JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(12), 438–448
https://doi.org/10.12911/22998993/208881
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.07.24
Accepted: 2025.09.01
Published: 2025.10.01

Evaluation of the effectiveness of a biological protection system for greenhouse cucumbers against major phytophagous pests

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ABSTRACT

Global climate change, moisture deficiency, and the impact of various biotic and abiotic factors on agricultural crops increasingly hinder the realization of plant productivity potential. The use of controlled greenhouse conditions allows for a significant increase in crop productivity and protection from the adverse effects of environmental stressors. However, short crop rotations and year-round cultivation across two seasons create favorable conditions for the mass development of harmful organisms, necessitating the development of effective and safe control methods. This study presents the results of evaluating the effectiveness of biological plant protection agents based on microbial preparations and entomophagous under greenhouse conditions. The experiment included a comparison of four treatment options: Boverin BT + Liposam, Bitoxibacillin BT + Liposam, Actofit BT + Liposam, a complex of entomophagous, and an untreated control. The highest yield was achieved with the use of Boverin BT + Liposam (18.9 kg/m²). The variants using Bitoxibacillin (17.4 kg/m²), Actofit (16.5 kg/m²), and the entomophagous complex (16.1 kg/m²) also outperformed the untreated control (12.3 kg/m²) in terms of yield. The obtained data indicate that the use of biological preparations not only reduces the population density of phytophagous pests but also indirectly promotes plant growth and development, likely by enhancing nutrient uptake, increasing root system activity, and optimizing the physiological and biochemical status of the crop. The most effective preparations were those containing Beauveria bassiana, due to their ability to combine entomopathogenic activity with endophytic colonization of plants. The results confirm the effectiveness of biological products as components of integrated pest management (IPM) systems under conditions of restricted chemical pesticide use. The proposed protection systems can be recommended for implementation in commercial practice as part of sustainable vegetable production in Ukraine.

Keywords: bioinsecticides, entomophagous insects, crop productivity, crop yield, insect pests, leaf area index, biological control agents

INTRODUCTION

Vegetable crops play a vital role in the human diet, providing nearly all essential vitamins and micronutrients. Among them, cucumber (*Cucumis sativus* L.) holds a prominent position, as the area under cultivation and the total production volume continue to grow steadily. According to FAOSTAT (2020), the global area under cucumber cultivation in 2018 was 1.984 million hectares, yielding 75.2 million tonnes (Haijun et al., 2021). By 2022, these figures had increased to 2.153 million hectares and 94.7 million tonnes, respectively (FAO, 2022).

At the current stage of horticultural development, there exists a wide range of agronomic practices for cucumber cultivation in both open-field and protected environments (such as greenhouses with unregulated and regulated climates, film and glass greenhouses, hydroponic, aquaponic, and aeroponic systems) (Sabir and Singh, 2013). Growing conditions significantly influence cucumber productivity. In modern greenhouses equipped with automated environmental controls (temperature, lighting, air and substrate humidity, etc.), cucumber yields have already exceeded 70 kg/m² – nearly ten times higher than yields in open-field cultivation (EastFruit, 2022).

Protected cultivation systems allow for nearly optimal regulation of critical growth factors – water, temperature, light, and nutrients – thus enabling the crop to fully realize its genetic yield potential (Wraight et al., 2017). However, these highly favorable growing conditions – including high air and substrate humidity, elevated and stable temperatures, and year-round crop presence (spring–summer and autumn–winter cropping cycles) – create preconditions for the mass proliferation of harmful organisms such as pests and pathogens (Shipp et al., 2017; Adly and Sanad, 2024).

A critical feature of greenhouse agroecosystems is the absence of natural ecological relationships among key components, such as phytophagous insect populations and beneficial entomofauna (pollinators and natural enemies), as well as microbial populations that, under open-field conditions, contribute to the biological regulation of pest density (van Lenteren et al., 2018; Messelink et al., 2021). Currently, phytophagous species in greenhouse conditions are most effectively controlled with synthetic chemical pesticides, which offer high efficacy, residual activity, and rapid suppression of pest outbreaks to protect crop yields (Güncan et al., 2006).

However, the use of synthetic pesticides, despite their benefits, has several disadvantages: first, potential toxicity to workers and consumers if application guidelines are not followed; second, the risk of pesticide residue accumulation in produce; and third, the development of resistance in pest populations with repeated use (Wu et al., 2020).

