



Synergistic insecticidal efficacy of *Beauveria bassiana* with silver nanoparticles against Bihar hairy caterpillar (*Spilarctia obliqua*) infesting green gram (*Vigna radiata*)

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ABSTRACT

Bihar hairy caterpillar [*Spilarctia obliqua* (Walker)], a voracious defoliator of green gram, inflicts significant economic losses in pulse production. Biocontrol agents such as entomopathogenic fungi provide a sustainable alternative for managing defoliating pests; however, their efficacy often falls short when compared to chemical insecticides. To maximise their biocontrol potential, this study was designed to assess the nano-biocontrol combination between the entomopathogenic fungus *Beauveria bassiana* and biosynthesised silver nanoparticles (AgNPs) against *S. obliqua* in green gram [*Vigna radiata* (L.) R. Wilczek]. The study was carried out during 2023 at College of Agriculture, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand. Different AgNPs concentrations (1.25, 2.5, 5, 10, 20 and 40 ppm) with and without *B. bassiana* were evaluated including control. Laboratory assays confirmed that AgNPs up to 10 ppm inhibited less than 50% growth of *B. bassiana* according to Hassan's toxicity classification index, inferring mutual compatibility. The nano-biocontrol combination of *B. bassiana* (6.1×10^8 conidia/mL) with AgNPs (40 ppm) attained LC₅₀ value of 11.16 ppm and LT₅₀ of 77.31 h, demonstrating 2.85-fold higher toxicity than AgNPs alone (LC₅₀: 31.90 ppm; LT₅₀: 106.31 h) against *S. obliqua*. Under nethouse conditions, this combination achieved 100% mortality of *S. obliqua* by the 8th day after treatment on green gram plants. The findings suggest that nano-biocontrol combinations have the potential to improve efficacy of microbial biocontrol agents and contribute to the sustainable management of insect-pests.

Keywords: Defoliator pest, Nano-biocontrol combinations, Sustainable pest management

Bihar hairy caterpillar [*Spilarctia obliqua* (Walker)] is a highly destructive and polyphagous defoliator attacking over 100 different plant species across 25 families, including pulse crops. (Bhadauria *et al.* 2001, Goel *et al.* 2004). Early instar larvae feed gregariously, skeletonising leaves and turning them dusty white, with a perforated appearance, while later instars voraciously consume foliage, tender stems, and pods. In green gram [*Vigna radiata* (L.) R. Wilczek], severe infestations result in rapid defoliation, stunted growth, and even complete crop failure, causing yield and economic losses (Sridhar *et al.* 2025). Biocontrol agents such as entomopathogenic fungi offer an eco-friendly alternative for managing such pests. Among them, *Beauveria bassiana* (Balsamo) Vuillemin (Ascomycota: Hypocreales) is widely recognised for its broad host range. It has a unique ability to

infect insects through natural openings, leading to mycosis characterised by visible mycelial growth and powdery conidia (Deb and Dutta 2021, Yadav *et al.* 2025). It has been documented to infect over 700 insect species, belonging to orders Lepidoptera, Hemiptera, Coleoptera, Hymenoptera, Hemiptera, and Orthoptera (Shah and Pell 2003, Rai *et al.* 2014). However, a major limitation of *B. bassiana* under field conditions is its relatively slower action and reduced efficacy compared to chemical insecticides (Moore and Prior 1996, Altinok *et al.* 2019). To address these constraints, integrating nanotechnology with biocontrol agents via nano-biocontrol combination has emerged as a potential strategy for improving efficacy of biocontrol agents in sustainable pest management.

Several studies reported that biosynthesised nanoparticles, particularly at lower concentrations, can interact synergistically with biocontrol agents, enhancing their insecticidal activity (Asghar *et al.* 2022, Pokhriyal 2022, Joshi 2022). Silver nanoparticles (AgNPs) possess unique physicochemical properties, including a high surface-to-volume ratio, broad-spectrum compatibility, and

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bioactivity (Khan *et al.* 2021, Jaskulski *et al.* 2022, Yah and Simate 2015). Therefore, the present study was carried out to evaluate the compatibility of AgNPs with *B. bassiana* and assess their combined insecticidal efficacy against *S. obliqua* under laboratory and nethouse conditions.

