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Field Application of SeMNPV (*Spodoptera exigua* Multiple Nucleopolyhedrovirus) for Controlling *Spodoptera exigua* on Shallot and Scallion in the Mekong Delta, Vietnam

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ABSTRACT

Shallot and scallion are among the essential horticultural crops in the Mekong Delta of Vietnam, and their yields and quality are affected by the beet armyworm, *Spodoptera exigua*. To control this pest, farmers have used a large number of insecticides, which has led to resistance due to continuous use and environmental harm, thereby increasing interest in biological methods, including the *Spodoptera exigua* multiple nucleopolyhedrovirus (SeMNPV). The study aims to assess the efficacy of the liquid and powder formulation of SeMNPV against *Spodoptera exigua* under the actual agricultural conditions of Soc Trang (Shallot) and Vinh Long provinces (Scallion). The experimental arrangement used four treatments: SeMNPV liquid, SeMNPV powder, Radiant 60SC (a chemical insecticide), and the control. Some of the factors evaluated were larval density, level of leaf damage, yield, and natural enemies attack. The SeMNPV powder had the least damage, only 0.97 per cent (damage of plant), and a yield of 28.59 t/ha, and was almost equally good as the Radiant 60SC, which produced a damage of 2.53 per cent (damage of plant) and a yield of 29.41 t/ha. SeMNPV treatments significantly reduced larval numbers (down to fewer than 10 larvae/m^2 by day 40) and enhanced natural enemies, parasitoids, and microsporidia. The untreated one had the highest damage (8.03%), while the yield was lowest

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at 19.61 t/ha. Therefore, SeMNPV in powder form has the potential to control *S. exigua* infestations and to encourage biological control, making it a favourable, environmentally friendly addition to synthetic insecticides in the cultivation of shallot and scallion.

Keywords: Beet Armyworm; *Spodoptera exigua*; Multiple Nucleopolyhedrovirus; Shallot; Scallion

1. Introduction

In tropical crop regions, increased productivity has led to more intense pest outbreaks, driving the excessive use of chemical insecticides. Shallots (*Allium ascalonicum*) and scallions (*Allium fistulosum*) are widely grown vegetables in Vietnam, where the Mekong Delta is one of the country's most critical vegetable-producing regions and one of the world's most populous and productive regions [1]. Soc Trang and Vinh Long are the leading provinces [2] where shallot and scallion are grown on almost 14,000 hectares, producing over 200,000 tons per year [3]. Onions, especially shallots, are significant crops to smallholder farmers and essential for domestic and export markets [4]. However, there is a significant threat to shallot production in the Delta due to the beet armyworm, *Spodoptera exigua* (Hübner), a highly destructive lepidopteran pest in the crop [5]. This pest has a highly voracious feeding habit, feeding on the leaves of the shallot plant, thus reducing the plant's photosynthesis capability and yielding up to 40% in severe cases [6]. Since the Mekong Delta has a warm and humid climate and crop production is done throughout the year, it favours *S. exigua* breeding [7]. This problem has been further increased by the development of resistance in *S. exigua* to chemical insecticides, particularly pyrethroids and organophosphates, which has increased 100-fold in South Vietnam [8]. Furthermore, challenges regarding the contamination of crops with pesticides pose potential threats to human health through food products and health risks to labourers [8,9]. Hence, there is an imminent need for alternative methods of sustainable plant protection.

The constant application of chemicals to control pests, such as *S. exigua*, has led to the emergence of resistance and environmental degradation [10]. In the Mekong Delta of Vietnam, excessive use of chemical pesticides has led to soil and water pollution in the region [11]. The continued use of the chemical also impacts non-target species, valuable insects such as pollinators and natural enemies, and causes health hazards to farmers [12]. Frequent rainfall and insecticide applications have contributed to the development of resistance in *S. exigua* larvae to chemicals such as pyrethroids, organophosphates, and carbamates [13].

