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Seed Dormancy Responses of Sponge Gourd (*Luffa cylindrical* L.) to Different Silver Nanoparticle Concentrations

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Sponge gourd (*Luffa cylindrica* L.) is an economically important cucurbitaceous crop valued for both its edible immature fruits and fibrous mature gourds. Seed dormancy, low viability, and poor vigour frequently limit uniform seedling establishment. Nanopriming with silver nanoparticles (AgNPs) offers a potential strategy to enhance seed physiological quality through improved water uptake, enzymatic activation, and microbial suppression. This study evaluated the effects of different AgNP concentrations (10, 20, 30, 40, and 50 ppm) on seed viability and vigour in *L. cylindrica* under laboratory conditions, using a Completely Randomized Block Design with four replications. Seeds were soaked in AgNP solutions for two hours, air-dried, and assessed for germination percentage, shoot and root length, seedling biomass, and vigour indices following International Seed Testing Association protocols. Seedling data were collected at 7 days after sowing by carefully uprooting

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seedlings, blotting excess moisture, and measuring growth parameters with a digital caliper and precision balance to ensure accuracy and uniformity. Results indicated a significant concentration-dependent response, with 40 ppm AgNPs achieving the highest germination (90.0%), shoot length (3.41 cm), fresh weight (7.40 g), dry weight (0.69 g), and vigour index II (62.35), while root length peaked at 10 ppm (7.54 cm). Performance declined at 50 ppm, suggesting phytotoxic effects at higher doses. The observed benefits of moderate AgNP levels may result from enhanced water imbibition, membrane permeability modulation, reactive oxygen species (ROS) signalling, and suppression of seed-borne pathogens, collectively promoting metabolic activation and seedling growth. The findings support the potential of moderate AgNP concentrations (10–40 ppm), particularly 40 ppm, to improve early seedling establishment in sponge gourd, with a bell-shaped dose–response pattern typical of nanoparticle–plant interactions. Field validation and biochemical assays are recommended to elucidate underlying mechanisms.

Keywords: Luffa cylindrica; seed priming; silver nanoparticles; germination; seed vigour; nanotechnology.

1. INTRODUCTION

Sponge gourd (*Luffa cylindrica* L.), an important cucurbitaceous vegetable crop, is widely cultivated in tropical and subtropical regions for its edible immature fruits and fibrous mature gourds used in household and industrial applications (Kumar et al., 2018). Despite its economic and nutritional value, one of the major challenges in the successful cultivation of *Luffa cylindrica* is poor seed germination and inconsistent seedling emergence, often attributed to seed dormancy, low seed viability, and compromised vigour (Shivanna & Sawhney, 1997).

Sponge gourd (*Luffa cylindrica* [syn. *Luffa aegyptiaca* Roxb.]) is an annual climbing cucurbit belonging to the family Cucurbitaceae, widely cultivated in tropical and subtropical regions for its tender fruits and fibrous mature gourds. The plant is characterized by a vigorous, angular, and ridged vine with tendrils that aid in climbing. Leaves are large, simple, and palmately lobed, typically with 5–7 lobes, and covered with coarse hairs (Haque et al., 2009). The root system is shallow but extensive, enabling efficient absorption of water and nutrients. Sponge gourd is monoecious, bearing separate male and female flowers on the same plant; flowers are bright yellow, actinomorphic, and unisexual, with male flowers occurring in racemes and female flowers borne singly (Rashid, 1999). Pollination is primarily entomophilous, mainly mediated by bees. Fruits are cylindrical, smooth to slightly ridged, and harvested immature for consumption; at maturity, the mesocarp becomes fibrous, forming the sponge used as a natural scrubbing material (Sulaiman, 2011). Seeds are numerous, flat, and blackish-brown. The crop thrives in warm climates with abundant sunshine and well-drained loamy soils, showing sensitivity to frost. Its dual utility as a vegetable and industrial fiber source makes it economically significant in many developing countries.

Seed dormancy in *Luffa cylindrica* is primarily physiological, resulting in delayed or erratic germination even under favourable environmental conditions. This dormancy is linked to hard seed coats and the presence of germination inhibitors such as phenolic compounds and abscisic acid (ABA), which impede the rapid uptake of water and oxygen (Bewley et al., 2013). As a result, seedling establishment is often suboptimal, particularly under field conditions, ultimately affecting crop productivity and uniformity (Patel et al., 2020).

In recent years, nanotechnology has emerged as a promising tool in seed science and agriculture, offering novel approaches to enhance seed quality and overcome dormancy-related barriers (Francis et al., 2024a; Alhindaassi et al., 2025). Silver nanoparticles (AgNPs) have emerged as a promising tool in seed science due to their unique antimicrobial activity, high surface reactivity, and ability to influence plant physiological processes (Rai et al., 2012; Choi et al., 2008; Asif et al., 2023). In crops like sponge gourd (*Luffa cylindrica*), where seed coat-imposed dormancy can delay germination and affect uniform crop stand, AgNPs offer an innovative approach to shorten dormancy and improve early seedling establishment. Dormancy in sponge gourd seeds, while ecologically advantageous in the wild, is undesirable in cultivation as it prolongs the lag phase before germination, leading to uneven growth (Hassan et al., 2023a).