MATERIALS AND METHODS

Experimental site: The experiment was conducted during *zaid* 2023 at College of Agriculture, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar (29°N, 79.3°E; at an elevation of 244 m amsl), Uttarakhand, situated at the foothills of the Shivalik range of the Himalayas.

Bio-synthesis of silver nanoparticles and characterisation: The synthesis of AgNPs was conducted using a co-precipitation method as described by Shukla *et al.* (2010) and Tripathy *et al.* (2010) with little modifications. The synthesised AgNPs were characterised using UV-Vis spectrophotometry, Dynamic Light Scattering (DLS), Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscope (SEM). The UV-Vis and FTIR spectra were acquired using repeated scans to ensure reproducibility of spectral characteristics. The DLS measurement included hydrodynamic particle size and polydispersity index (PDI) obtained using automatic replicate measurement mode to record multiple correlation functions, and reports averaged values. SEM observations were performed on multiple fields of view to ensure representative morphology from SEM micrographs at a 100 nm scale bar using ImageJ software (version 1.8.0).

Compatibility evaluation of nano-biocontrol combination: The *B. bassiana* isolate was obtained from Microbial Type Culture Collection (MTCC), IMTECH, Chandigarh (Accession No. MTCC-9967), originally isolated from Pantnagar, Uttarakhand. Conidial viability was assessed before application, following the procedure suggested by Gillespie (1986). Viability assessment was performed by directly counting both viable and non-viable conidia under a light microscope at 400x magnification after 20–22 h of incubation. Conidial spores were considered germinated when the germ tube length equaled or exceeded the diameter of the conidium. Counts of viable and non-viable conidia were continued until a total of 300 conidia had been examined. Conidial viability was calculated as:

$$\% \text{ viability} = (V \times 100) / (V + N)$$

Where V, Viable conidia; N, Number of non-viable conidia.

Only conidial suspensions exhibiting more than 90% germination were used for subsequent experiments. For the mass multiplication of *B. bassiana*, Potato Dextrose Agar (PDA) and Potato Dextrose Broth (PDB) were prepared as given by the method of Kadam and Jaichakravathy (2003). For maximum spore density, the fungus was incubated in PDB for 15 days before application. Spore density was quantified using an Improved Neubauer Haemocytometer (Weber) after serial dilution, yielding a concentration of 6.1×10^8 spores/mL. To improve dispersion, 0.02% Tween-20[®]

was added to the suspension containing the homogenised mycelial mat and spores. The compatibility of AgNPs with *B. bassiana* was evaluated using the poisoned disc technique as described by Moorhouse *et al.* (1992). The fungal media as well as the AgNP solutions were prepared with double-strength concentrations. Then, 10 mL of AgNPs solution was poured into a 9 cm diameter sterilised Petri dish using a needle to remove any contamination present in it, followed by 10 mL of simmered melted media, which was immediately mixed with the help of a sterilised glass rod, and fungal spores of *B. bassiana* were inoculated in the center of the media. In the control treatment, 10 mL of distilled water was added to the prepared media. Each treatment was replicated four times. The Petri dishes were then sealed with paraffin wax strips and stored in a BOD incubator at $27 \pm 5^\circ\text{C}$ temperature. Radial mycelial growth was recorded at 10 and 15 days after inoculation (DAI), and the percentage inhibition of mycelial growth was calculated compared to the control, following the method of Hokkanen and Kotiluoto (1992). The percentage growth inhibition of *B. bassiana* by AgNPs was calculated using the formula:

$$X = (Y - Z) / Y \times 100$$

Where X, Percent inhibition; Y, Radial growth in the control; Z, Radial growth in the treated media.