The ecological and biotechnological responses to control pests based on baculovirus-based biopesticides. A host-specific entomopathogen, *S. exigua* multiple nucleopolyhedroviruses (SeMNPV), has been perceived to have great potential as a microbial biological control agent with little to no harmful effects [9]. It can be easily integrated effectively into integrated pest management (IPM). It is a tropical Spodoptera virus that is safe for beneficial insects, humans, and other animals because it targets and kills only *S. exigua* larvae [14]. SeMNPV is very selective; it does not cause any form of resistance, remains effective in the environment, and offers the benefits of residual control [15]. SeMNPV has been shown to significantly reduce pest populations in field conditions [6,9]. Therefore, it is possible and practical to biocontrol *S. exigua* in the shallot production system in the Mekong Delta. However, there is a lack of data on the impact, effectiveness and residual activity of SeMNPV under the various meteorological conditions of the Mekong Delta [16]. There is a lack of knowledge regarding the relationships between SeMNPV and relevant agroecological practices, such as the use of pesticides and intercropping. There is a lack of related studies that have assessed the relative economic cost-benefit and effectiveness of SeMNPV compared to conventional insecticides for shallot production [17]. It is essential to note that currently, no information is available on the effect of SeMNPV on non-target species and the general biodiversity of the shallot-growing system [18]. Filling these gaps would enhance the practical adoption and application of IPM in the Vietnamese and other similar tropical agricultural environments.

It is hypothesised that the application of SeMNPV significantly decreases or suppresses *S. exigua* infestations in shallot fields. Furthermore, it is expected that the use of SeMNPV will reduce leaf damage and increase shallot yield compared with chemical insecticides under Mekong Delta field conditions. This study aims to assess the effect of applying SeMNPV as a biological control agent against

S. exigua under field conditions in shallot farming in the Mekong Delta, Vietnam. The objectives focused on assessing the ability of SeMNPV to suppress pest populations. Furthermore, the objective focused on analysing the effectiveness of liquid and wet powder formulations of SeMNPV over chemical insecticides in terms of pest mortality, leaf damage, and shallot yield. This research is essential for incorporating viral biopesticides into contemporary IPM (integrated pest management) solutions that provide an understanding of biological control agents in applied plant science.

2. Materials and Methods

2.1. Study Area

The field trials were conducted in the two largest provinces of shallots and scallion cultivation in the Mekong Delta region of Vietnam: the shallot field in Soc Trang and the scallion field in Vinh Long. The study was conducted in the primary growing season of 2023. The choice of these areas was influenced by the high pressure of the *S. exigua* pest and the intensive history of pesticide use, which developed an excellent environment to test the effectiveness of a biotechnology solution in the field. The experiments were conducted in standard management systems in privately owned farms to produce an actual agro-ecological scenario. Temperatures were relatively high (25–33 ℃), and the relative humidity (>80%) and rainfall during the cropping seasons were periodic, which favoured the proliferation of pests as well as the persistence of viruses. These crops, given their susceptibility to beet armyworm attack, are suitable for evaluating the efficacy of the SeMNPV treatments.

2.2. Nucleopolyhedrovirus Isolation and Propagation

SeMNPV was isolated from a diseased larva of a beet armyworm collected from a vegetable field of shallots. Occlusion bodies (OBs) were produced in the fourth instars of *S. exigua* on artificial diet. Larvae infected with the viruses were homogenized in 0.1% (wt/v) sodium dodecyl sulfate (SDS) solution and subjected at 500 rpm for 5 min to remove whole debris. Afterwards, the supernatant was centrifuged at 3000 rpm for 10 min to pellet the viral OBs. The resulting pellet was then washed with distilled water, appropriately diluted, and aliquots were counted with the help of Thoma's hemocytometer and observed with the help of a phase-contrast microscope [19]. The purified OBs were placed on ice for short-term use or stored at −20 ℃ for long-term storage.

2.3. Experimental Design

The studied crops were shallot (*Allium ascalonicum*) and scallion (*Allium fistulosum*) due to their economic significance and vulnerability to *S. exigua*. An RCBD (randomised complete block design) with four treatments, four replicates, and 32 plots was applied, including four replicates at each location. The plots were 20 m^2 in size, with a 1-m distance between each plot to minimise cross-contamination chances. The research included the following four options: (1) SeMNPV in liquid suspension formulation, (2) SeMNPV in wettable powder formulation, (3) chemical insecticide (chlorfenapyr/Ohayo100SC for shallot field in Soc Trang and Spinetoram/Radiant 60SC for scallion field in Vinh Long) as adopted, and (4) an untreated control which was water alone. They all were kept in standard agronomic practice. However, they were all irrigated, fertilised, and weed-managed to the same extent.

2.4. Application and Treatment Groups

The viral preparations of SeMNPV were obtained from a certified biological control centre and checked to demonstrate purity and occlusion body (OB) concentration by phase-contrast microscopy. They were then counted using a hemocytometer. Four treatments were applied to test the efficiency of SeMNPV on *S. exigua* larvae. The liquid and powder were formulated at a standard concentration of 2.2×10^{12} OB/ha. SeMNPV was dissolved in water up to a final concentration of 320 L per hectare and sprayed with calibrated backpack sprayers using cone nozzles to achieve thorough foliar coverage. The third group received the chemical insecticide chlorfenapyr/Radiant 60SC. The fourth group had no treatment and served as the standard control group. Early symptoms of *S. exigua* infestation were detected (approximately 15 days after planting). Afterwards, applications of SeMNPV were initiated, followed by repeated spray application at 7-day intervals with a maximum of three spray events during a single cropping cycle. SeMNPV spray was applied in the early morning hours to reduce degradation by UV and maximise viral attachment to foliage.