The healthy eating trend, actively promoted over the past decades, has created numerous opportunities for organic farming and the production of environmentally safe food. A significant share of this demand is met by vegetable crops, as they are commonly consumed fresh and immediately after harvest (Alsanius et al., 2019; Ilakiya et al., 2020). The production of certified organic vegetables is only possible with the complete avoidance of synthetic pesticides and the substitution of such chemicals with biologically based insecticides (fungal or bacterial preparations) or biological control agents– natural enemies of harmful insects (Adly, 2016).

In greenhouse cucumber production in Ukraine and worldwide, the major harmful organisms include representatives of the spider mite family (Tetranychidae) and insect pests such as aphids (Aphididae), whiteflies (Aleyrodidae), and thrips (Thripidae). Most of these species are polyphagous, characterized by high ecological plasticity, reproductive potential, and low natural mortality rates (Sharma et al., 2016; Tkalenko & Tkalenko, 2017; Dudchenko et al., 2024).

In polyethylene-covered greenhouses of the Kyiv region, researchers have most frequently recorded three species of spider mites: the common spider mite (*Tetranychus urticae* Koch), the carmine spider mite (*T. cinnabarinus* Boisduval), and the two-spotted spider mite (*T. bimaculatus* Harvey). Among the crops cultivated under protected conditions, cucumber plants are most heavily infested by these pests. Plant infestation rates can exceed 45%, with an average density of 65 individuals per leaf (Tkalenko and Tkalenko, 2017; Dudchenko et al., 2024).

Aphids are another group of dangerous phytophagous pests affecting cucumbers in greenhouses. The most damaging species include the green peach aphid (*Myzodes persicae* Sulzer), the black bean aphid (*Aphis fabae*), and the cotton aphid (*Aphis gossypii*). In recent years, cucumber infestation by these aphids has reached over 25%, with population densities occasionally exceeding 115 individuals per leaf (Tkalenko, 2013).

In temperate climate regions, the distribution and phytosanitary impact of certain cucumber pests are increasingly prevalent both in greenhouse conditions and open-field cultivation. One such emerging pest is the greenhouse whitefly (*Trialeurodes vaporariorum* Westw), which has demonstrated considerable damage potential (Singh and Kaur, 2020). Another highly destructive phytophagous species from the order Thysanoptera – the tobacco thrips (*Thrips tabaci* Lind) – has colonized nearly all greenhouses used for vegetable production, including cucumber, and consistently causes significant yield losses (Klechkovskiy et al., 2019).

To date, a wide range of synthetic chemical insecticides has been developed, exhibiting high efficacy against phytophagous insects across various taxonomic groups. These compounds typically offer prolonged protective action against both adult and larval stages of insects and mites, and certain formulations are even known to exert ovicidal effects (Saleem et al., 2020). While the primary objective of pesticide application is pest suppression and enhancement of crop productivity, edible plant products grown with chemical protection remain the most common route of pesticide residue ingestion in humans (Leili et al., 2016).

As alternatives to synthetic insecticides, biological control agents (including parasitoids and predators) and bioinsecticides based on entomopathogenic fungi, bacteria, and plant-derived extracts are widely adopted in modern integrated pest management strategies (Singh and Kaur, 2020; Ali et al., 2017; Ullah et al., 2019). Commercial formulations utilizing biocontrol agents include a diverse array of organisms, such as predatory mites (*Phytoseiulus persimilis* Athias-Henriot), dipteran species (*Aphidoletes aphidimyza* Rand, *Episyrphus balteatus* De Geer), coleopterans (*Adalia bipunctata* L.), hemipterans (*Macrolophus pygmaeus* Rambur, *Nesidiocoris tenuis* Reuter), hymenopterans (*Trichogramma* spp.), neuropterans (*Chrysoperla carnea* Stephens), nematodes (*Heterorhabditis bacteriophora* Poinar), entomopathogenic microorganisms including bacteria (*Bacillus thuringiensis* Berliner), fungi (*Beauveria bassiana* [Bals.-Criv.] Vuill., *Metarhizium anisopliae* Metsch), and baculoviruses (*Spodoptera exigua* NPV, *Helicoverpa armigera* NPV), among others (van Lenteren et al., 2020; Tribuntsova and Barkhatova, 2021; Iosob et al., 2021).