The toxicity of AgNP treatments was further categorised using Hassan's classification scheme (Hassan 1989) based on a 1–4 scoring index: 1 = Harmless (<50% inhibition), 2 = Slightly harmful (50–79%), 3 = Moderately harmful (80–90%), and 4 = Harmful (>90%).

Efficacy of nano-biocontrol combination against *S. obliqua*: A preliminary range-finding experiment was conducted to determine the appropriate concentration range of AgNPs for estimating the no observed effect concentration/dose and median lethal concentration (LC_{50}) against *S. obliqua* as described by Finney (1971) and Robertson *et al.* (1980). Based on the observed dose-response relationship, a geometric series of AgNPs concentrations (1.25, 2.5, 5, 10, 20, and 40 ppm) was selected for subsequent bioassay with and without *B. bassiana* (6.1×10^8 spores/mL) and the control was tap water. For fungal treatments, 0.02% Tween20[®] was added to facilitate dispersion. In each Petri dish, lined with filter paper, ten *S. obliqua* larvae of the F_2 generation (6 days old) were released. Each treatment was replicated five times. The prepared formulations were sprayed directly onto released insects using a hand atomiser and then transferred to plastic vials (125 mL volume). After 24 h of treatment, larval mortality was determined by gently probing the larvae with a fine paintbrush. Larvae were categorised as alive, moribund, or dead. Moribund larvae are defined as severely affected individuals exhibiting uncoordinated movement and inability to return to an upright position when placed on their dorsal surface and gently stimulated with a fine probe or forceps (Monke *et al.* 1985, Miller *et al.* 2010). Larvae showing no response to gentle stimulation with a paintbrush were considered dead.

Under nethouse conditions, green gram seeds (Pant Mung-09) were sown in plastic pots (40 cm × 25 cm), with

4–5 seeds/pot. Standard agronomic practices were followed throughout the growing period. The nethouse was maintained at a temperature of 26–30°C and a relative humidity of 60–70%. The experiment was conducted in a randomised complete block design with five replications. Pots were randomly arranged within the nethouse and periodically repositioned to minimise positional effects as suggested by Hartung *et al.* (2019). One month after sowing, the prepared formulations were applied using a hand atomiser at a spray volume of 25 mL/plant to ensure uniform foliar coverage. Following treatment application, ten 6-day-old *S. obliqua* larvae (F_2 generation) were released onto each pot. To prevent larval escape, each pot was covered with a muslin cloth bag secured at the base with a thin rope. Larval mortality (including both moribund and dead larvae) was recorded at 24 h intervals until 100% mortality was observed in at least one treatment.

Quantification of synergism and statistical analysis: The level of synergism between the nano-biocontrol combination (*B. bassiana* and AgNPs) was quantified by laboratory method by determining the median lethal concentration (LC_{50}) for AgNPs alone and in combination with the entomopathogen. The mortality data were calculated using Abbott's formula (Abbott 1925), considering natural mortality in the control.

$$\text{Corrected mortality\%} = \frac{\text{Percent treatment mortality} - \text{Percent control mortality}}{100 - \text{Percent control mortality}} \times 100$$

The corrected mortality was subjected to Probit analysis for concentration-mortality regression equations and LC_{50} values, following the method of Finney (1971). The synergistic ratio (SR) was calculated using the formula:

$$SR = LC_{50} \text{ of AgNPs alone} / LC_{50} \text{ of AgNPs} + B. \text{ bassiana}$$

An SR value >1 indicates synergism, <1, antagonism; and 1 suggests an additive effect. The compatibility experiment under laboratory conditions was statistically analysed by using a two-factor completely randomised design (CRD). Percent inhibition data were subjected to arcsine transformation, while mean values were square root transformed ($\sqrt{x + 0.5}$) following Snedecor and Cochran (1967). The significance of the data was assessed using analysis of variance (ANOVA) in the online OPSTAT software (Sheoran *et al.* 1998).

