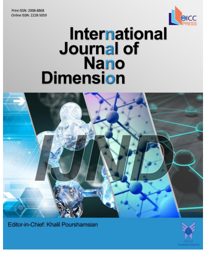

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Original Research

Endophytic Nanoparticles: Promising Growth Promoter, Modulate Biochemical Constitutes in *Vigna radiata* Seedlings, and Antifungal Activity

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Abstract:
Over the years, nanotechnology has been utilized in the agricultural sector for sustainable production. The application of endophytes-mediated silver nanoparticles is gaining momentum in various sectors including agriculture. This current study aims to evaluate the impact of endophytic bacteria-mediated silver nanoparticles in promoting plant growth and improving biochemical constituents in *Vigna radiata* by using the nanopriming method. *Bacillus cereus* isolated from the flower of *Nyctanthes arbor-tristis* was identified and utilized for silver nanoparticles synthesis, this is called *Bacillus cereus* silver nanoparticles (BC-AgNPs). Synthesis of silver nanoparticles was confirmed by colour change and characterization by UV-Vis spectrophotometer, FESEM, FTIR, DLS, and EDAX. Seeds of *Vigna radiata* were treated with different concentrations (1 ppm, 2.5 ppm, 5 ppm and 10 ppm) of BC-AgNPs. Plant growth was enhanced at a concentration of 5 ppm of BC-AgNPs. In addition, an increase in photosynthetic pigments, protein, and carbohydrate was observed in the nanoprimed seedlings when compared to that of the control. Also, the ability of the synthesized particles to inhibit the growth of phytopathogenic fungi *Penicillium janthinellum* was examined. The results suggest that silver nanoparticles synthesized via endophytic bacteria can be utilized as dual-function agent in sustainable agriculture–both as a plant growth enhancer and as a biocontrol agent.

Keywords: *Bacillus cereus*; Biochemical constituents; *Nyctanthes arbor-tristis*; Nanopriminig; Phytopathogens; Silver nanoparticles; *Vigna radiata*

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1. Introduction

Scientific exploration of nanotechnology has increased rapidly, impacting medical, agricultural, and environmental sectors. Due to the rising global population, leading to the high demand for food produce and agriculturally based products as reported by the Food and Agricultural Organization [1], there is need for innovative technological methods to enhance agricultural output estimated to be an addition of 2.4×10^9 tonnes/year [2]. Unlike chemical fertilizers, which degrade soil quality, nanotechnology can produce high-quality, nutrient-rich, disease-resistant crops that are safe for humans and the environment [3, 4].

Plant roots, flowers, stems, seeds, and leaves contain diverse endophytic bacteria communities influenced by species composition, plant development, soil type, genotype, and colonized tissues, promoting growth [5, 6, 7]. Endophytes promote plant growth through both direct and indirect mechanisms. Direct mechanisms involve the microbial synthesis of phytohormones like indole-3-acetic acid (IAA), gibberellins, cytokinins, and abscisic acid, which regulate root elongation, shoot growth, and stress responses [8, 9]. For instance, IAA-producing endophytes have been shown to increase root length and the number of roots in plants, enhancing nutrient uptake and growth [10, 11]. Additionally, endophytic bacteria can fix atmospheric nitrogen, solubilize phosphates, and produce siderophores that chelate iron, thereby improving nutrient availability to plants [12]. Indirect mechanisms of endophytes include the suppression of plant pathogens through the production of antifungal and antibacterial compounds, competition for nutrients and space, and the induction of systemic resistance in the host plant [13]. Certain Plant growth-promoting rhizobacteria (PGPR) endophytic bacteria are known to produce hydrolytic enzymes that degrade pathogen cell walls, thereby inhibiting their growth [14, 15, 16]. Moreover, the mutualistic relationship between endophytic bacteria and plants can enhance soil fertility by improving the availability and uptake of micro- and macronutrients [17, 18].

Nyctanthes arbor-tristis, commonly known as the night-flowering jasmine, was chosen for this study due to its rich microbial diversity and reported medicinal properties [19, 20]. Previous research has shown that endophytic bacteria like *Bacillus* species, from medicinal plants can enhance nanoparticle synthesis by acting as reducing and stabilizing agents [21, 22]. In this study, *Bacillus cereus* was isolated for the first time from the flowers of *N. arbor-tristis*, making it a novel microbial source for the biosynthesis of silver nanoparticles (AgNPs). *B. cereus* has been shown to produce AgNPs via enzymatic reduction, supporting antibacterial and growth-promoting effects in agriculture [2, 23, 24, 25], however, there is limited research on its nanopriming effects in legumes, making this study a significant contribution to this field.

Metal nanoparticles, including copper, silver, aluminum, and gold, are used by endophytic microorganisms for the synthesis of nanomaterials [26, 27]. Among these, AgNPs are notably common due to their broad range of applications [28, 29, 30]. Research indicates that AgNPs, when used in suitable quantities, can manage plant diseases, enhance growth, and improve yield, chlorophyll content, and photosynthetic efficiency [31, 32, 33, 34]. Seed germination is a crucial aspect of agriculture, as it directly influences plant growth, quality, and yield [35]. Studies have shown positive effects of AgNPs on germination across numerous plant species, such as tobacco, barley, tomatoes, wheat, fenugreek, and rice [4, 36, 37]. AgNPs also serve as a safer alternative to harmful pesticides, effectively combating pests and diseases like *Xanthomonas campestris* pv. *campestris* [38], bacterial canker, *Monilinia fructigena* and *Alternaria alternata* [31, 32, 33, 34].