However, despite the environmental safety of using biological insecticides and natural enemies of phytophagous pests, their effectiveness is often influenced by several factors, including the population density and dynamics of pest species, species composition, developmental stage distribution, and the host specificity of the bioinsecticides and biocontrol agents applied for crop protection. Therefore, the development of application protocols for modern bioinsecticides, in combination with the use of natural enemies of harmful species, remains a relevant and pressing task. It is essential to ensure the production of environmentally safe vegetable crops while maintaining adequate crop productivity.

MATERIALS AND METHODS

Plant material and growth condition

The study was conducted under greenhouse conditions at the greenhouse complex of PJSC „Myronivka Cereal and Feed Plant", located in Myronivka, Bila Tserkva District, Kyiv Region, Ukraine (49°39′36″ N, 30°58′56″ E).

For the experiment, the universal ultra-early parthenocarpic hybrid Kibria F1 RZ was used. Seedlings and plants were grown in winter glass block-type greenhouses with soil substrate and a water-pipe heating system, following standard cultivation technology for protected ground conditions. The sowing date for seedling production was July 7, 2023, and transplanting to the greenhouse took place on August 3, 2023.

Prior to transplanting, sanitation and disinfestation of the greenhouse facility were carried out in accordance with the technological protocol, including fumigation, washing of greenhouse structures, flaming of metal frames, soil steaming, soil flushing, and the application of Trichodermin.

At 25–26 days of age, when plants had developed 3–4 true leaves, the seedlings were transplanted to their permanent growing site. Irrigation was performed via a drip system, maintaining soil moisture at 70–80% of field capacity prior to flowering, and 80–90% during peak flowering and fruit formation. Soil moisture levels were monitored using tensiometers.

Application of bioinsectoacaricides and entomophagous insects

The experiment evaluated the effectiveness of the following bioinsectoacaricides: Actofit BT – a preparation containing avermectins, a group of natural neurotoxins with contact and ingestion activity (150 mL per 10 liters of water); Boverin BT – a microbiological formulation based on Beauveria spp. containing toxic metabolites and fungal conidia, exhibiting both infectious and toxigenic effects (300 mL per 10 liters of water); Bitoxibacillin BT – a biopesticide containing rhizosphere-derived spore-forming bacteria of the genus Bacillus and two types of toxins: β-exotoxin and δ-endotoxin (300 mL per 10 liters of water). The following entomophagous species were used: Aphidoletes aphidimyza (Rondani) – predatory gall midge (10 cocoons/m²); Chrysoperla carnea (Stephens) – common green lacewing (100 larvae/m²), whose larvae feed on various species of aphids; Macrolophus pygmaeus (Rambur) – a generalist predatory mirid bug (1 individual/m²) that feeds on eggs, larvae, and adults of whiteflies, as well as other sucking pests such as aphids, thrips, and spider mites. Bioinsecticides and entomophagous insects were applied after transplanting the seedlings to the permanent growing site, throughout the vegetative period, at 10–day intervals until the onset of peak fruiting. To enhance the effectiveness of the bioinsecticides, the biosticker Liposam was added to the working solution at a rate of 30 mL per 10 liters.

Experimental design

The total area of the greenhouse block allocated for cucumber cultivation was 345.6 m², with an effective planting area of 320 m². A total of 500 plants were transplanted, resulting in a planting density of 2.4–2.8 plants/m². The area of each experimental plot was 4 m², with 10 plants selected for observation and data collection per plot. The experiment was designed using a randomized complete block design (RCBD) with four replications.

Monitoring of phytophagous pest populations

Monitoring of phytophagous pest populations was carried out using yellow sticky traps and by assessing plant infestation levels, starting from the date of transplanting to the permanent growing site. Observations were recorded at the following crop development stages: PS (planting of seedlings), BF (beginning of fruiting), IF (Increasing fruiting), MF (mass fruiting), and CF (cessation of fruiting).

Pest population density was determined on 25 randomly selected plants in each greenhouse block. Observations were conducted at three canopy levels (lower, middle, and upper) using a LEMANSO magnifying lens (diameter = 90 mm).