2.5. Data Collection and Measurement Parameters

The density of the larvae was determined by counting the number of *S. exigua* found in a randomly chosen 1 m^2 area in each plot, and the plots were monitored every week. The evaluation of the damage to the leaves was conducted 30 and 50 days after transplanting using a standardised visual rating scale (0 to 9) based on the extent of defoliation, which was further extrapolated to estimate percent damage.

Bulbs deemed not marketable were not used in the yield calculation at harvest time. A bulb was considered marketable when the following information was present: (1) The bulb was at least 2 cm in diameter, (2) the bulb had no visible pest-induced damage, (3) the bulb had no indication of mechanical damage, including bruises, splits, and rot, and (4) the bulb had appropriate firmness, shape, and skin qualities; these are commercial grades. The bulbs that did not meet the said criteria were not included in the yield. Marketable yield was also quantified as total fresh weight (before curing) per 5 m^2 of harvested area per plot and extrapolated to tonnes per hectare (t/ha).

The third larval stage was sampled in each treatment plot on three separate occasions (after each spray) and placed under laboratory conditions to assess the broader biological control effect. *S. exigua* control assessment is necessary to understand larval mortality through other parasitic factors like nucleopolyhedrovirus (NPV), entomopathogenic fungi, or parasitic wasps infesting larvae [20]. Larval mortality caused by natural enemies was noted and ranked into different categories based on morphological appearance and microscopy. For instance, Nucleopolyhedrovirus (NPV), microsporidia, parasitoid emergence, fungal infection, or unknown, depending on the signs or microscopies.

2.6. Statistical Analysis

The results were analyzed using Analysis of Variance (ANOVA) to determine the significance of the four treatments on all recorded factors, including pest density, leaf loss, grain yield, and *S. exigua* mortality. In this study, a one-way ANOVA was performed to determine whether the means of each treatment were significantly different from one another at the 95% confidence level ($p < 0.05$) [21]. Such statistical analysis helped compare the reforestation rate of SeMNPV with that of chemical and untreated controls under actual field conditions.

3. Results

3.1. Effect of SeMNPV on *S. exigua* Population on Sallot Experiment at Soc Trang Province

The results from the field trial experiment in Vinh Chau District, Soc Trang province, further demonstrate differences in pest control effectiveness and shallot productivity between the treatments. This untreated control recorded the highest plant damage (8.57%) and the lowest yield (10.643 t/ha), indicating significant yield loss from *S. exigua*. The SeMNPV powder formulation performed best, with damage of 0.43% and a yield of 19.433 t/ha. The SeMNPV liquid treatment also successfully minimised damage to 1.47% and achieved a yield of 17.740 t/ha. Therefore, the damage control with the chemical insecticide Ohayo 100SC was 2.21%, with a yield of 19.212 t/ha. The results analysis revealed that all the treatments caused significant reductions in the damage compared to the control treatment. SeMNPV powder provided a yield equivalent to chemical control, though with the added advantage of low damage numbers, supporting the theory of the suitability of biopesticide (see **Table 1**).

Table 1. Damage estimates and yield of shallots at Vinh Chau District, Soc Trang province.

Treatment	Volume (mL/gr per hectare)	Damage to Plants (%)	Yield (t/ha)
SeMNPV liquid	1000	1.47 ± 0.09^a	17.74 ± 0.52^b
SeMNPV powder	1000	0.43 ± 0.04^a	19.43 ± 0.61^a
Ohayo 100SC	500	2.21 ± 0.12^a	19.21 ± 0.57^a
Untreated control	water	8.57 ± 0.33^b	10.64 ± 0.48^c

Note: The mean percentage damage and means ± standard error are described in each value. The marketable yield is given as fresh, unshelled before the curing process. The superscript letters represent the statistically significant variations between treatments (Tukey HSD < 0.05).