Vigna radiata, commonly known as mung bean, is one of the most widely consumed legumes, cultivated globally, particularly in Asian countries, and valued for its nutritional benefits, including protein, dietary fiber, minerals, and vitamins [39]. According to recent estimates, the global cultivation area for mung bean is approximately 7.3 million hectares, yielding about 5.3 million tons annually [40], with India and Myanmar being the top producers, each contributing about 30%, followed by China with 16%, while Thailand, Kenya, Indonesia, and Tanzania also play significant roles [41]. Mung beans play a crucial role in the diets of many Asian countries, especially in China and India, where they have been consumed for centuries [39], they are also consumed in Southern Europe and the southern United States [41, 42]. Future market forecasts indicate that the rising global demand for plant-based proteins will boost mung bean market growth [43]. Thus, *V. radiata* was chosen for this study due to its availability, widespread consumption, rising market demand, and rapid growth cycle.

Nanopriming is an emerging seed treatment technique that uses nanoparticles to enhance germination, and overall plant growth. This method improves water uptake, nutrient mobilization, and enzyme activation compared to traditional priming [44, 45]. This study identifies the endophytic bacterium *B. cereus* from *N. arbor-tristis* flowers for the first time, and utilized it for the synthesis of silver nanoparticles (BC-AgNPs). The growth-promoting effects of BC-AgNPs were assessed in *V. radiata*, focusing on chlorophyll, carotenoids, proteins, and carbohydrates content. Additionally, BC-AgNPs exhibited antifungal activity against the pathogen *Penicillium janthinellum*, indicating their potential in sustainable agriculture.

2. Materials and Methods

2.1 Isolation and identification of endophytic bacteria

Flowers of *Nyctanthes arbor-tristis* (NAT) were collected from B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai, India, and subjected to surface sterilization following the method described by Love and Hemalatha [46]. Briefly, after rinsing with distilled water, the flowers were sterilized using 70% ethanol, 0.1% sodium hypochlorite and another 70% ethanol all for 1 minute per step, and finally rinsed with sterile distilled water. This process, which removes epiphytic microbes from the flowers [47], was followed by inoculation of sterilized flowers onto nutrient agar plates and incubated at 37 °C. Growth of endophytic bacteria observed after 24 hours was sub-cultured into Luria-Bertani (LB) broth, and maintained as pure cultures. Genomic DNA was then isolated from the endophytes [48] and amplified using primers targeting the 16S rRNA gene [49]. The amplified product was resolved on an agarose gel, visualized using a gel documentation system, and sequenced. The sequence was deposited in the GenBank NCBI database under accession number MN81404. A phylogenetic tree was constructed using MEGA X software [50].

2.2 Synthesis and characterization of BC-AgNPs

Nanoparticles are synthesized from endophytic bacteria [46, 48], from the pure culture, a few inoculate of *B. cereus* endophytes was put into 100 mL of LB and reserved overnight in a rotary shaker at 37 °C and 110 rpm. The culture was centrifuge for 10 minutes at 10000 rpm and the supernatant collected from it was mixed with aqueous solution of Silver Nitrate ($AgNO_3$) in a 1:2 ratio. This mixture was incubated in the dark for 3-5 days to produce nanoparticles, which were then harvested and dried for analysis.

To confirm the synthesis of nanoparticles, the optical properties of *B. cereus* silver nanoparticles (BC-AgNPs) were analysed using a Jasco V-730 spectrophotometer within the wavelength range of 200-800 nm. Additionally, the functional groups and bonding patterns present in BC-AgNPs were examined using a Jasco FT/IR-6300 Fourier Transform Infrared Spectrometer (FTIR) in the spectral range of 400-4000 cm^{-1}. The shape and morphology of BC-AgNPs were evaluated through Field Emission Scanning Electron Microscopy (FESEM), while elemental composition was determined using Energy Dispersive X-ray Analysis (EDAX). Both analyses were conducted using a Supra 55 SEM/EDXM/S (Carl Zeiss, Germany). Finally, the surface charge distribution and polydispersity index (PDI) of BC-AgNPs were assessed using Zetasizer Ver. 7.12, which analysed the Dynamic Light Scattering (DLS) of the synthesized nanoparticles.

2.3 Plant growth and nanopriming

The seed germination technique employed in this study followed the method described by Haji et al. [51]. Briefly, approximately 1 g of *Vigna radiata* seeds were soaked in 5 mL of various concentrations of BC-AgNPs (1 ppm, 2.5 ppm, 5 ppm, and 10 ppm) for 8 to 12 hours. After soaking, the seeds were removed from the nanoparticle solutions and placed in sterilized plastic petri dishes (5–6 seeds per dish) lined with filter paper. Each treatment was prepared in triplicate. The seeds were then sprayed with 2 to 2.5 mL of the corresponding BC-AgNPs concentration for five consecutive days under natural daylight conditions. Seed sprouting was observed starting from day 2, and by the fifth day, the fully germinated Vigna radiata seedlings were ready for analysis. A control group was also prepared, in which seeds were soaked in water and sprayed daily with water following the same procedure.

2.4 Plant growth analysis and biochemical parameters

Following the growth of plants over a period of 5 days, the plants were carefully pulled out and the impacts of synthesized BC-AgNPs on them were physically examined and compared with the control. This was followed by measuring the growth parameters such as wet weight with a weighing balance, and the shoot and root length with a measuring tape. In addition, using appropriate procedures as highlighted by Ranjani et al. (2021), the chlorophyll and carotenoid biochemical constituents were analyzed [52], the proteins and carbohydrates contents were also measured in both the control and nanoprimed seedlings [53, 54].