Efficacy of bioinsecticides and entomophages

The efficacy of biological insecticides and the use of biological control agents under greenhouse conditions were assessed in separate compartments during the flowering onset and early fruiting stages, using a modified Abbott's formula (Formula 1):

$$E = \left(1 - \frac{K_1}{K_2} \times \frac{O_2}{O_1}\right) \times 100\% \quad (1)$$

where: K_1, K_2 – the pest population on control model plants before and after treatment, respectively; O_1, O_2 – the pest population on treated model plants after and before treatment, respectively.

Crop yield and plant biometric parameters

Cucumber yield was determined by harvesting fruits every two days at the beginning of fruiting and daily during the peak fruiting phase, followed by weighing using precision scales. Biometric parameters (plant mass, length of the main stem, number of lateral shoots) were measured using precision balances, a measuring ruler (cm), and direct counting (units). Leaf area was determined using the disc method (Formula 2):

$$S = M \cdot S_1 / M_1 \text{ см}^2 \quad (2)$$

where: M – total leaf mass, g; S_1 – area of a single disc (punch), cm²; M_1 – mass of the discs, g.

Statistical analyses

Experimental data were analyzed using standard statistical procedures to assess the significance of the effects of bioinsecticides and entomophagous on plant growth, development, and productivity. Cucumber yield parameters were evaluated by one-way analysis of variance (ANOVA) to determine the statistical significance of differences between treatments. Duncan's Multiple Range Test (DMRT) was applied to compare treatment means at a significance level of $\alpha = 0.05$. Statistical analysis was performed using Statistica 13 software, and the interpretation of the results was conducted in accordance with agronomic and biostatistical criteria.

RESULTS AND DISCUSSION

Monitoring of phytophagous pest populations

Monitoring of phytophagous species revealed that their population peaked in the untreated block during the second half of the plant vegetation period. As the fruiting phase came to an end, the number of controlled pest species gradually declined, which was attributed to the loss of trophic attractiveness of the plants due to the physiological aging of the leaves. From the moment cucumber plants were transplanted to their permanent growing site, individual adult specimens of the two-spotted spider mite (*Tetranychus urticae*) were observed; however, their abundance remained below the economic threshold until the onset of the intensive fruiting phase. During the subsequent stages of vegetation, the number of both adults and larvae of the spider mite increased in the absence of control measures, reaching a maximum during the peak fruiting phase (03 November 2023), exceeding the economic injury level sixfold, with an average of 31.5 individuals per leaf (Figure 1A).

With the completion of the intensive fruiting phase, a gradual decline in the population of *Tetranychus urticae* Koch was observed. However, as of 03 December 2023, its population density remained above the economic injury threshold and amounted to 12.6 individuals/m².

The analysis of *Trialeurodes vaporariorum* Westwood population dynamics indicated a high level of cucumber plant infestation throughout the vegetation period. Whitefly adults appeared on the plants two weeks later than the two-spotted spider mite, which was likely due to species-specific phenological traits and adaptive responses to microclimatic conditions. The gradual increase in whitefly numbers led to the population reaching the threshold level on 14 October 2023, coinciding with the end of the first third of the mass fruiting phase. The whitefly population reached its maximum at the end of this phase, with 60.7 individuals per leaf (Figure 1B).

Adults of the green peach aphid (*Myzodes persicae* Sulz.) were recorded on yellow sticky traps immediately after cucumber transplanting. The pest population increased rapidly, and by the beginning of the peak fruiting phase, the infestation level exceeded the economic threshold for the first half of the vegetation period, with 26.3% of the examined plants infested. The highest infestation rates were recorded in the middle of the mass fruiting phase, when the proportion of infested plants reached 35.6–36.4%. In the following stages of vegetation, the number of both adults and larvae decreased, and by the end of the fruiting period, the percentage of infested plants dropped to 22.5% (Figure 1C).

Adults of the onion thrips (*Thrips tabaci* Lindeman) were detected on cucumber plants in the greenhouse throughout the study period. The first individuals were found on both the plants and yellow sticky traps 10 days after transplanting. During the early stages of vegetation, the population density of T. tabaci remained low and did not exceed the economic injury threshold (11 individuals per leaf) until the beginning of the peak fruiting phase. Subsequently, a sharp increase in population density was recorded, and by mid-mass fruiting, the number of individuals exceeded the