RESULTS AND DISCUSSION

Characterisation of silver nanoparticles: In the UV spectroscopy analysis between 300 and 620 nm, an absorbance peak of 0.437 at 425 nm was observed, indicating AgNP formation (Fig. 1A). Similar peaks were reported by Veeraswamy *et al.* (2011) at 438 nm, Ahmad *et al.* (2016) at 436–445 nm, Nagar *et al.* (2016) at 433 nm, and Asghar *et al.* (2022) at 412 nm. The average hydrodynamic diameter of AgNPs analysed by DLS was 66.63 nm and a polydispersity index (PDI) of 0.160 (Fig. 1B). Here, a single peak was observed at 78.42 nm which indicated the average size of

nanoparticles in terms of interplanar spacing (d-spacing). The FT-IR spectrum (400–4,000/cm) between transmittance (%) versus wave number (cm^{-1}) was analysed and the results are presented in the Fig. 1(C). A broad absorption band between 3313.35/cm is due to the N-H stretching vibration of the group NH_2 and OH, the overlapping of the stretching vibration attributed to water and *A. indica* leaf extract molecules. The bands at 2889.19/cm and 2116.88/cm correspond to the methyl ($-\text{CH}_3$) group and the alkyne group ($\text{C}\equiv\text{C}$), respectively. The characteristic band at 1752.25/cm and 1636.46/cm corresponds to Ester (RCOOR') and amide ($\text{C}=\text{O}$) stretching due to phytoconstituents in the extract. The absorption peak at 1400.83/cm corresponds to the tertiary alcohol, OH stretch. The absorption peaks at 1167.36/cm and 1088.89/cm showed ether linkages, suggesting the presence of flavones or terpenoids absorbed on the surface of silver nanoparticles. The SEM image of the synthesised AgNPs is represented in the Fig. 1(D). The particles were globular and spherical in shape, with an average size of 63.56 nm. A similar shape in SEM and bonds in FT-IR were observed in AgNPs by Ahmad *et al.* (2016) and Asghar *et al.* (2022). All these physicochemical characterisations indicated that silver nanoparticles had been formed within the nano range with efficient capping.

Compatibility evaluation of nano-biocontrol combination under laboratory conditions: Biological characteristics of *Beauveria bassiana* on PDA treated with various concentrations of AgNPs indicated that the concentration of AgNPs was inversely proportional to the radial growth of the fungus *B. bassiana* (Table 1). With an increase in the concentration of AgNPs, the radial growth of the mycelium significantly decreased. For each concentration, the radial growth and the time of inoculation exhibited a positive correlation. The interaction of concentration of AgNPs and days of interval for inoculation varied non-significantly at $p=0.05$. At 10 DAI, maximum radial growth of *B. bassiana* was recorded at the lowest concentration of AgNPs (5.34 cm), while the minimum was in the highest concentration of AgNPs (2.34 cm), as compared to the control, which was 7.18 cm.

At 15 DAI, similar observations were found for radial growth. The maximum percent inhibition of *B. bassiana* over control was recorded for the highest concentration while the minimum was in the lowest concentration. As the maximum percent inhibition was less than 50% in all concentrations except higher concentrations, lower concentrations of AgNPs were found to be highly compatible. While the concentrations 20 ppm and 40 ppm fall under scoring index of 2 as per Hassan's classification index, and are classified as 'slightly harmful' for the fungal mycelium growth.

Similarly, an experiment conducted by Joshi (2022) evaluated the compatibility of *B. bassiana* with ZnO NPs at different concentrations (5, 10, 15, 20, and 25 ppm). At 15 DAI, maximum inhibition recorded for the highest concentration was 39.13 %, while minimum was 23.73 % at the lowest concentration, which revealed high compatibility