2.5 Anti fungal assay

The antifungal activity of BC-AgNPs against the phytopathogen *Penicillium janthinellum* was evaluated using the potato dextrose agar (PDA) medium assay, following the method described by Jenish et al., [55]. Briefly, BC-AgNP solutions were prepared at concentrations of 6.25, 12.5, 25, 50, and 100 µg/mL and mixed with 15-20 mL of prepared PDA, which was then poured into sterile Petri dishes and allowed to solidify. Control plates were prepared as follows:

- Positive control: Petri plates treated with fluconazole (25 µg/mL) as a standard antifungal drug.
- Negative control: Plates without any treatment to assess natural fungal growth.

Fungal strains were inoculated onto the plates using the hyphal tip method and incubated at 28 ± 2 °C for nine days. Radial fungal growth was measured at three-day intervals until the ninth day.

Statistical analysis: Results of experiments assessed are given as mean ± standard deviation by one-way analysis, T-test of data was evaluated using the data analysis toolkit of Microsoft Excel. P-value ≤ 0.05 is represented by (*), P value ≤ 0.01 is represented by (**) and value ≤ 0.001 is represented by (***), these values were considered statistically significant.

3. Results and discussion

3.1 Identification of endophytic bacterium

The 16S rRNA sequencing was used to identify the endophytic bacteria as *Bacillus cereus* and deposited in the GenBank of NCBI with the accession number MN81404. As showed in Fig. 1, the phylogenic tree of *B. cereus* was developed in relation with species that are closely related. The neighborhood – joining method is used by MEGA X software to determine the relationship between identified specie and other related species [56]. The maximum composite likelihood method is used to analyze evolutionary distances which are in the same unit as branch length and number of base substitutes per sites [50].

3.2 Characterization of BC-AgNPs

Change in colour of synthesized nanoparticles showed the production of silver ions [57, 58]. One of the obvious results that confirmed the successful synthesis of AgNPs in the presence of endophytic bacterial extract is the gradual change of solution to brown on the addition of $AgNO_3$ to the bacteria supernatant (Fig. 2 a), and this is important evidence that establishes the formation of BC-AgNPs. UV-Vis absorption spectrum of synthesized BC-AgNPs was measured at 425 nm (Fig. 2 b). The formation of silver ions from metallic silver causes an increase in free electrons that are responsible for the formation of absorption peak known as surface plasmon resonance (SPR) absorption band [48].

FTIR results showed a total of ten spectra spread through the different regions of the mid-IR spectrum with a major peak at 3764.37 cm^{-1} (Fig. 2c). Different functional groups were identified in the nanoparticles as indicated by the wavenumbers (Table 1). The spectrum is found in the major wavenumber regions; near-IR spectrum (4000-13000 cm^{-1}), mid-IR spectrum (400-4000 cm^{-1}), and far-IR spectrum (< 400 cm^{-1}). From our analysis, we deduced that BC-AgNPs have methyl group, aromatic compounds with hydrogen bonds [59, 60].

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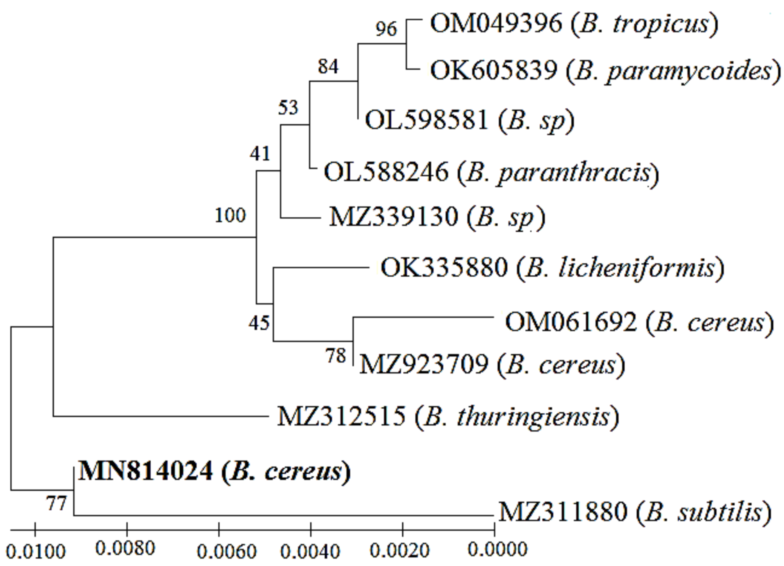

Figure 1. Phylogenic tree of isolated endophytic bacteria from NAT plant flowers.