3.2. Yield Improvement

The data shown in **Figure 1** reveal how various treatments affect the survivors of beet armyworm (*S. exigua*) larval density in shallot crops over the period highlighted. The untreated control always had the highest mean larval density, reaching 75 larvae/m^2 at 45 days post-treatment. On the other hand, the SeMNPV powder treatment maintained the lowest larval density from day 20 to 54, ranging between 0 and 10 larvae/m^2. The reciprocal in the liquid treatment of SeMNPV was moderate, decreasing larval density by 15–30 larvae/m^2. Ohayo 100SC chemical had a similar, comparably potent impact on larval density, curbing it to 15–20 larvae/m^2 from day 30 onwards. These results show that both formulations of SeMNPV impacted larval growth, with SeMNPV powder showing the most significant effect, and that the effect was greater than that of the control. This confirms the possibility of being an effective, natural pest control in shallot production that can replace synthetic chemical pesticides (**Figure 1**).

3.3. Mortality of *S. exigua*

The results in **Table 2** show a reduced incidence of *S. exigua* larvae infected by natural enemies, including NPV, microsporidia, fungi, and parasitoids, after the treatments. It is evident that all the SeMNPV-based treatments were effective in inducing direct viral infection; in addition, there was an increase in the activity of other natural enemies of third instar larvae compared with the chemical insecticide treatment and the check.

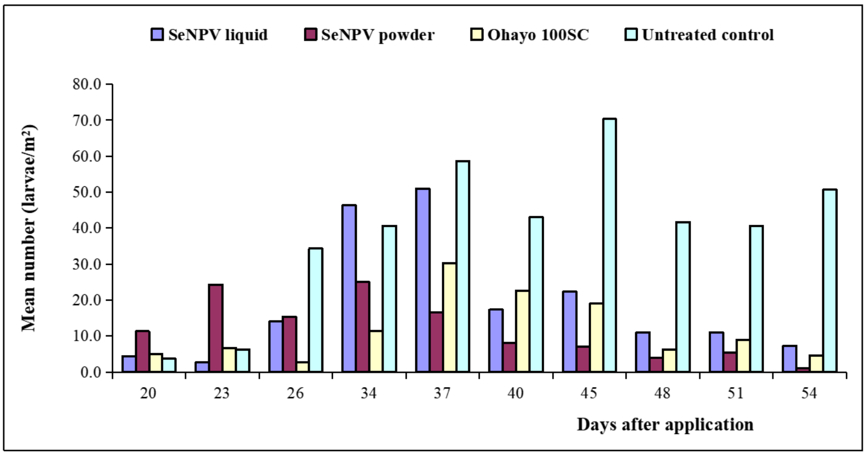

Figure 1. Beet armyworm larval density on shallot in Soc Trang province.

Table 2. Percent of *S. exigua* larvae infected with natural enemies in the shallot field at Soc Trang province.

Treatment	Spray Time	n	Per cent Larvae with Natural Enemies					
			NPV	*Microsporidium* sp.	Fungi	Parasitoids	Unknown*	Healthy
SeMNPV liquid	1	25	20.0	12.0	0.0	32.0	4.3	31.7
	2	16	12.5	25.0	6.3	37.5	0.0	18.8
	3	17	17.6	0.0	0.0	17.6	5.9	58.8
SeMNPV powder	1	19	21.1	15.8	0.0	15.8	10.5	36.8
	2	23	8.7	17.4	4.3	26.1	17.4	26.1
	3	28	10.7	0.0	0.0	10.7	3.6	75.0
Ohayo 100SC	1	0.0	6.7	0.0	0.0	0.0	13.3	80.0
	2	8.3	0.0	0.0	8.3	8.3	33.3	50.0
	3	0.0	9.1	0.0	0.0	0.0	9.1	81.8
Untreated control	1	28	7.1	10.7	0.0	10.7	7.1	64.3
	2	30	6.7	3.3	0.0	10.0	13.3	66.7
	3	27	7.4	3.7	0.0	11.1	3.7	74.1

Note: NPV: Nucleopolyhedrovirus; *: Unknown: cause of health could not be determined; Healthy: Larvae developed to adults.

The result of an assessment of the biological effectiveness of the first spray of the SeMNPV liquid formulation was a 20% infection rate by NPV, 12% by Microsporidium, and 32% by parasitoid, while only 31.7% of the larvae remained healthy. The second spray reduced the healthy larvae to 18.8%; of the remaining, 12.5% were infected with NPV, and 25.0% were affected by Microsporidium. In comparison, the parasitoids affected 37.5% of the total healthy larval population. The healthy population on the third spray reached 58.8%, likely due to reduced larval populations, NPV environmental infection, and variability in parasitoid abundance; nevertheless, 17.6% were infected with NPV and 17.6% with parasitoids.