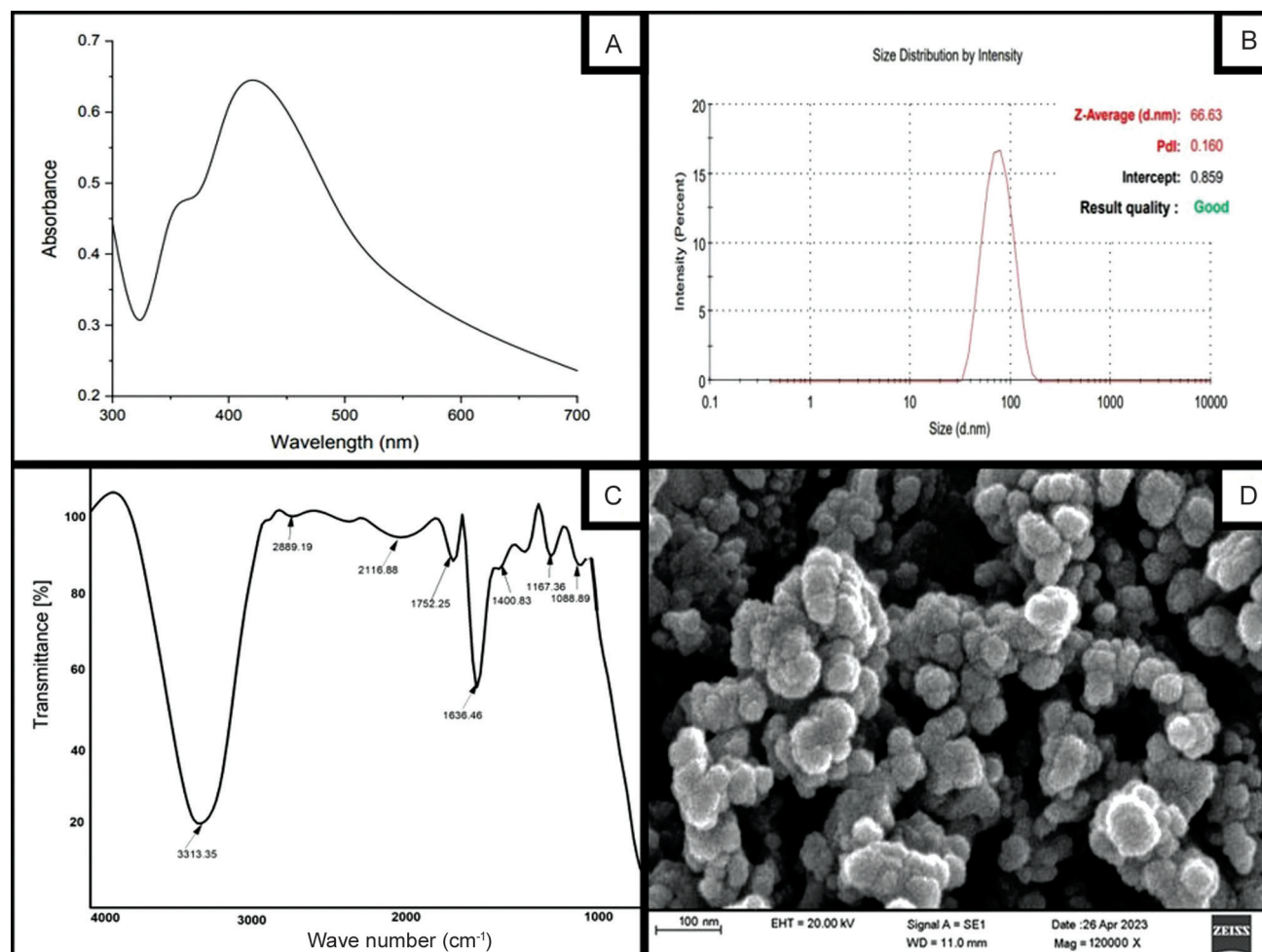


Fig. 1 Characterisation of synthesised silver nanoparticles.

(A), UV-Vis Spectrophotometry; (B), Dynamic Light Scattering (DLS); (C), Fourier Transform Infrared Spectroscopy (FT-IR); and (D), Scanning Electron Microscope (SEM).

of ZnO NPs with *B. bassiana*. Pokhriyal (2022) tested the compatibility of *B. thuringiensis* with ZnO NPs and observed very slight bacterial growth inhibition, with percent inhibition after 2, 6, and 36 h being 4.54%, 17.29% and 41.30%, respectively.

