Jurnal Sumberdaya HAYATI June 2026
Vol. 12 No. 2, p 39-45

Available online at:
https://journal.ipb.ac.id/index.php/sumberdayahayati

Bioefficacy of *Steinernema* sp. as a Biocontrol Agent Against *Spodoptera frugiperda* Under Laboratory Conditions

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Received June 3, 2023/Received in revised form February 7, 2026/Accepted February 19, 2026

***Spodoptera frugiperda* control in agricultural crops, particularly corn crops, is a major challenge. The bioefficacy of the entomopathogenic nematode *Steinernema* sp. in suppressing *S. frugiperda* larvae was studied in this work. The *Steinernema* sp. isolate was obtained from the Biological Control Agent Service Post in Sidodai, while the *S. frugiperda* isolate was propagated at the University of Jember's Plant Pest Laboratory. In bioefficacy evaluations, different doses of *Steinernema* sp. were applied to third-instar *S. frugiperda* larvae, and mortality rates, lethal time 50% (LT50), and infection rates were monitored over 120 hours. The findings indicated the ability of *Steinernema* sp. to cause mortality in *S. frugiperda* larvae. Mortality increased with time, showing effective pest suppression. Significant differences among *Steinernema* sp. doses indicated a density-dependent impact. Greater nematode populations resulted in lower LT50 values, indicating quicker mortality induction. Infection rates decreased over time at all doses, although the highest concentration of 1,000 IJ mL^{-1} consistently had the highest infection rate. These data confirm the potential of *Steinernema* sp. as an environmentally friendly biological control agent for *S. frugiperda* in corn crops.**

Key words: corn, entomopathogen, *in vitro*, LT_{50}, mortality

INTRODUCTION

Spodoptera frugiperda J.E. Smith (Lepidoptera; Noctuidae) is an invasive species that may cause major harm to crops in Indonesia, especially corn crops (Sartiami *et al.* 2020). *S. frugiperda* is native to the American continent, as reported by Tay *et al.* (2023). Due to its ability to disperse up to 100 km per day at the adult stage and utilize up to 80 host plant species, *S. frugiperda* spreads rapidly and shows high ecological adaptability (Guo *et al.* 2018). *S. frugiperda* has been spreading in Indonesia since 2019 and has become a major pest in corn fields since 2020 (Hutasoit *et al.* 2020; Herlinda *et al.* 2022). The severity of their attacks may result in corn crop losses of more than 50% (Bhusal & Bhattarai 2019). *S. frugiperda* attacks caused 60% of the damage in Bogor Regency (Russianzi *et al.* 2021). Furthermore, if not handled, *S. frugiperda* damage may result in losses of up to 80% and crop failure (Sari 2020).

S. frugiperda initially damages young shoots, leaves, and immature ears of corn, with the highest infestation occurring during the vegetative stage due to the plant's tender tissues (Bhusal & Chapagain 2020). Furthermore, *S. frugiperda* consumes the immature corn ears during the generative period. Since the larvae are constantly hunting for food, the third instar stage of *S. frugiperda* larvae is the most destructive (Shylesha *et al.* 2018). Early infestations of *S. frugiperda* damage the central growth point of young corn plants, with peak incidence at around 40 days after sowing and an average plant loss of 18.7%, highlighting the need for early management (Overton *et al.* 2021).

Farmers commonly rely on synthetic pesticides such as chlorantraniliprole to control *S. frugiperda*, achieving up to 100% mortality within five days; however, excessive and prolonged use can cause environmental damage and promote insect resistance (Bolzan *et al.* 2019). Consequently, alternative control strategies using Biological Control Agents (BCAs) such as bacteria, fungi, and entomopathogenic nematodes have been explored, as they align with IPM principles, reduce reliance on chemical pesticides, and offer environmentally sustainable pest management without harmful residues (Paredes-Sánchez *et al.* 2021; Idrees *et al.* 2022).