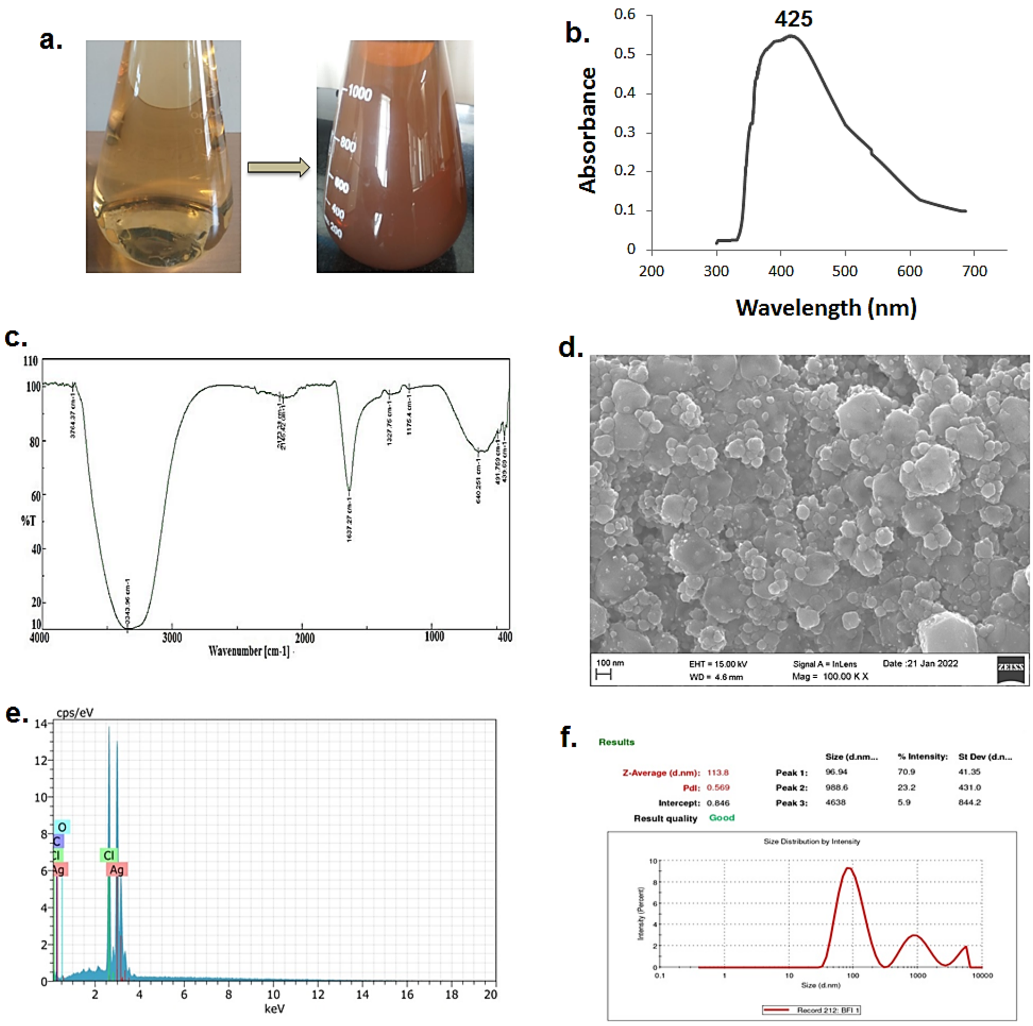

Figure 2. Synthesis and characterization of BC-AgNPs (a) Colour change was observed in solution used for BC-AgNPs synthesis (b) UV-Vis absorption spectrum of biosynthesized BC-AgNPs (c) FTIR analysis of BC-AgNPs (d) FESEM analysis of BC-AgNPs (e) EDAX analysis of BC-AgNPs (f) DLS analysis of BC-AgNPs.

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Table 1. FTIR analysis of BC-AgNPs.

Regions	IR-Spectrum Wavenumber (cm^{-1})	Possible Assigned Functional Groups
Single Bond Region	3764.37	Non-bonded hydroxyl group (OH stretch)
(O-H, N-H, C-H)	3343.96	Hydroxyl group (H- bonded OH stretch), Normal polymeric OH stretch, Aliphatic primary amine (NH stretch), Aliphatic secondary amine (>N-H stretch), Imino compounds (=N-H stretch)
Triple bond region	2173.38	Thiocyanate (- SCN stretch)
(C≡C and C≡N)	2145.42	Thiocyanate (- SCN stretch), Carbodiimide (N=C=N stretch)
Double bond (C=C, C=O, C=N)	1637.27	Alkenyl (C=C stretch), Primary amine (NH bend), Secondary amine (> N-H bend), Open chain azo (-N=N-), Carbonyl compounds
Fingerprint region	1327.76	Aromatic amino (CN stretch), Phenol (OH bend)
	1115.4	Aromatic C-H in –plane bend, Aromatic phosphates (P–O–C stretch)
	640.251	Thioethers (CH_3–S–), Alkyne C–H bend, Aliphatic organohalogen (C–Br stretch)
	491.759	Aryl disulfides (S–S stretch)
	439.69	Aryl disulfides, polysulfides

Morphological analysis of BC-AgNPs using a higher resolution and greater energy instrumentation called FESEM revealed the size at 100 nm, surface, and spherical shape of the synthesized nanoparticles (Fig. 2 d). EDAX analysis associated with FESEM revealed the types and percentage of elements found in BC-AgNPs (Fig. 2 e), which shows the presence of silver (Ag), chlorine (Cl), carbon (C), and oxygen (O) at several peaks, with Ag having the highest peak at 3 keV, this further confirmed the formation of BC-AgNPs [61]. Results of FTIR also confirmed the presence of carbon, oxygen, and chlorine; these elements help in the bio-capping of BC-AgNPs. Dynamic light scattering showed the hydrodynamic, also called Z-average value and polydispersity (PDI) index value of BC-AgNPs (Fig. 2 f). The result showed good quality of synthesized nanoparticles with a size distribution of 113.2 nm and PDI of 0.569. Generally, The PDI value ranges from 0 (monodispersed) to 1 (polydispersed). PDI of BC-AgNPs is slightly above mid-value and can be considered as a good quality and in an acceptable range [46].