Regarding the SeMNPV powder treatment, the first spray showed 21.1% SeMNPV infection, 15.8% microsporidia, 15.8% parasitoid infection, and 36.8% healthy individuals. The second spray led to a decline of about 8.7% SeMNPV infection, while the parasitoid rate only reduced to 26.1%. Finally, by the third spray treatment, the health of individuals was 75.0%, while SeMNPV and parasitoid infection were 10.7%, each demonstrating the significance of early application in biological control. The low results recorded by all the Ohayo 100SC chemical insecticides across the different sprays indicate low natural enemy activity. For instance, at spray time 3, 81.8% of the larvae were healthy, and no signs of SeMNPV or parasitoids were observed. This demonstrates that chemical insecticides reduce the action of natural enemies and may hamper long-term pest control.

The untreated check showed moderate activity of the natural enemy. During the three spray periods, more than half of the larvae were healthy, with rates of 64.3% to 74.1%; infection levels of SeMNPV and parasitoids were 6.7% and 11.1%, respectively. These findings imply that SeMNPV, particularly in the early stages of pest buildup, promotes the addition of natural enemies to pest management programs and is more environmentally friendly than chemical applications (see **Table 2**).

3.4. Effect of SeMNPV on *S. exigua* Population in Scallion Experiment at Vinh Long Province

Research conducted in Vinh Long province found that all treatment methods reduced plant damage and increased scallion yield compared with the control. The untreated control had the highest damage (8.03%) and the lowest yield (19.61 t/ha), demonstrating that *S. exigua* significantly affected the crop. Both liquid (1.37%) and powder (0.97%) significantly reduced damage levels and thereby increased yields to 27.78 and 28.59 t/ha, respectively. Radiant 60SC was also effective in minimizing damage, resulting in 2.53%, while the yield was 29.41 t/ha. Therefore, the SeMNPV treatments are as effective as chemical control in yield and more effective in reducing leaf damage, indicating the possibility of using these treatments for safe biological management of *S. exigua* in scallion crops (**Table 3**).

Table 3. Damage estimates and yield of scallion at Vinh Long province.

Treatment	Volume (mL/gr per hectare)	Damage to Plants (%)	Yield (t/ha)
SeMNPV liquid	1000	1.37 ± 0.10^{a}	27.78 ± 0.55^{a}
SeMNPV powder	1000	0.97 ± 0.08^{a}	28.59 ± 0.62^{a}
Radiant 60SC	500	2.53 ± 0.13^{b}	29.41 ± 0.70^{a}
Untreated control	water	8.03 ± 0.27^{c}	19.61 ± 0.60^{b}

Note: The mean percentage damage and means ± standard error are described in each value. The marketable yield is given as fresh, unshelled before the curing process. The superscript letters represent the statistically significant variations between treatments (Tukey HSD < 0.05).

The data indicate changes in the population of *S. exigua* larvae over time under the different treatments shown in **Figure 2**. The untreated control group maintained the highest larval density of any treatment throughout the study, surpassing 40 larvae/m^2 around day 38, indicating a highly infested site. On the other hand, SeMNPV powder, as well as Radiant 60SC, yielded low numbers of larvae recorded on the leaves, below 10 larvae/m^2, starting on the 40th day. SeMNPV liquid also reduced the number of larvae gradually and less intensely than the powder formulation of the product. Radiant 60SC followed the same pattern as the control at the first few points; it populated very little after application. Thus, both the SeMNPV formulations and Radiant 60SC significantly reduced larval density compared to the untreated control. At the same time, the SeMNPV powder maintained larval suppression for a longer period, which indicates its eco-friendly insecticide when compared to chemical control in scallion against the pest.