Biological control employs natural enemies to suppress pest populations, among which entomopathogenic nematodes have attracted considerable attention due to their ability to infect target insects through natural openings such as the mouth, anus, spiracles, and cuticle (Hade *et al.* 2020). After entering the host, entomopathogenic nematodes release lethal symbiotic bacteria that destroy host

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tissues, leading to insect death, with genera such as *Heterorhabditis* sp. and *Steinernema* sp. shown to be effective against lepidopteran leaf-feeding pests (Caccia *et al.* 2014; Binda-Rossetti *et al.* 2016).

The University of Jember currently maintains Steinernema sp. isolates obtained from the Biological Control Agent Service Post in Sidodadi, Kediri Regency, Indonesia, which have been applied by local horticultural and food crop farmers; however, their efficacy against *S. frugiperda* has not been evaluated. Therefore, this study aimed to assess the bioefficacy of *Steinernema* sp. against *S. frugiperda*.

MATERIALS AND METHODS

Source of *Steinernema* sp. Isolate. The *Steinernema* sp. isolate used in this study was obtained from the Biological Control Agent Service Post in Sidodai, where it had been maintained in the Plant Protection Study Program at the University of Jember. In the laboratory, the isolate was cultured on Tenebrio molitor larvae to maintain and multiply its population. The entomopathogenic nematodes were extracted by dissecting the *T. molitor* larvae and soaking them in an aquades suspension for 3 hours. Afterward, the extracted nematodes were filtered through a 400 mesh sieve and collected in a container. The population of the nematodes was then counted before being utilized in subsequent testing.

Source of *Spodoptera frugiperda* Isolate. The *S. frugiperda* isolate was obtained through a rearing process conducted at the Plant Pest Laboratory, Faculty of Agriculture, University of Jember. *S. frugiperda* larvae were collected from various locations in Jember Regency, where corn fields were present. Subsequently, the larvae were reared in specialized boxes and provided with untreated corn leaves as their food source. During the adult stage (imago), *S. frugiperda* were given a 10% honey solution placed on cotton wool, which was suspended in the rearing container. Regular checks were performed every 2 days to ensure the honey solution remained moist, and additional honey solution was added when necessary. The adult *S. frugiperda* were housed in a maintenance box, where folded oil paper served as a surface for egg attachment. To create a conducive environment for egg laying and reduce stress, the rearing boxes for the adults were covered with a black cloth. The *S. frugiperda* rearing boxes were placed at room temperature (Xie *et al.* 2021).

Bioefficacy Assay. Infective juveniles (IJs) of *Steinernema* sp. were applied to third instar larvae of *S. frugiperda* using a droplet application method on the skin. The *S. frugiperda* larvae were treated with a 0.2 mL suspension of *Steinernema* sp. containing different concentrations of nematodes: 200 IJs mL^{-1}, 400 IJs mL^{-1}, 600 IJs mL^{-1}, 800 IJs mL^{-1}, and 1,000 IJs mL^{-1}. As a control, another group of *S. frugiperda* larvae were treated with a sterile water suspension without *Steinernema* sp. The test was repeated four times, with each repetition involving 10 *S. frugiperda* larvae. The *Steinernema* sp. was applied using a 9 cm diameter petri dish lined with gauze at the bottom. Following the treatment of *S. frugiperda* larvae, an incubation period of 3 hours was observed to allow nematode penetration into their bodies.

After the incubation period, when the gauze surface had slightly dried, the *S. frugiperda* larvae were moved to testing boxes. These testing boxes were equipped with fresh corn leaves as their food source. Daily cleaning of the testing boxes and replacement of food were performed throughout the observation period. Observations were conducted at specific time intervals: 12 hours after application (HAA), 24 HAA, 48 HAA, 72 HAA, 96 HAA, and 120 HAA.

In this bioefficacy test, the variables under observation encompass the mortality of *S. frugiperda*, the lethal time 50% (LT_{50}), and the rate of infection. The analysis of *S. frugiperda* mortality was conducted through the Analysis of Variance (ANOVA). In the event of a significant disparity being detected, a subsequent Duncan Multiple Range Test (DMRT) was carried out with a confidence level of 95%. Subsequently, the LT_{50} value was determined by means of probit analysis (Caccia *et al.* 2014).