Synergistic effect of *B. bassiana* with AgNPs: Mean lethal concentration (LC_{50}) of AgNPs alone was 31.90 ppm, with the fiducial limits of 14.30–71.16 ppm, whereas the combination of AgNPs + *B. bassiana*, the value of estimated LC_{50} was 11.16 ppm, with fiducial limits 6.84–18.20 ppm (Tables 2). With an increase in concentration of AgNPs (individually and in combination), a significant increase in mortality of *S. obliqua* was observed. The LC_{30} and LC_{90} values for the treatment with and without *B. bassiana* were 7.98, 944.16, and 3.14, 247.26 ppm, respectively. On the basis of fiducial limits, the LC_{50} value in combination varies non-significantly with individual treatments of AgNPs and *B. bassiana*, and the nano-biocontrol combination was found to be 2.85 times more toxic than AgNPs alone. The results of the present study were similar to that of Joshi (2022) and Pokhriyal (2022), in which they observed ZnO NPs combination with *B. bassiana* and *Bacillus thuringiensis*

was 2.59 and 2.16 times more toxic than ZnO NPs alone, respectively. Priyadarshini *et al.* (2012) and Devi *et al.* (2014) observed LC_{50} value for AgNPs against *Anopheles stephensi* and *Helicoverpa armigera* was 10.14 and 2.90, respectively. Asghar *et al.* (2022) observed LC_{50} values of the third, fourth, and fifth instars of *H. armigera* against AgNPs were 114.67 ppm, 112.07 ppm, and 130.89 ppm, respectively. While with ZnO NPs, LC_{50} values of the third, fourth, and fifth instar of *H. armigera* were observed at 127.79, 114.069, and 155.38 ppm, respectively.

The estimated LT_{50} value for *B. bassiana* and AgNPs (40 ppm) individually was found to be 113.71 h with fiducial limits 93.68–120.65 h and 106.31 h with fiducial limits 68.44–87.34 h, respectively (Tables 3). The LT_{50} value for AgNPs with *B. bassiana* was recorded at 77.31 h, with fiducial limits of 68.44–87.34 h. On the basis of fiducial limits, the LT_{50} value in combination was significantly different from the individual treatments, and the combination doses of AgNPs with *B. bassiana* took less time to kill the larvae of *S. obliqua* under laboratory conditions. Similar results were found by Joshi (2022), where LT_{50} for ZnO NPs and *B. bassiana* alone was 111.19 and 127.78 h, respectively,

Table 1 Biological characteristic of *B. bassiana* on PDA media treated with AgNPs

Concentration (ppm) (B)	Radial growth (cm) #			Percent inhibition**			Hassan classification index
	Days of interval (A)			Days of interval (A)			
	10	15	Mean	10	15	Mean	
1.25	5.34 (2.51)	6.21 (2.68)	5.78 (2.68)	25.61 (30.39)	24.03 (29.34)	24.82 (29.86)	1
2.5	4.59 (2.36)	5.36 (2.52)	4.97 (2.44)	36.15 (36.94)	34.51 (35.95)	35.32 (36.44)	1
5	4.03 (2.24)	4.70 (2.38)	4.36 (2.31)	43.90 (41.48)	42.52 (40.68)	43.21 (41.08)	1
10	3.54 (2.13)	4.37 (2.30)	3.93 (2.21)	50.67 (44.36)	47.25 (43.40)	48.96 (44.38)	1
20	3.15 (2.03)	3.88 (2.21)	3.51 (2.12)	56.19 (48.53)	52.54 (46.43)	54.36 (52.65)	2
40	2.34 (1.82)	3.01 (2.00)	2.67 (1.91)	67.39 (55.16)	63.22 (52.65)	65.30 (53.90)	2
Control	7.18 (2.86)	8.18 (3.03)	7.68 (2.94)	-	-	-	-
CD (<i>p</i> =0.05)	A = 0.06 (0.01), B = 0.12 (0.02), A × B = NS			A = 0.78 (0.47), B = 1.47 (0.88), A × B = NS			
SEM±	A = 0.03 (0.005), B = 0.05 (0.01), A × B = 0.08			A = 0.26 (0.16), B = 0.50 (0.30), A × B = 0.71 (0.42)			

#Parentheses values are square root transformed. ** Parentheses values are arcsine transformed. NS, Non-significant.