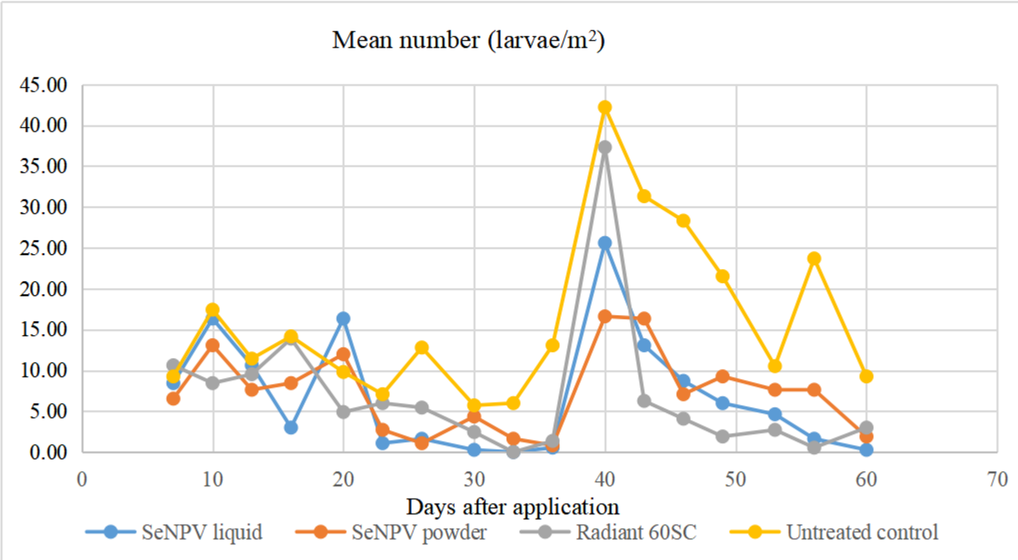

Figure 2. Beet armyworm larval density on scallion at Vinh Long province.

3.5. Mortality of *S. exigua* Collected from Each Plot on Scallion at Vinh Long Province

The data from **Table 4** illustrate the percentage of S. exigua larvae infected by various natural enemies across five spray times in different treatments. The SeMNPV powder treatment consistently resulted in higher rates of infection by natural enemies compared to the SeMNPV liquid, radiant 60SC, and untreated control. Specifically, the SeMNPV powder treatment achieved the highest combined infection rate on the second application, with 25% infected by SeMNPV, 21.88% by microsporidia, and 34.38% by parasitoids, leaving only 16.95% of larvae healthy. This indicates a strong synergistic effect between SeMNPV and naturally occurring entomopathogens. SeMNPV liquid also showed a similar trend but with slightly lower effectiveness. By the fifth application, the results showed 27.59% NPV infection and 5.41% fungal infection, reducing the healthy larval population to 55.95%.

In contrast, Radiant 60SC showed minimal influence on natural enemy activity, with a high percentage of healthy larvae ranging from 54.8% to 79.3% and little to no parasitoid or SeMNPV activity. The untreated control consistently showed high percentages of healthy larvae, especially from spray times 2 to 5 (ranging from 56.4% to 96.9%), indicating low natural enemy infection without intervention. These results suggest that SeMNPV treatments, particularly the powder formulation, not only control pest populations directly but also enhance the activity of natural biological control agents in the field.

Table 4. Percent of S. exigua larvae infected with natural enemies in the scallion at Vinh Long province.

Treatment	Spray time	n	Per cent Larvae with Natural Enemies					
			SeMNPV	*Microsporidia* sp.	Fungi	Parasitoid	Unknown*	Healthy
SeMNPV liquid	1	38	5.26	10.53	2.63	15.79	4.32	61.47
	2	41	19.51	17.07	0.00	26.83	1.8	34.79
	3	43	20.93	0.00	0.00	13.95	2	63.12
	4	31	10.00	8.33	1.67	2.80	0	77.20
	5	29	27.59	6.76	5.41	4.30	0	55.95

Table 4. *Cont.*

Treatment	Spray time	n	Per cent Larvae with Natural Enemies					
			SeMNPV	*Microsporidia* sp.	Fungi	Parasitoid	Unknown*	Healthy
SeMNPV powder	1	29	6.90	13.79	3.45	20.69	0.00	55.17
	2	32	25.00	21.88	0.00	34.38	1.8	16.95
	3	37	24.32	0.00	0.00	16.22	2	57.46
	4	35	20.00	14.29	2.86	14.29	3	45.71
	5	28	28.57	17.86	14.29	7.14	0	32.14
Radiant 60SC	1	31	6.5	12.9	0.0	0.0	25.8	54.8
	2	37	0.0	18.9	0.0	0.0	1.8	79.3
	3	29	0.0	0.0	0.0	20.7	2	77.3
	4	30	0.0	16.7	3.3	16.7	3	60.0
	5	15	6.7	0.0	0.0	13.3	33.3	46.7
Untreated control	1	30	6.7	10.3	0.0	0.0	26.7	56.4
	2	24	3.4	6.5	0.0	3.3	0	86.8
	3	29	0.0	1.3	0.0	20.7	0	78.0
	4	32	0.0	0.0	3.1	0.0	0	96.9
	5	33	3.0	7.2	3.6	0.0	0.0	86.2

Note: The data correspond to the laboratory evaluation of larvae extracted from field plots. Types of pathogens are NPV, microsporidia and fungi; emergence of the parasitoids was registered as well. Values were mean percentages/treatment/spray time; NPV: Nucleopolyhedrovirus; *: Unknown: cause of health could not determine; Healthy: Larvae developed to adults.