RESULTS

Mortality of *Spodoptera frugiperda*. This investigation aimed to determine the effect of administering *Steinernema* sp. on the mortality of *S. frugiperda* larvae at various time intervals, including 12 hours, 24 hours, 48 hours, 72 hours, 96 hours, and 120 hours following application. The findings demonstrated a similar induction of death in *S. frugiperda* larvae across all concentrations examined, beginning at the 12-hour point after treatment. Mortality gradually increased throughout the duration of the observation period, peaking at the end of the 120-hour evaluation. In striking contrast, the control treatment showed no cases of death in the observed *S. frugiperda* larvae during the whole 120-hour period.

The results also showed statistically significant differences in the mortality impact for each incremental increase in the population of *Steinernema* sp. from 12 to 120 hours after treatment. This shows that an increase in population density increases *Steinernema* sp.'s ability to control *S. frugiperda* mortality correspondingly. The mortality effects on the *S. frugiperda* larvae were more severe at higher *Steinernema* sp. population densities.

With the exception of the populations of 800 IJ mL^{-1} and 1000 IJ mL^{-1}, significant differences were seen between the investigated treatments at the 120-hour mark. In terms of statistics, there was no difference between these two groups' mortality rates, which were both 97.5%. This suggests that the mortality rates inflicted on the *S. frugiperda* larvae by the two population densities were comparable. For a thorough comprehension of the findings, Table 1 presents specific information about the mortality associated with *S. frugiperda* larvae after the administration of *Steinernema* sp.

The results of the study showed unique morphological alterations in the larvae, including a change in body cuticle color to a dark brown or blackish-brown hue, a fragile and watery feel upon pressure, and eventually lysis with just the wrinkled exoskeleton left. Due to the presence of *Steinernema* sp. and the activity of the symbiotic bacteria, *Xenorhabdus* spp., infected larvae previously showed lower activity and decreased eating behavior. Figure 1 provides a clear visual picture of the observed alterations by comparing *S. frugiperda* larvae before and after infection with *Steinernema* sp.

The LT_{50} of *Steinernema* sp. on *S. frugiperda*. The Lethal Time 50 (LT_{50}) is a significant measure used to evaluate a treatment's efficacy in generating mortality in examined insects. It denotes the amount of time necessary to cause 50% mortality in the target insect population. The LT_{50} values obtained from various treatment concentrations in the current investigation involving *S. frugiperda* larvae showed substantial variability. The treatment with 200 IJ mL^{-1} had the longest LT_{50} value of 95.88 hours, suggesting that it needed the longest period to cause 50% mortality in the studied larvae. In contrast, 1000 IJ mL^{-1} treatment resulted in an LT_{50} value of 32.60 hours, indicating the lowest time required to attain the same level of mortality.

The difference in LT_{50} values between treatments shows that they are not equally effective in suppressing *S. frugiperda* larvae. A greater LT_{50} number indicates inferior effectiveness since the treatment takes longer to attain the required mortality rate. A lower LT_{50} number, on the other hand, suggests greater efficacy because the treatment reaches 50% mortality more quickly.

The observed pattern suggests that as the concentration of treatment increases, the LT_{50} values tend to fall, reflecting a greater efficiency in inducing mortality. For example, 400 IJ mL^{-1} treatment resulted in an LT_{50} value of 57.76 hours, whereas 600 IJ mL^{-1} treatment resulted in an LT_{50} value of 46.59 hours. Furthermore, the LT50 value for the 800 IJ mL^{-1} treatment was 38.05 hours. These data point to a gradual improvement in treatment efficacy as the concentration of the treatment ingredient increases.

The LT_{50} values obtained from the tested treatment doses give important information on the time dynamics of mortality induction in *S. frugiperda* larvae. These findings help to improve knowledge of the efficacy of varied treatment doses in managing the target pest population, allowing for improved pest management strategy decisions. Table 2 contains detailed information on the LT_{50} values of *Steinernema* sp. on *S. frugiperda*.