Table 2 Concentration mortality response of AgNPs against *S. obliqua* under laboratory condition

Treatments	Heterogeneity χ^2 *	Regression equation	LC values (ppm)	Fiducial limits (ppm)	Synergistic ratio
AgNPs	1.45	$y = 0.846x + 3.712$	LC ₃₀ -7.98 LC ₅₀ -31.90 LC ₉₀ -944.16	4.67-13.63 14.30-71.16 98.69-9032.67	2.85
AgNPs + <i>B. bassiana</i>	1.22	$y = 0.941x + 4.012$	LC ₃₀ -3.14 LC ₅₀ -11.16 LC ₉₀ -247.26	1.74-5.68 6.84-18.20 56.07-1090.30	

*Non-significant at $p=0.05$. AgNPs, Silver nanoparticles.

while in combination, it was 78.56 h. Pokhriyal (2022) also recorded LT₅₀ in combination of ZnO NPs + *B. thuringiensis* was 60.30 h, while individual treatment of ZnO NPs and *B. thuringiensis* was 68.23 and 109.85 h, respectively.

Under nethouse conditions, the mortality of *S. obliqua* increased with increasing concentrations for all the treatments (Table 4). The combination of AgNPs with *B. bassiana* is recorded to induce higher mortality than AgNPs and *B. bassiana* alone. Enhancement in the toxicity was noticed from the 3rd DAT. At 3rd DAT, the combination of AgNPs (40 ppm) + *B. bassiana* was found to cause 53.33% mortality, whereas the individual treatment of *B. bassiana* and AgNPs (40 ppm) resulted in 6.67% and 30.00% mortality, respectively. At 6th DAT, 83.33% mortality was recorded in the combination of AgNPs (40 ppm) +

B. bassiana. This combination recorded 100% mortality, whereas individual treatment of *B. bassiana* and AgNPs (40 ppm) resulted in only 42.85 and 53.57% mortality of *S. obliqua* at 8th DAT. Similar results were also recorded by Joshi (2022), where a combination of ZnO NPs (25 ppm) with *B. bassiana* caused 100% mortality at 7 DAT, whereas ZnO NPs (25 ppm) alone caused only 43.75% mortality of 6-day-old larvae of *S. litura*. Pokhriyal (2022) also recorded a similar trend of mortality for 6-day-old larvae of *S. litura* when ZnO NPs (25 ppm) were used in combination with *B. thuringiensis*.

In conclusion, the nano-biocontrol combination of *B. bassiana* and silver nanoparticles (AgNPs) was more effective against *S. obliqua* than the individual treatments, resulting in significantly reduced LC₅₀ and LT₅₀ values.

Table 3 Duration mortality response of AgNPs against *S. obliqua* under laboratory condition

Treatments	Heterogeneity χ^2 *	Regression equation	LT ₅₀ (h)	Fiducial limits (h)
AgNPs*	2.62	y = 4.498x - 3.298	106.31	93.68–120.65
AgNPs* + <i>B. bassiana</i>	2.38	y = 4.042x - 2.94	77.31	68.44–87.34
<i>B. bassiana</i>	1.24	y = 3.940x - 2.864	113.71	99.78–129.71

*At highest concentration. AgNPs, Silver nanoparticles.