3.3 Plant growth analysis

Silver nanoparticles synthesis from different substrates has been used to determine plant growth activities of different crops, and one major similarity in the outcome of these studies is that the use of silver nanoparticles on crops is dose-dependent. In this study, the growth of *V. radiata* seeds treated with 1 ppm concentration (Fig. 3 a), 2.5 ppm concentration (Fig. 3 b), 5 ppm concentration (Fig. 3 c), 10 ppm concentration (Fig. 3 d) BC-AgNPs, as well as control seeds treated with water (Fig. 3), was observed to be healthy. However, notable differences in growth parameters and biochemical constituents were recorded between BC-AgNP-treated seeds and control seeds, as will be analyzed below. These differences could be attributed to the ability of BC-AgNPs to penetrate seeds, influencing the seed germination process and enhancing plant growth [31, 51, 62].

The different concentrations of BC-AgNPs treated plants showed higher wet weight than the control, with the highest percentage of wet weight of 151.34% at 5 ppm BC-AgNPs (Fig. 4 a). The influence of silver nanoparticle on the growth of has been reported in other studies, such as that observed in the seed germination and growth performance of *Pisum sativum* [62], nanoparticle-treated seeds of watermelon which resulted in longer and thicker vines than the unrimed controls [63], and seed germination promotion of *C. annuum* treated with AgNPs [64].

Treated seedlings showed the root length in BC-AgNPs is dose-dependent, and 10 ppm seedlings have the highest length of 7.33 cm, while the control seedlings showed the root length of 5.78 cm (Fig. 4 b). Also, graphical representation of shoot length of varying concentrations showed the highest shoot length was observed in 5 ppm BC-AgNPs treated seeds as 12 cm, while that of control was 9.11 cm (Fig. 4 c). Previous findings revealed that foliar application of AgNPs to Fenugreek (*Trigonella foenum-graecum*) seeds at various concentrations resulted in significant increases in shoot length, number of leaves per plant, and shoot dry weight and the growth promotion was attributed to AgNPs' potential role in modulating ethylene signalling pathways, thereby

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Figure 3. Effect of nanopriming in seeds of *V. radiata* treated with various concentrations of BC-AgNPs (a) 1 ppm (b) 2.5 ppm (c) 5 ppm (d) 10 ppm.

enhancing photosynthetic efficiency and overall plant growth [4]. Also, Broad Bean (*Vicia faba*) seed priming with AgNPs led to increased root and shoot growth [65]. The presence of nanoparticles is suggested to have leads to an increase in the expression of genes responsible for activating plant hormones, which are essential for promoting cell elongation and growth of shoots [66, 67].

Estimation of photosynthetic pigments present in the leaves showed high amounts of chlorophyll a in 2.5 ppm (Fig. 5 a), while 5 ppm plants exhibited higher amounts of chlorophyll b (Fig. 5 b), total chlorophyll (Fig. 5 c), and carotenoids (Fig. 5 d). Our result showed general increase in photosynthetic pigments, chlorophyll, and carotenoids in BC-AgNPs treated leaves when compared to the control. Although some studies have reported that AgNP exposure can lead to oxidative stress and inhibit photosynthesis, resulting in reduced chlorophyll content and photosynthetic efficiency in plants like barley leaves,