The Infection Rate of *Steinernema* sp. on *S. frugiperda*. For each treatment concentration, the data demonstrated dynamic patterns in infection rates over time. The infection rate at 24 HAA was reported to be 8 larvae in the case of treatment with 200 IJ mL^{-1}. The infection rate significantly decreased throughout the duration of the study, with 6 larvae infected at 48 HAA

Figure 1. Morphology of *S. frugiperda* prior to infection with *Steinernema* sp. (top) and after being infected with *Steinernema* sp. (bottom)

Table 1. The effect of *Steinernema* sp. treatment on the mortality of *S. frugiperda* larvae

Treatments	Mortality (%) at the observation time of - hours					
	12	24	48	72	96	120
Control	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}	0.0^{a}
200 IJ mL^{-1}	2.5^{b}	5.0^{b}	15.0^{b}	27.5^{b}	45.0^{b}	75.0^{b}
400 IJ mL^{-1}	7.5^{c}	150^{c}	40.0^{c}	52.5^{c}	70.0^{c}	87.5^{c}
600 IJ mL^{-1}	10.0^{d}	22.5^{d}	50.0^{d}	60.0^{d}	75.0^{d}	95.0^{d}
800 IJ mL^{-1}	17.5^{e}	27.5^{e}	52.5^{e}	70.0^{e}	85.0^{e}	97.5^{e}
1000 IJ mL^{-1}	20.0^{f}	30.0^{f}	62.5^{f}	75.0^{f}	92.5^{f}	97.5^{e}

Values followed by different superscript letters are significant at P≤0.05 over control

Table 2. The LT_{50} values of *Steinernema* sp. on *S. frugiperda*

Treatments	LT_{50}	Regression equation	R	Interval Limit		Slope	SE Slope
				Upper limit	Lower limit		
200 IJ mL^{-1}	95.88	y = 2.8724x – 0.6923	1	114.21	80.50	2.87	0.38
400 IJ mL^{-1}	57.76	y = 2.5285x + 0.5458	1	67.97	49.08	2.53	0.31
600 IJ mL^{-1}	46.59	y = 2.5096x + 0.8132	1	55.18	39.33	2.51	0.31
800 IJ mL^{-1}	38.05	y = 2.461x + 1.1108	1	45.49	31.83	2.46	0.30
1000 IJ mL^{-1}	32.60	y = 2.5314x + 1.1654	1	39.31	27.23	2.53	0.30

and 4 larvae infected at 72 HAA. This suggests that the larvae's sensitivity to *Steinernema* sp. infection decreases with time. At 24 HAA, the treatment with 400 IJ mL^{-1} resulted in an infection rate of 10 larvae. However, as the observation period progressed, the infection rate fell to 6 larvae at 48 HAA and then to 5 larvae at 72 HAA. These data indicate that the treatment concentration's efficiency in infecting the larvae decreased over time.

The treatment with 600 IJ mL^{-1} resulted in an infection rate of 12 larvae at 24 HAA, which gradually dropped to 8 larvae at 48 HAA and 7 larvae at 72 HAA. Similar to the previous treatment concentrations, this suggests a declining trend in infection susceptibility. The infection rate was 14 larvae at 24 HAA for the treatment with 800 IJ mL^{-1}. Over time, the infection rate reduced to 10 larvae at 48 HAA and then to 7 larvae at 72 HAA. These findings indicate that the efficacy of Steinernema sp. infection with this specific treatment concentration decreased as the observation time progressed.

Notably, the treatment with 1000 IJ mL^{-1} had the greatest infection rate of all the doses studied. At 24 HAA, 16 larvae were infected, showing a high degree of vulnerability. However, as the observation period progressed, the infection rate reduced steadily to 13 larvae at 48 HAA and then to 9 larvae at 72 HAA. This shows that the larvae's total infection susceptibility has decreased with time, albeit retaining a significantly greater infection rate as compared to other concentrations. Figure 2 also shows a comprehensive graphical representation of the infection rate of *Steinernema* sp. on *S. frugiperda*.

DISCUSSION

Entomopathogenic nematodes (EPNs), particularly *Steinernema* sp., are widely applied in biological control due to their rapid insecticidal action, broad host range, and suitability for soil-dwelling and foliar pest stages. The life cycle and mode of infection of this nematode are distinctive. The infective juvenile (IJ) stage penetrates the host through the cuticle or natural openings, particularly in actively feeding larval stages with relatively soft integuments (Burnell & Stock 2000; Stock 2019). Once inside, they let out *Xenorhabdus* spp., the symbiotic bacteria that associate with the nematodes. The interaction of *Steinernema* sp. with the symbiotic bacteria causes the insect host to quickly die. The nematodes and the symbiotic bacteria both produce numerous immunosuppressive virulence factors, which aid in this. These elements interfere with the insect's immune system and lead to the host's quick death, usually within 48 hours (Ferreira & Malan 2014; Abd-Elgawad 2022).