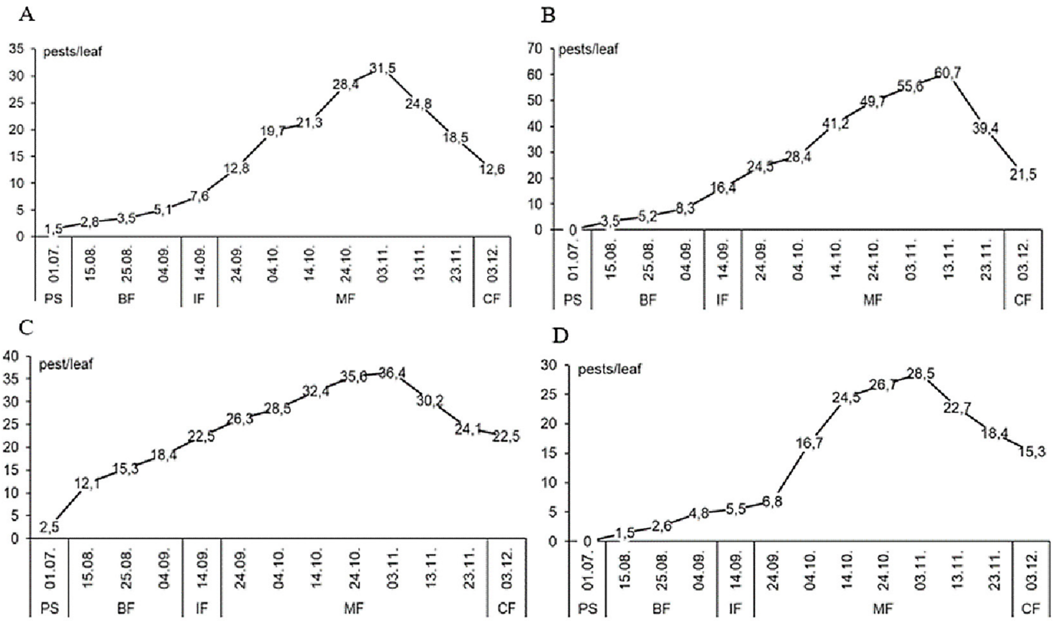

Figure 1. Population dynamics of (A) *Tetranychus urticae*, (B) *Trialeurodes vaporariorum*, (C) *Myzodes persicae*, and (D) *Thrips tabaci* on cucumber plants under greenhouse conditions (PS – planting of seedlings, BF – beginning of fruiting, IF – increasing fruiting, MF – mass fruiting, CF – cessation of fruiting)

threshold more than twofold, reaching 28.5 individuals per leaf (Figure 1D).

Efficacy of bioinsecticides and entomophages

Based on the evaluation of the efficacy of biological insecto-acaricides and a complex of entomophagous natural enemies against Tetranychus urticae under greenhouse conditions, it was established that the biological insecto-acaricides effectively suppressed the increase in the numbers of T. urticae adults and larvae both at the onset of flowering and at the beginning of the fruiting stage. The application of Boverin BT and Bitoxibacillin BT reduced spider mite density on cucumber plants by 4.8–5.4 times at early flowering and by 3.5–4.3 times at early fruiting. The efficacy of the biological insecto-acaricides at the first assessment was 79.3–81.6%, and at the second assessment 72.2–76.8%. The complex of entomophagous agents, selected considering the broad spectrum of phytophagous pests present in the greenhouse, demonstrated somewhat lower efficacy compared with the biological insecto-acaricides; depending on the time of application, efficacy ranged from 61.5% to 69.7% (Table 1).

Analysis of the efficacy of different biological control strategies against *Trialeurodes vaporariorum* indicated relatively low performance of the bioformulations Boverin BT and Actofit BT when applied at the beginning of the flowering phase, with effectiveness ranging from 68.0% to 72.0%. The insecto-acaricide Bitoxibacillin BT demonstrated higher efficacy during this period, reaching 75.2%. The application of a complex of entomophagous agents during early flowering was also less effective – 55.2%, likely due to the initially low population density of the pest at this stage. According to post-treatment assessments following the second application of biological control agents, the efficacy of all tested options increased. In particular, the application of biological insecto-acaricides resulted in efficacy ranging from 70.7% to 76.2%, while the use of the entomophage complex achieved a 66.8% reduction in whitefly numbers (Table 2).