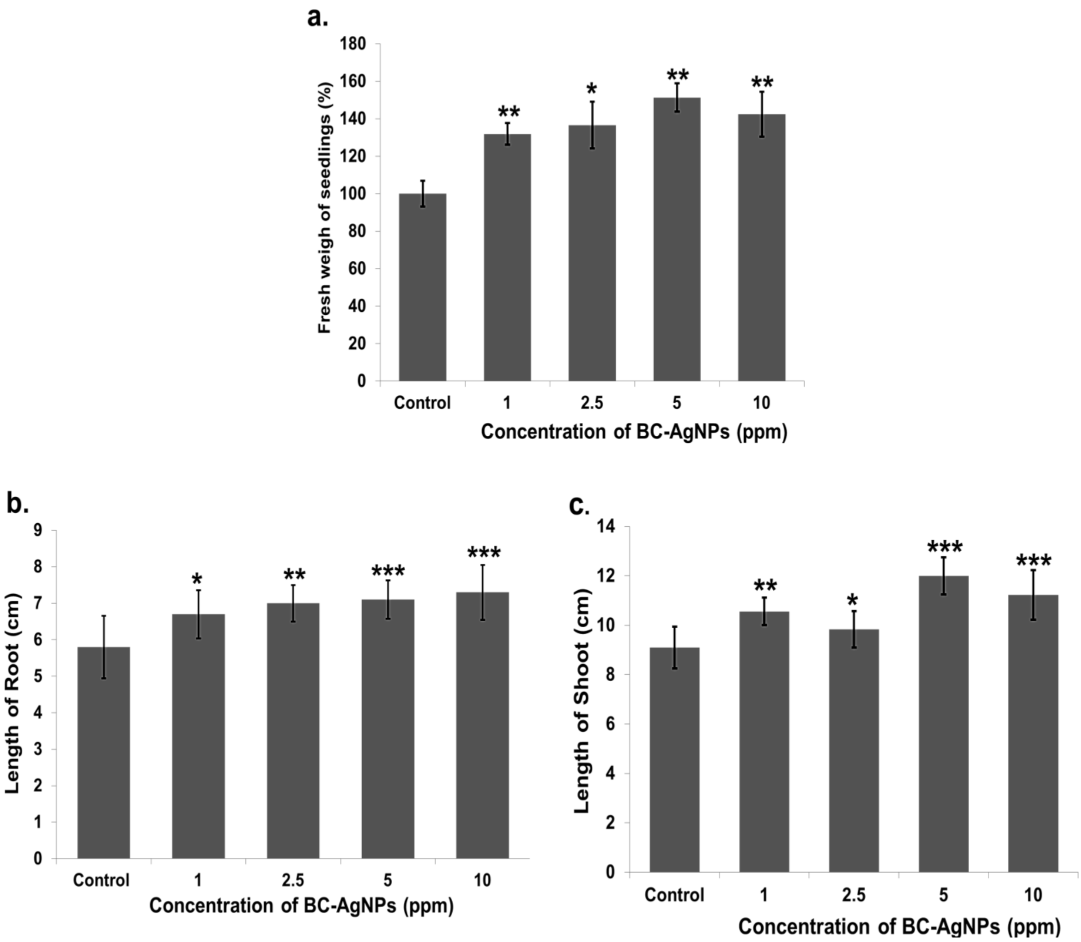

Figure 4. Effect of BC-AgNPs treatment on (a) Fresh weight (b) Root length (c) Shoot length in *V. radiata* seedlings (* represents P ≤ 0.05, ** represents P ≤ 0.01, *** represents P ≤ 0.001).

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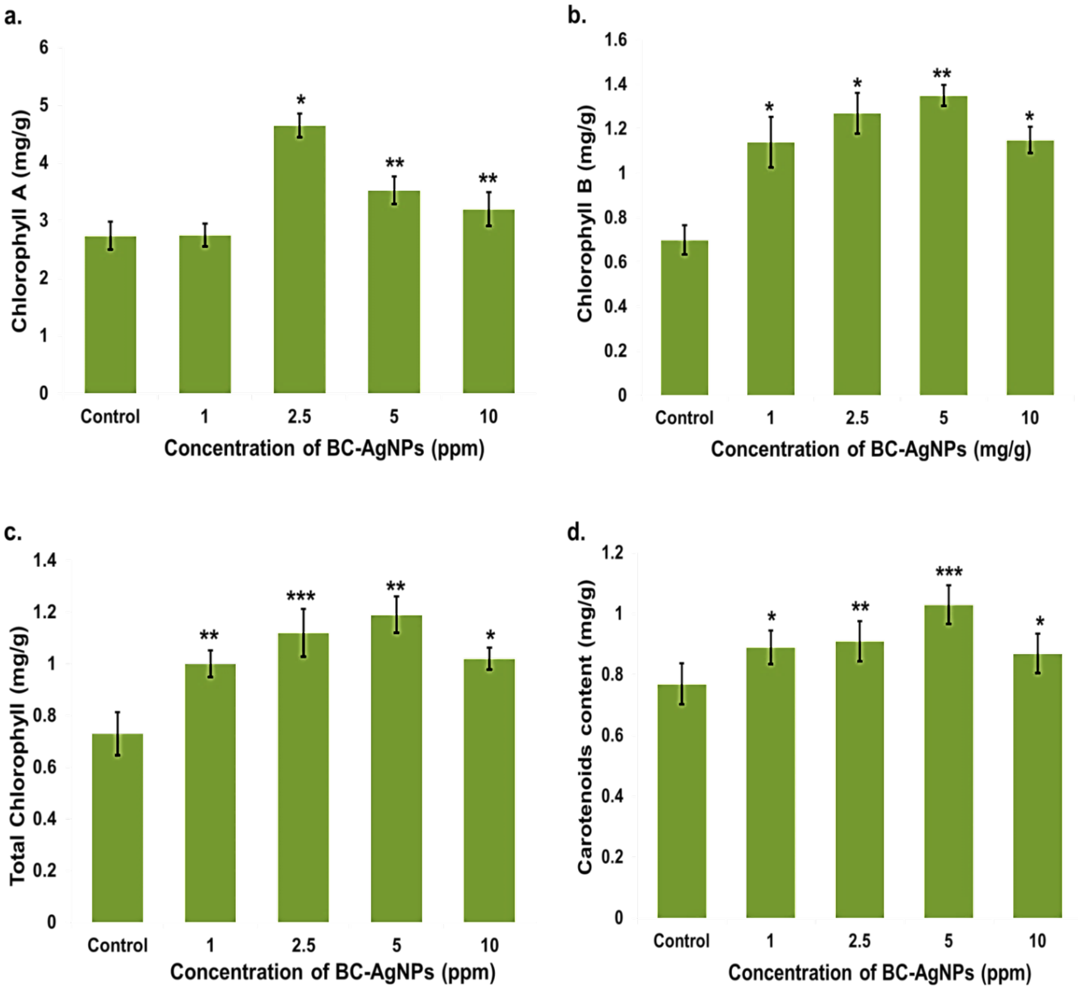

Figure 5. Effect of BC-AgNPs on photosynthetic pigments such as (a) Chlorophyll a (b) Chlorophyll b (c) Total chlorophyll (d) Carotenoids content in *V. radiata* seedlings (* represents P ≤ 0.05, ** represents P ≤ 0.01, *** represents P ≤ 0.001).

peanut leaves, tobacco and *Vicia faba* [68, 69], however, other studies report that at optimal concentrations, AgNPs may enhance photosynthetic activity and promote growth in terrestrial plants [64, 70, 71]. This contrast highlights the importance of concentration and exposure conditions in determining the effects of AgNPs on plant physiology. According to research by Zhou et al., [72], a high level of photosynthetic pigments means a high rate of photosynthesis, which promotes plant growth and results in an increase in the wet weight of plants as seen in our study.