The efficacy of *Steinernema* sp. against *S. frugiperda* is strongly influenced by host developmental stage, nematode concentration, and exposure duration, reflecting stage-specific susceptibility and dose-dependent pathogenicity. Larval stages, particularly early to mid instars, are generally more susceptible to EPN infection due to thinner cuticles, higher feeding activity, and reduced immune competence compared to later developmental stages. Several studies have demonstrated strong larvicidal and pupicidal activity of entomopathogenic nematodes against *S. frugiperda*, confirming their broad pathogenic potential across multiple developmental stages (Bastidas *et al.* 2014; Acharya *et al.* 2020). Exposure to *Steinernema* sp. at concentrations of 10–800 infective juveniles per larva resulted in mortality rates of 43.75–100% in third-instar larvae and 25–100% in fifth-instar larvae, indicating a clear decline in susceptibility with increasing larval age.

Previous studies have extensively evaluated the insecticidal efficacy of *Steinernema* sp. against economically important lepidopteran pests. Uhan (2008) reported that application of *Steinernema* sp. at a density of 800 infective juveniles (IJ) mL^{-1} caused 78.3% mortality in *Spodoptera litura* larvae, demonstrating the high pathogenic potential of this nematode against noctuid pests. These findings suggest that *Steinernema* sp. exhibits consistent virulence within the genus *Spodoptera*, although susceptibility may vary among species and experimental conditions. In a more target-specific study, Hade *et al.* (2020) evaluated the pathogenicity of *Steinernema* sp. against *S. frugiperda* larvae. They reported that a nematode density of 600 IJ per 3 mL effectively controlled the pest, with an LC_{50} value of 186.5 IJ mL^{-1}, indicating a relatively high susceptibility of *S. frugiperda* larvae to *Steinernema* sp.

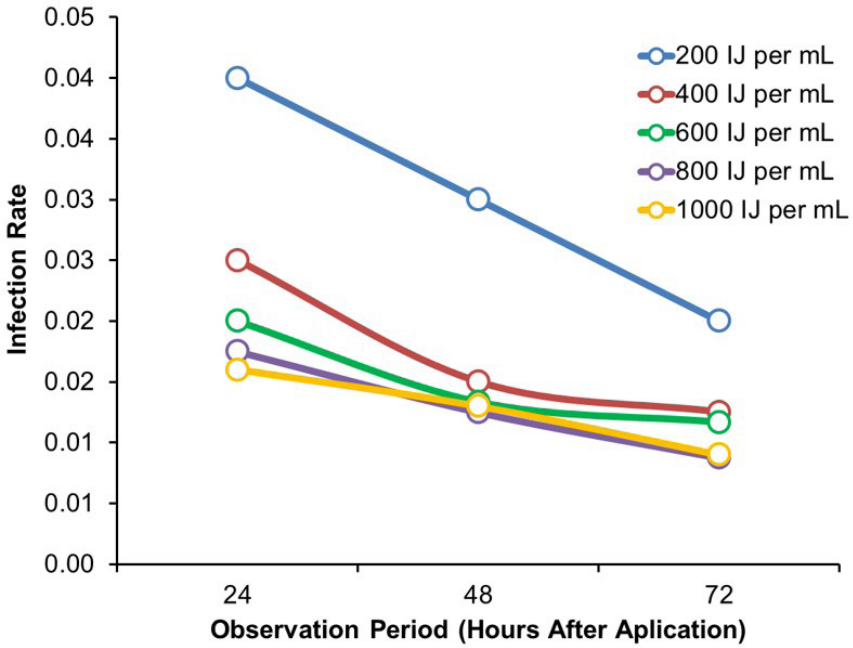

Figure 2. Infection rate of *Steinernema* sp. against *S. frugiperda*

In addition, Acharya *et al.* (2020) evaluated the effect of varying *Steinernema* sp. nematode densities on insect mortality. Their findings revealed a link between nematode density and the rate of mortality in the studied insects. This shows that increased *Steinernema* sp. nematode concentrations result in higher mortality rates in the target insect population, including *S. frugiperda*. These data from several research give compelling evidence that *Steinernema* sp. is effective in controlling *S. frugiperda* and other pest insects.