Based on the assessment of the effectiveness of biological control agents against the green peach aphid (*Myzodes persicae*) on cucumber, it was established that the efficacy of the entomophage complex was comparable to that of biological insecto-acaricides and amounted to 62.8%. In the treatments with biological insecto-acaricides, the efficacy at the first application ranged from 66.9% to 76.0%. During the early fruiting phase, the efficacy increased across all treatments, likely due to the cumulative effect of both the biological insecto-acaricides and the entomophage complex. Specifically, the application of Bitoxibacillin BT, Actofit BT, and Boverin BT resulted in efficacies of 77.2%, 79.5%, and 81.0%, respectively. The use of entomophages during early fruiting also contributed to a substantial reduction in aphid populations – cucumber plant infestation levels in this treatment were 62.8% lower compared to the control, with an overall efficacy of 72.6% (Table 3).

Among the tested biological control agents, the highest efficacy in controlling the population of tobacco thrips (*Thrips tabaci*) was observed with the use of the bioinsecticide Boverin BT, which achieved an effectiveness of 81.9%, exceeding the performance of other treatments by 11.4–41.7%. At the second time point of application, the efficacy of all biological control agents ranged from 66.5% to 79.0% (Table 4).

The highest level of efficacy was observed in the treatment with Boverin BT, where the infestation of cucumber plants by *T. tabaci* adults and larvae was 4.8 times lower compared to the

Table 1. Efficacy of biological insecto-acaricides and entomophagous insects against *T. urticae* on greenhouse-grown cucumber plants

Treatment variant	Onset of flowering		Onset of fruiting	
	Infested plants, %	Efficacy, %	Infested plants, %	Efficacy, %
Control (untreated)	16.9	-	36.7	-
Actofit BT + Liposam	4.1	75.7	9.5	74.1
Bitoxibacillin BT + Liposam	3.1	81.6	8.5	76.8
Boverin BT + Liposam	3.5	79.3	10.2	72.2
Entomophagous complex*	6.5	61.5	11.1	69.7

Note: **Macrolophus pygmaeus* Rambur, *Chrysoperla carnea* Stephens, *Aphidoletes aphidimyza* Rondani.

Table 2. Efficacy of biological insecto-acaricides and entomophagous insects against *Tr. vaporariorum* on greenhouse-grown cucumber plants

Treatment variant	Onset of flowering		Onset of fruiting	
	Infested plants, %	Efficacy, %	Infested plants, %	Efficacy, %
Control (untreated)	12.5	-	25.6	-
Actofit BT + Liposam	3.5	72.0	6.4	75.0
Bitoxibacillin BT + Liposam	3.1	75.2	6.1	76.2
Boverin BT + Liposam	4.0	68.0	7.5	70.7
Entomophagous complex*	5.6	55.2	8.5	66.8

Note: **Macrolophus pygmaeus* Rambur, *Chrysoperla carnea* Stephens, *Aphidoletes aphidimyza* Rondani.

Table 3. Efficacy of biological insecto-acaricides and entomophagous insects against *M. persicae* on greenhouse-grown cucumber plants.

Treatment variant	Onset of flowering		Onset of fruiting	
	Infested plants, %	Efficacy, %	Infested plants, %	Efficacy, %
Control (untreated)	12.1	-	26.3	-
Actofit BT + Liposam	4.0	66.9	5.4	79.5
Bitoxibacillin BT + Liposam	3.5	71.1	6.0	77.2
Boverin BT + Liposam	2.9	76.0	5.0	81.0
Entomophagous complex*	4.5	62.8	7.2	72.6

Note: **Macrolophus pygmaeus* Rambur, *Chrysoperla carnea* Stephens, *Aphidoletes aphidimyza* Rondani.

Table 4. Efficacy of biological insecto-acaricides and entomophagous insects against *T. tabaci* on greenhouse-grown cucumber plants

Treatment variant	Onset of flowering		Onset of fruiting	
	Infested plants, %	Efficacy, %	Infested plants, %	Efficacy, %
Control (untreated)	8.3	-	16.7	-
Actofit BT + Liposam	2.5	69.7	4.8	71.3
Bitoxibacillin BT + Liposam	2.2	73.5	4.0	76.1
Boverin BT + Liposam	1.5	81.9	3.5	79.0
Entomophagous complex*	3.5	57.8	5.6	66.5

Note: **Macrolophus pygmaeus* Rambur, *Chrysoperla carnea* Stephens, *Aphidoletes aphidimyza* Rondani.

untreated control, indicating stable activity of the product throughout the vegetation period.