4. Discussion

The research findings revealed that baculovirus-based biocontrol- namely *Spodoptera exigua* multiple nucleopolyhedrovirus (SeMNPV) is an effective biotechnological agent to control the lepidopteran pests in horticultural production. The experimental data show that both formulations of SeMNPV, especially the powder form, significantly reduced larval density and leaf damage by controlling *S. exigua* populations. The results also revealed results similar to the usage of conventional chemical insecticides. These findings confirm the feasibility of SeMNPV in pest-intensive environments with high pest pressures and its contribution to promoting integrated pest management (IPM) systems.

Similarly, Yan et al. (2022) emphasised that SeMNPV in the formulation of powder was the most suitable method of delivering the virus to pests as it reduced the damage caused by the leaves and produced yields [22]. The results of the liquid formulation were also encouraging despite the fact that the formulation was marginally less effective as compared to the powder. Moldovan et al. (2022) noted the factors of high virulence and field stability of NPVs in controlling lepidopteran pests in tropical environments. Further, the decrease of larval density over time in SeMNPV-treated plots is a healthy testimony to how the bioinsecticide creates cycles of epizootics in the pest populations [23]. As described by Zhou et al. (2023), NPVs have the potential to cause epidemics in pest populations, leading to diseased populations and reduced density [9].

On the other hand, the untreated control had more larvae on plants and damage to the crop, which supports the causative agent for significant economic loss if not controlled. While Ohayo 60SC insecticide had potential for pest control, there was little variation in its yield potential compared to SeMNPV. This view is in agreement with Gelaye and Negash (2023), who stressed that baculoviruses like SeMNPV are environmentally and ecologically friendly as opposed to toxic chemical pesticides. SeMNPV, especially in powdered form, may serve as a potential biocontrol agent to minimise the use of synthetic pesticides in shallot farming and fit well into the principles of IPM [20]. The study by Dai and Zhang (2018) illustrated that SeMNPV, particularly in powder formulation, contributed to the increase of *S. exigua* through both direct viral infection and indirect assessment through natural enemies. The re-infection rates of the larvae by other natural pathogens, namely nucleopolyhedrovirus (NPV), microsporidia and parasitoids, when combined with SeMNPV, also increase, implying a synergistic relationship that improves the biocontrol impact. SeMNPV was applied successfully during the early stage, and its percentage of healthy larvae and infection rates of useful natural enemies were enhanced [24]. These findings support the observations of Mengual Martí (2024), who argued that viruses such as SeMNPV can improve the native antagonist's activity against the pest, thereby stabilising its destruction [25].

In addition, Poveda (2021) supported the idea that biological agents, such as viruses, enhance the effects of existing parasitoids and fungi when used to manage pests in the field [26]. In addition, the chemical insecticide treatment (Radiant 60SC) controlling *S. exigua* on yield was highly significant as compared to the biological method. Still, it also showed a very low level of natural enemies due to broad-spectrum insecticides that are lethal to other non-target organisms. Rovicky et al. (2024) reported that natural enemies were observed in the untreated control at a moderate level; they were insufficient to control the high larval survival rates; hence, there is a need to intervene actively [6]. Concisely, the study endorses SeMNPV, especially the powder formulation, as efficient, ecologically friendly, and compatible with an existing entomological system in nature. Baker et al.'s (2020) study provides a direct pest control method. Still, it is an important way to conserve and support biological pest control, a key concept in IPM [27].

Mawcha et al. (2024) demonstrated that infection rates of *S. exigua* larvae by natural enemies, including NPV, microsporidia, fungi, and parasitoids, are higher with SeMNPV in the powder formulation [28]. It is also evident from the data collected during spray time 2 that the higher rate of infection recorded could be a result of interaction between SeMNPV and other entomopathogenic fungi already existing in the environment. Hamid et al. (2024) emphasised that the baculoviruses may have positive external effects on natural enemies for biological control in field conditions [29]. The fact that there is evidence of natural enemies in SeMNPV plots even after successive spraying shows signs of the compatibility of ecological pest control. However, it is clearly evident from these percentages that Radiant 60SC had a low impact on the natural enemy population with a consistently high percentage of healthy larvae compatible. The natural enemy effect in the untreated control was also low, indicating that there is an urgent need to apply other approaches like SeMNPV to enhance biocontrol. Moore and Jukes (2019) also support the usage of SeMNPV as a microbial insecticide and as an additional naturally occurring pest control tool. This makes it a better candidate for integrated pest management (IPM), which seeks to bring down the use of chemicals and embrace eco-friendly methods of pest control [30].