The LT_{50} values obtained in this study are consistent with previous studies conducted by Indrayani & Gothama (2005), who reported that the average LT_{50} values of the *Steinernema* sp. in causing 50% mortality in test insects ranged from 1 to 4 days, or 24 to 96 hours after application. This shows that the *Steinernema* sp.'s efficiency in producing mortality differs based on the time frame after administration. Furthermore, Fuxa *et al.* (1988) discovered that the average period of insect mortality following *Steinernema* sp. administration was 42.5 hours. This suggests that the nematodes cause death in the target insects quickly.

The speed at which *Steinernema* sp. kills its insect host is governed by multiple biological and ecological factors related to nematode reproduction, bacterial symbiosis, and host exploitation. One key factor is the ability of *Steinernema* sp. to reproduce rapidly within the host, where infective juveniles remain for approximately 10–14 days and undergo multiple reproductive cycles. This capacity to reproduce quickly contributes to their efficiency in managing the target insect population (Hazir *et al.* 2003; Snyder *et al.* 2007). Another critical determinant of time to kill is the pathogenic activity of symbiotic bacteria, particularly *Xenorhabdus* spp., which proliferate rapidly in the hemocoel and produce toxins, proteases, and immunosuppressive compounds that disrupt host tissues and physiological functions. These bacteria are critical in assisting nematodes in invading the host's tissues and leading to the insect's death. Following completion of their life cycle or host death, newly produced infective juveniles emerge from the cadaver and actively search for new hosts, ensuring sustained transmission and continued population regulation (Goodrich-Blair & Clarke 2007; Castillo *et al.* 2011).

The findings of this study add to the results of Wagiyana *et al.* (2008), since they show an identical pattern with the peak infection rate happening 24 hours after application. This consistency across independent experiments strengthens the reliability of the findings and supports the effectiveness of *Steinernema* sp. as a biological control agent. The rapid onset of infection within the first 24 hours suggests an early and effective host invasion process, likely driven by fast nematode penetration and rapid proliferation of symbiotic bacteria. However, nematode virulence is not solely determined by the isolate used, but is also strongly influenced by host-specific morphological and physiological characteristics.

The physical properties of the insect's body structure have a crucial effect in *Steinernema* sp. infection success (Castillo *et al.* 2011). Cuticle thickness, respiratory and digestive systems, and other structural traits can all affect how well the nematodes infect the insect. A thicker cuticle, for example, may act as a barrier, making it more difficult for nematodes to enter and develop an infection (Labaude & Griffin 2018; Liu *et al.* 2020). Similarly, changes in both the digestive and

respiratory systems might affect nematode survival and reproduction inside the host insect (Martens & Goodrich-Blair 2005).

Furthermore, species-specific insect immune responses can limit the establishment and survival of inoculated entomopathogenic nematodes. One of the primary cellular defense mechanisms is encapsulation, mediated by plasmatocytes and granulocytes in the hemolymph, which immobilizes invading nematodes and restricts their development (Sanda *et al.* 2018). Such immune responses reduce the proportion of infective juveniles that successfully establish within the host, thereby lowering nematode virulence and delaying host mortality. When assessing the overall efficacy of *Steinernema* sp., the interaction between the nematodes and the insect's immune system is critical (Toubarro *et al.* 2013).

The development of infective juveniles in *S. frugiperda* larvae is inconsistent due to the delicate nature of their integument. Following host death, the fragile larval integument may rupture prematurely, leading to early emergence of adult nematodes before completion of optimal reproduction cycles. This premature emergence increases nematode exposure to unfavorable external conditions, reducing adult survival and limiting the production of new infective juveniles. As a result, the delicate integument of *S. frugiperda* larvae adds to the difficulty of establishing a stable and effective nematode population within the host (Wang *et al.* 2022).

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