. fumosorosea* reduced the population fluctuation of *B. tabaci* nymphs and adults in *C. chinense* production

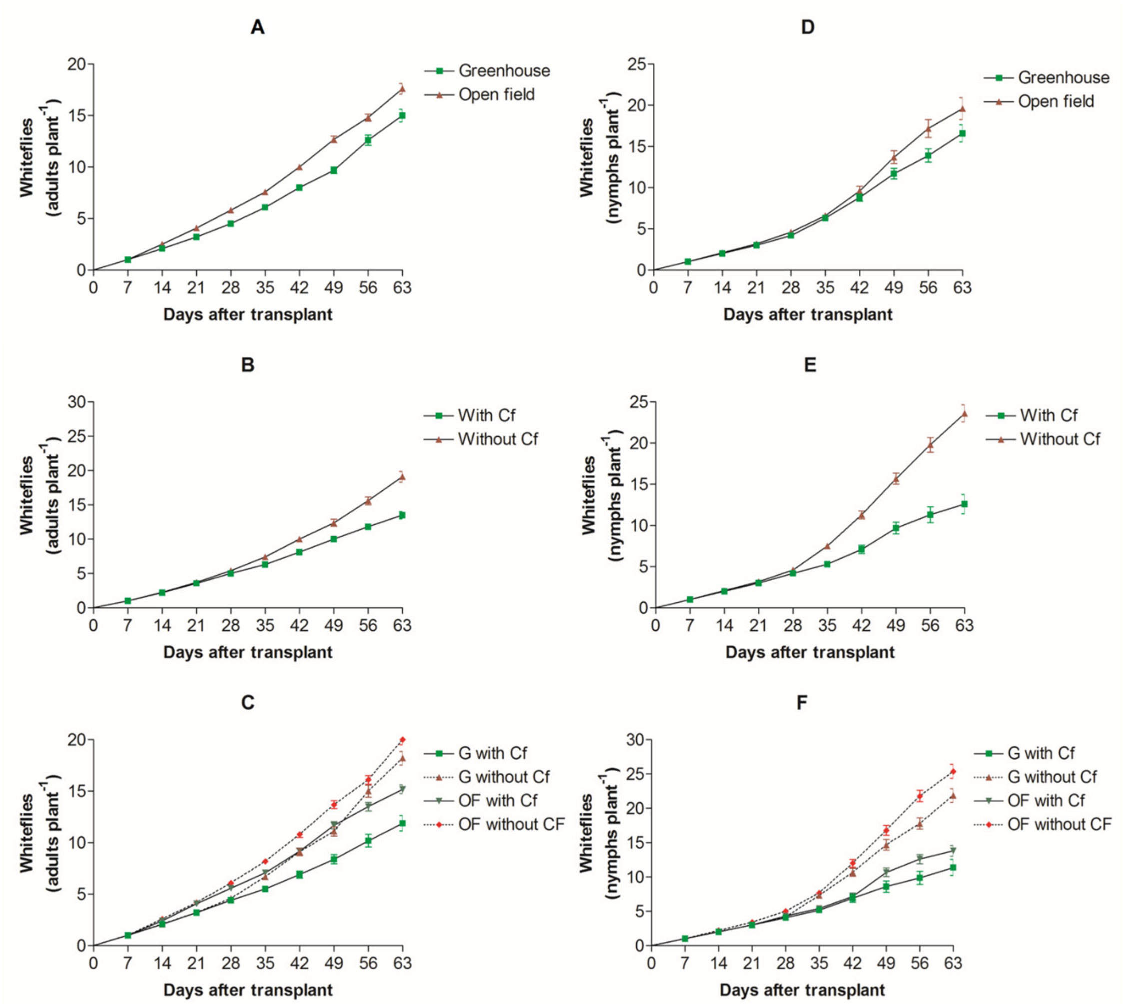

Fig. 1. Area under the population progress curve (AUPPC) of *B. tabaci* adults (A, B and C) and nymphs (D, E and F) in *Capsicum chinense* cultivation under greenhouse (G) and open-field (OP) conditions through the application of *Cordyceps fumosorosea* (Cf). Mean (± standard error).

systems under both open-field and greenhouse conditions. The population fluctuation of *B. tabaci* adults and nymphs is greater if the application of *C. fumosorosea* is not integrated into the cultivation of *C. chinense*, under both open-field and greenhouse conditions.

ACKNOWLEDGMENTS

The authors would like to thank Agronomy student Omar Gomez for his participation in the agronomic management of the crop where the experiment was carried out.

Author Contributions

The authors declare active participation in the bibliographic review: Omar Pinto González, Wilberth Chan Cupul and Andrea Mendoza Arceo; in the development of the methodology: Wilberth Chan Cupul and Omar Pinto González; in the discussion of the results: Omar Pinto González and Wilberth Chan Cupul; in review and approval of the final version of the article: Wilberth Chan Cupul and Andrea Mendoza Arceo.

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