Crop yield and plant biometric parameters

According to the results of a comparative analysis of the effects of biological insecto-acaricides and the entomophagous complex on plant biomass, the application of Boverin BT + Liposam resulted in the highest biomass increase, significantly surpassing all other treatments. The application of Bitoxibacillin BT + Liposam and the use of the entomophagous complex also contributed to a more substantial development of cucumber aboveground biomass, significantly exceeding the corresponding values in both the untreated control and the Actofit BT + Liposam treatment. The Actofit BT + Liposam variant demonstrated a moderate effect on biomass increase, with significantly higher values compared to the control. The untreated variant showed the lowest aboveground biomass accumulation, confirming the positive impact of biological plant protection products (Table 5).

The analysis of the effects of biological insecto-acaricides and the entomophagous complex revealed a statistically significant influence on the length of the main stem in cucumber plants. The treatment with Boverin BT + Liposam resulted in the greatest stem length – 281 cm – which was significantly higher than all other treatments, according to statistical analysis. The stem lengths in

Table 5. Biometric parameters of the cucumber hybrid Kibria during the mass fruiting stage depending on biological insecto-acaricides and entomophagous

Treatment variant	Plant mass (g)	Main stem length (cm)	Lateral shoots (pcs)	Leaf area (dm²/plant)
Control (untreated)	812.0 ± 5.03d*	212±4.32d	18±2.58d	1321±20.28d
Actofit BT + Liposam	908.0 ± 6.45c	245±7.53c	24±2.87c	1395±20.16c
Bitoxibacillin BT + Liposam	924.0 ± 5.16b	252±6.84b	29±2.78a	1564±21.21b
Boverin BT + Liposam	968.0 ± 11.08a	281±7.94a	30±2.58a	1721±21.68a
Entomophagous complex	918.0 ± 6.83b	258±7.41b	27±3.51b	1643±18.17b

Note: *The means followed by the same letter do not differ significantly at the 5% threshold (Duncan test, $\alpha = 0.05$). NB: the data are the average of 4 repetitions per treatment ± standard deviation.

the treatments with Bitoxibacillin BT + Liposam and the entomophagous complex were 252 cm and 258 cm, respectively; these values did not differ significantly from each other but were statistically greater than those in the untreated control, indicating a positive effect on plant growth. The Actofit BT + Liposam treatment resulted in a stem length of 245 cm, which was significantly lower than the other biocontrol treatments but still considerably higher than the control (Table 5).

The results of the statistical analysis of cucumber protection treatments against a complex of phytophagous pests indicate a significant influence of different application schemes of biopreparations and entomophagous agents on leaf area development. According to Duncan's Multiple Range Test ($\alpha = 0.05$), statistically significant differences were found between the mean values of leaf area. The treatment with Boverin BT + Liposam resulted in the largest leaf area – 1721 dm² per plant. Treatments 3 and 5 (Bitoxibacillin BT + Liposam and the entomophagous complex, respectively) showed statistically lower values compared to treatment 4 – 1564 and 1643 dm² per plant, respectively – and were grouped together based on their similar level of impact. The Actofit BT + Liposam treatment showed the lowest efficacy, with a leaf area of 1395 dm² per plant (Table 5).

The study also demonstrated that the application of biological control agents had a significant effect on cucumber yield, which is consistent with previous research on productivity enhancement through biocontrol-based strategies. The treatment with Boverin BT + Liposam resulted in the highest yield (18.9 kg/m²), statistically exceeding all other plant protection treatments ($LSD_{05} = 0.71$ kg, $p < 0.05$). This confirms the high potential of *Beauveria bassiana*-based products not only for effective pest suppression but also as plant growth promoters that enhance nutrient uptake and physiological efficiency (Rajab et al., 2020; Macuphe et al., 2021; Rajab et al., 2023) (Figure 2).