Table 4 Larval mortality of *S. obliqua* under nethouse conditions

Treatment	Larval mortality (%)							
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
AgNPs 1.25 ppm	0.00 (0.00)	0.00 (0.00)	6.67 (3.82)	16.67 (7.33)	20.00 (8.12)	23.33 (8.74)	24.13 (9.35)	25.00 (9.97)
AgNPs 2.5 ppm	0.00 (0.00)	3.30 (1.91)	10.00 (5.73)	20.00 (8.12)	23.33 (8.74)	26.67 (9.26)	31.03 (10.50)	32.14 (11.01)
AgNPs 5 ppm	3.30 (1.91)	10.0 (5.73)	20.00 (8.12)	23.33 (8.74)	26.67 (9.35)	30.00 (9.87)	34.48 (11.01)	39.28 (12.00)
AgNPs 10 ppm	10.0 (5.73)	16.7 (7.33)	23.33 (8.74)	26.67 (9.35)	30.00 (9.97)	33.33 (10.50)	37.92 (11.47)	42.85 (12.45)
AgNPs 20 ppm	13.3 (6.53)	20.0 (7.94)	26.67 (9.35)	30.00 (10.50)	36.67 (11.01)	40.00 (11.53)	44.82 (12.45)	46.42 (12.87)
AgNPs 40 ppm	16.7 (7.33)	23.3 (8.74)	30.00 (9.97)	33.33 (7.34)	40.00 (11.47)	43.33 (12.00))	48.27 (12.87)	53.57 (13.75)
Bb	0.0 (0.00)	3.3 (1.91)	6.67 (3.85)	16.67 (11.47)	30.00 (9.87)	36.67 (10.85))	37.92 (11.53)	42.85 (12.45)
Bb +AgNPs 1.25ppm	3.3 (1.91)	23.3 (8.74)	30.00 (9.97)	40.00 (13.33)	46.67 (12.41)	50.00 (12.87)	58.61 (14.14)	67.85 (15.31)
Bb +AgNPs 2.5 ppm	16.7 (7.33)	30.0 (9.97)	43.33 (11.99)	53.33 (13.33)	63.33 (14.56)	63.33 (14.56)	65.51 (14.94)	71.42 (15.69)
Bb +AgNPs 5ppm	20.0 (7.94)	33.3 (10.39)	46.67 (12.45)	53.33 (13.35)	60.00 (14.17)	60.00 (14.14)	68.96 (15.31)	82.14 (16.76)
Bb +AgNPs 10ppm	26.7 (9.35)	36.7 (11.01)	50.00 (12.91)	56.67 (13.75)	66.67 (14.94)	73.33 (15.70)	75.85 (16.06)	85.71 (17.10)
Bb +AgNPs 20 ppm	30.0 (9.87)	40.0 (11.47)	50.00 (12.87)	63.33 (14.56)	70.00 (15.34)	76.67 (16.06)	86.20 (17.10)	92.85 (17.78)
Bb +AgNPs 40 ppm	36.7 (11.01)	43.3 (12.00)	53.33 (13.34)	66.67 (14.94)	76.67 (16.04)	83.33 (16.76)	93.10 (17.78)	100 (18.42)
CD ($p=0.05$)	(2.84)	(3.00)	(2.32)	(1.77)	(1.67)	(2.10)	(1.60)	(1.30)
SEM±	(0.97)	(1.02)	(0.79)	(0.60)	(0.57)	(0.72)	(0.54)	(0.44)

Parentheses values are arcsine transformed. AgNPs, Silver nanoparticles; Bb, *Beauveria bassiana*.

Nano-biocontrol [*B. bassiana* (6.1×10^8 conidia/mL) with AgNPs (40 ppm)] formulation accelerated fungal action and achieved 100% mortality within eight days under nethouse conditions. This improved efficacy observed in the combined treatment may be associated with nanoparticles-mediated disruption of the insect cuticle, which could facilitate fungal penetration, germination, and proliferation. However, these mechanisms were not directly investigated in the present study and require further investigation. Additional field-scale

validation, environmental risk assessment, and formulation optimisation are essential before large-scale adoption.

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