Application of BC-AgNPs on plants revealed that it induces the synthesis of proteins and carbohydrates, as seen in the concentration of protein in BC-AgNPs treated seedlings. From the results (Fig. 6 a), we observed a higher amount of protein in BC-AgNPs treated seedlings, with the highest at 5 ppm when compared to the control. Exposure to AgNPs has been shown to induce the expression of genes encoding antioxidant enzymes and other stress-related proteins, potentially leading to an overall increase in protein levels [73]. Also, in this analysis, a high concentration of carbohydrates in BC-AgNPs treated leaves is noted in 5 ppm treated leaves of seedlings (Fig. 6 b) which could be due to enhanced photosynthetic activity leading to increased production of photosynthates [74]. Additionally, AgNP exposure has been associated with the modulation of metabolic pathways, potentially resulting in the accumulation of carbohydrates as a stress response mechanism [75]. Previous work found that biosynthesized AgNPs showed a significant effect on seed germination and induced the synthesis of protein and carbohydrate of black gram and mung bean [66, 76], other studies showed that AgNPs increased plants' growth profile and biochemical attributes including chlorophyll, carbohydrate and protein contents of fenugreek, common bean, corn and sunflower [4, 32]. It is important to note that an appropriate concentration of silver nanoparticles is needed to achieve proper seed germination, plant growth, and improved biochemical parameters.

3.4 Antifungal analysis

Fungal plant diseases are responsible for the destruction of approximately one-third of the world's food crops annually, leading to significant economic losses and increased global poverty. Research suggests that if these losses were effectively managed, around 8.5% of the global population of 7 billion in 2011 could have been

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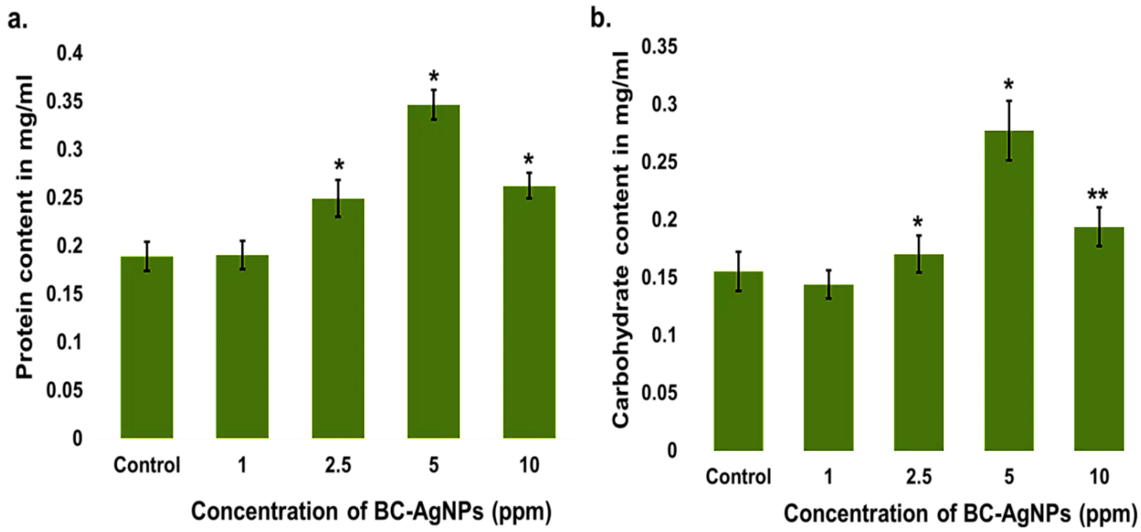

Figure 6. (a) Effect of BC-AgNPs on protein content (b) Effect of BC-AGNPS on carbohydrate content in *V. radiata* seedlings (* represents P ≤ 0.05, ** represents P ≤ 0.01).

adequately fed [77].

The findings of this study demonstrated that BC-AgNPs exhibited stronger inhibitory effects against *P. janthinellum* than fluconazole over a three-day period in a dose-dependent manner (Fig. 7). Furthermore, on the 9th day, radial growth of fungi observed in the untreated control plates (Fig. 8 a) was measured as 6.8 mm, whereas plates treated with fluconazole (Fig. 8 b) showed growth of 3.0 mm, while plates treated with 6.25 µg/mL (Fig. 8 c), 12.5 µg/mL (Fig. 8 d), 25 µg/mL (Fig. 8 e), and 50 µg/mL (Fig. 8 f) of BC-AgNPs exhibited further reductions in fungal growth compared to the controls. At the highest concentration of 100 µg/mL, fungal growth was almost entirely inhibited, with a radial growth of less than 0.2 mm (Fig. 8 g).

Several other studies have demonstrated the antifungal activity of biosynthesized silver nanoparticles (AgNPs) produced by endophytic microorganisms against various plant pathogens. Some of which are the use of biosynthesized AgNPs from using the endophytic bacterium *Pseudomonas poae* strain CO against *Fusarium graminearum*, the causative agent of Fusarium head blight in wheat [78]. Another study reported the biosynthesis of AgNPs from endophytic bacteria isolated from *Allium cepa*, which effectively inhibited the growth of *Magnaporthe oryzae*, the pathogen responsible for rice blast disease [79]. While the exact antifungal mechanism of silver nanoparticles is not fully known, studies have suggested that AgNPs exert antifungal effects by disrupting fungal cell membranes, leading to structural disintegration and inhibition of normal budding processes in fungi [77, 80].