This research has some limitations. The trials were carried out only for certain provinces within the Mekong Delta; the results obtained may not be generalisable to the rest of the shallot-growing areas. Further, future studies need to focus more on field trials under different climates to affirm the reliability of SeMNPV. Second, related to this issue, SeMNPV demonstrated excellent potential for biological control; however, the feasibility of producing SeMNPV in the form of its Bt bacteria and the feasibility of disseminating the formulation to such farmers were not evaluated. The pathogen, SeMNPV, will exist in the long term within the environment and interact with different agriculturally active entities, such as intercropping or organic farming. The study did not assess the possibility of damage to the non-target organisms at different time intervals after exposure to SeMNPV, such as pollinators and other beneficial insects. Implementing changes to overcome these restrictions will help to increase the practical utilisation and incorporation of SeMNPV in sustainable pest management.

Further, SeMNPV is a type of biological nanotechnology. It offers the advantage of the virus-infection process as a specific pest control approach. This research has been performed on the virus but not at the molecular level. Therefore, this provides a basis for subsequent research integrating the virus with transcriptomic or proteomic profiling to study host-pathogen interactions and the effectiveness of the virus or the acquired resistance.

Based on these findings, future studies should conduct long-term efficacy assessments of SeMNPV across different locations within the Mekong Delta and during other seasons. New experimental studies are required to establish the views of SeMNPV on agronomic practices, such as intercropping, the use of organic matter, and reduced pesticide application, as used in sustainable IPM [31]. Research should also be conducted on the cost-effectiveness and the B/C (benefit/cost) ratio of SeMNPV against conventional chemical insecticides in multiple cropping systems [32]. Furthermore, there is a need to test some aspects, such as the effects of SeMNPV on non-specific organisms, pollinators, and microbiota of the soil [33].

Transcriptomic or proteomic profiling of infected insects should demonstrate the dynamics of viral gene expression and host immune reaction that can deliver mechanistic information and can be useful in the development of evolved stronger viral varieties [34,35]. Meanwhile, microencapsulation-based or polymer-based delivery systems should be used to improve SeMNPV formulations to achieve improved environmental stability of the biopesticide, UV stability protection, and a longer field persistence that will enhance its potential toward scalable and viable biopesticides as commercialised products.

The research on shallot pests and their management demonstrated the development and improvement of formulation technologies to improve the shelf life of biopesticides [36]. In the field, persistence in increasing the rate of adoption and commercialisation of biopesticides and sustainable and environmentally friendly pest management is effective in safeguarding shallot and other crops.

5. Conclusion

This research work revealed that SeMNPV, specially formulated in powder form, is effective in managing *S. exigua* pests on shallots. Some of the observations made are a decrease in larval numbers and enhanced growth outcomes recorded compared to cohorts that were not exposed to the bacterial species. Furthermore, SeMNPV treatments favoured natural enemies such as parasitoids and microsporidia, all of which were low in chemical insecticide treatments. Therefore, these results further strengthen confidence in SeMNPV as an environmentally friendly biological pesticide solution to replace chemical pesticides. It stands as a good candidate for use in integrated pest management. The SeMNPV can be used in the IPM option, where farmers are encouraged to reduce the use of chemicals and the associated risks that come along with them. This research supports the value of SeMNPV as a plant protection method in biotechnology, complies with the objectives of sustainable farming, and reduces the use of pesticides. Although the research dedicated its attention to the agronomic and ecological results, it will lay a baseline for further molecular and formulation innovations, which may improve the accuracy, stability, and regulatory status of SeMNPV. Further development of SeMNPV that incorporates molecular diagnostics and more comprehensive environmental evaluation will be to gain all the potential benefits of this next-generation crop protection.

Author Contributions

The manuscript writing, study design, field experimentation, and data collection were done by X.T.T. and L.T.T.X. has also made a contribution to data analysis, interpretation of data, and critical revision of the article. S.P.K. guided the project and supported it during the research, as well as reviewed the manuscript and edited it. The final version of the manuscript was read and approved by all the authors.

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Institutional Review Board Statement

The research did not involve human subjects or vertebrate animals. Therefore, this research does not require ethical approval.

Informed Consent Statement

The local farmers' informed consent and cooperation were ensured in all field experiments. The research complied with institutional and national guidelines on the responsible conduct of agricultural research.

Data Availability Statement

All of the data that support the findings of this study are available in the main text or References.

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Conflicts of Interest

The authors declare no conflict of interest.

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