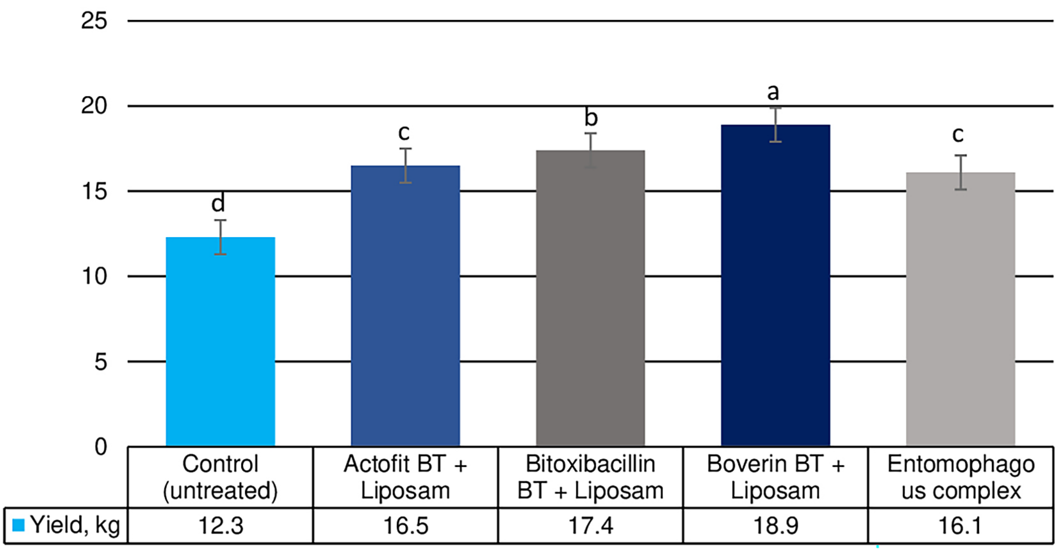

Figure 2. Yield of Kibria cucumber hybrid (kg/m²) under different variants of the biological pest control system. *Letters above columns indicate statistical groups (Duncan's test, $\alpha = 0.05$). $LSD_{05} = 0.71$ kg

The application of the bioinsecticide Bitoxibacillin BT + Liposam also resulted in high yield levels (17.4 kg/m²), consistent with previous studies confirming the efficacy of *Bacillus thuringiensis*-based products in vegetable crop protection (Bezousov et al., 2021; Zhang et al., 2019). Although the yield was statistically lower than that achieved with Boverin BT, it significantly exceeded the results obtained with Actofit, the entomophagous complex, and the untreated control. Treatments with Actofit BT + Liposam (16.5 kg/m²) and the entomophagous complex (16.1 kg/m²) did not differ significantly from each other, yet both resulted in significantly higher yields compared to the control. This indicates that even macrobiological regulation of pest populations, without a direct biostimulant effect, can have a significant positive influence on crop productivity – a similar effect has been observed in integrated plant protection systems (Yusupova and Gapparov, 2020).

The yield in the untreated control variant was 12.3 kg/m², highlighting the pronounced negative impact of uncontrolled phytophagous pest activity on cucumber productivity. These findings underscore the importance of implementing targeted biocontrol strategies under intensive cultivation conditions.

CONCLUSIONS

The results of the study confirm the high efficacy of biological insecto-acaricides and entomophagous complexes in controlling sucking phytophagous pests of cucumber under greenhouse conditions. The application of bioinsecticides Boverin BT and Bitoxibacillin BT in combination with the adjuvant Liposam led to a significant reduction in the populations of *Tetranychus urticae*, *Trialeurodes vaporariorum*, *Myzodes persicae*, and *Thrips tabaci* at different stages of crop development. It was found that biological insecto-acaricides exhibited equal or superior efficacy compared to the entomophagous complex, particularly in managing spider mites and greenhouse whiteflies.

In addition to their direct impact on pest suppression, the biological agents contributed to plant growth stimulation – significant increases in stem length, leaf area, and above-ground biomass were recorded in the treatments with Boverin BT + Liposam and Bitoxibacillin BT + Liposam. The highest yield (18.9 kg/m²) was achieved with the application of the *Beauveria bassiana*-based bioinsecticide (Boverin BT + Liposam), which was statistically superior to other plant protection options. This highlights the synergistic action of biopreparations as both biocontrol agents and potential plant growth bioregulators.

The entomophagous complex also demonstrated a considerable, though slightly lower, positive effect on biometric and yield parameters compared to the bioinsecticides. The findings support the feasibility of an integrated approach to vegetable crop protection, combining biological insecto-acaricides with beneficial organisms to ensure stable productivity under greenhouse cultivation. Future research should focus on optimizing application schemes for biological agents based on crop growth stages, pest infestation levels, and microclimatic conditions.

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