4. Conclusion

As the world population is projected to increase exponentially in the coming years, the development of alternative

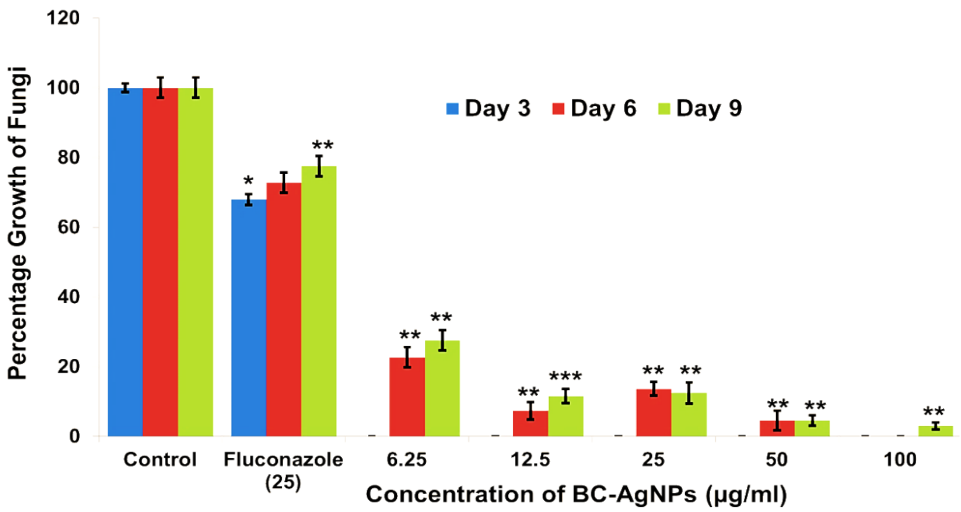

Figure 7. Percentage growth of *Penicillium janthinellum* after three consecutive days of inoculation after treatment with BC-AgNPs (* is P ≤ 0.05, ** is P ≤ 0.01).

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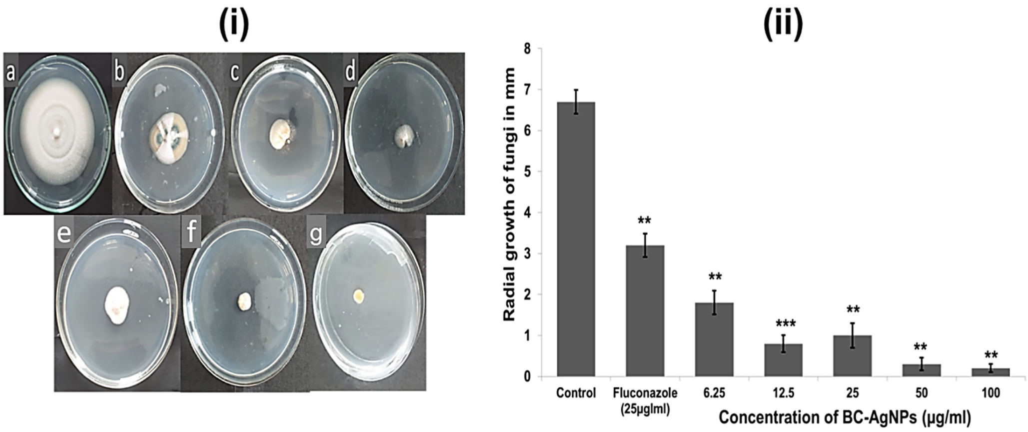

Figure 8. (i) Antifungal activity of BC-AgNPs against *Penicillium janthinellum* after 9 days of growth: (a) Untreated Control (b) Treated control with fuconazole (c) Treatment with BC-AgNPs at 6.25 µg/mL (d) Treatment with BC-AgNPs at 12.5 µg/mL (e) Treatment with BC-AgNPs at 25 µg/mL (f) Treatment with BC-AgNPs at 50 µg/mL (g) Treatment with BC-AgNPs at 100 µg/mL (ii) Growth of *Penicillium janthinellum* measured after 9 days (** represents $P \leq 0.01$, *** represents $P \leq 0.001$).

strategies to enhance crop growth and yield has become essential. Agricultural application of nanoparticles is presently being explored for effective crop production while minimizing the use of chemical fertilizer. The use of nano-primed methods for seed and plant germination have shown promise; however, their effectiveness depends on factors such as nanoparticle concentration, plant species, and the substrate used for AgNP synthesis. This study successfully demonstrated the biosynthesis of silver nanoparticles (AgNPs) using endophytic *B. cereus* isolated from *Nyctanthes arbor-tristis* and evaluated their role in the agricultural sector. The application of BC-AgNPs in *Vigna radiata* resulted in improved seed germination, promote plant growth and increased biochemical constituents. In addition, BC-AgNPs exhibited strong antifungal activity against *P. janthinellum*, highlighting their potential as an alternative to chemical fungicides. The findings suggest that BC-AgNPs can serve as a dual-function agent in sustainable agriculture – both as a plant growth enhancer and as a biocontrol agent.

Despite these promising results, the study has some limitations; The short experimental duration (5-day germination period), the use of controlled laboratory conditions, and the focus on a single plant species, indicate the need for further research. Future studies should aim to conduct long-term experiments across diverse crop species under field conditions to assess the wider agricultural applicability of BC-AgNPs. Moreover, further research is also needed to investigate the molecular mechanisms by which AgNPs enhance photosynthesis, nutrient uptake, and disease resistance. Understanding these pathways will pave the way for large-scale agricultural applications of biosynthesized nanoparticles, contributing to sustainable and eco-friendly farming practices.

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Authors contributions
SH: conceptualization, supervision, validation, Writing – review and editing. LEM: Methodology, investigation, validation, formal analysis, writing – original draft. All authors have read and agreed to submit this manuscript for publication.

Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the paper.

Conflict of interests
The authors assert that they do not have any identifiable conflicting financial interests or personal relationships that might be perceived to influence the work presented in this paper.

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