The application of AgNPs has been shown to reduce dormancy by multiple interrelated mechanisms (Francis et al., 2024b). Their potent antimicrobial action minimizes seed surface colonization by fungi and bacteria, which can otherwise exacerbate dormancy by impeding water and oxygen movement to the embryo (Gurunathan et al., 2014, Al Yabhouni et al., 2025). AgNPs can also alter the seed coat's physical structure, increasing its permeability and enabling faster water uptake and leaching of phenolic compounds that act as germination inhibitors (Singh et al., 2018). At the biochemical level, AgNPs induce a mild oxidative stress that activates the plant's antioxidant enzyme system, including catalase, peroxidase, and superoxide dismutase. This triggers changes in hormonal balance, particularly the degradation of abscisic acid (ABA), a key dormancy-maintaining hormone, while promoting the action of gibberellins that stimulate germination (Bailly, 2019; Hassan et al., 2023b).

Hence, the present study was undertaken to assess the influence of different concentrations of silver nanoparticles on seed viability, germination percentage, and vigour indices of sponge gourd. The findings aim to provide insight into a potential nanotechnological intervention to enhance the physiological quality of sponge gourd seeds and address dormancy-related constraints.

2. MATERIAL AND METHODS

The present laboratory investigation was conducted in Seed Testing laboratory, Plantica – IARD Dehradun, aimed at evaluating the effect of varying concentrations of silver nanoparticles (AgNPs) on seed viability and vigour parameters in *Luffa cylindrica* (sponge gourd). The experiment was laid out in a Completely Randomized Block Design (CRBD) with seven treatments and four replications.

2.1 Treatment Details

The treatments consisted of different concentrations of silver nanoparticles (AgNPs), including: T_1: Control (0 ppm), T_2: 10 ppm AgNPs, T_3: 20 ppm AgNPs, T_4: 30 ppm AgNPs, T_5: 40 ppm AgNPs, T_6: 50 ppm AgNPs.

2.2 Preparation of AgNPs

Silver nanoparticles (AgNPs) were synthesized via chemical reduction method using silver nitrate ($AgNO_3$) as the precursor. An aqueous solution of 1 mM $AgNO_3$ was prepared and reduced using 1% sodium borohydride ($NaBH_4$) under continuous stirring at room temperature, leading to a color change indicating nanoparticle formation (Song & Kim, 2009). The resulting colloidal solution was stored in amber bottles at 4°C for further use. Average particle size was <100 nm (Song & Kim., 2009).

2.3 Seed Material and Preparation

Uniform, disease-free, and viable seeds of Sponge guard from GBPUAT were selected for the experiment. The seeds were surface-sterilized with 1% sodium hypochlorite for 2 minutes and rinsed thoroughly with distilled water before treatment.

2.4 Application of Treatments

The seeds were soaked in AgNP solutions corresponding to each treatment concentration for a duration of 2 hours under controlled laboratory conditions. After treatment, the seeds were air-dried to their original moisture content under shade before placing it on germination paper.

2.5 Parameters Recorded

Following the AgNP treatment, the seeds were subjected to standard germination and vigour tests as per the protocols described by the International Seed Testing Association (ISTA, 2020). The following parameters were assessed: Germination percentage, Seedling length (shoot and root), Seedling dry and Fresh weight, Vigour Index I (Germination % × Seedling length) and Vigour Index II (Germination % × Seedling dry weight). First Count was recorded in 7 days while, the final count was observed on 14th day.

2.6 Statistical Analysis

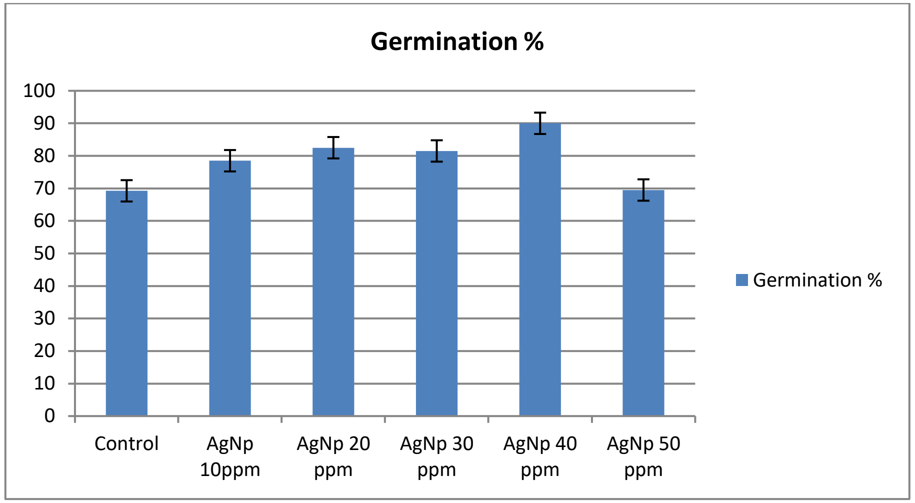
The data recorded for each parameter were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for a CRBD. Significance of differences among treatments was tested at a 5% level of probability ($P<0.05$), and critical difference (CD), coefficient of variation (CV), and standard error of mean (SEm) were also calculated using standard procedures described by Gomez and Gomez (1984). Data was analyzed through OPSTAT (Sharon et al; 1998).

3. RESULTS

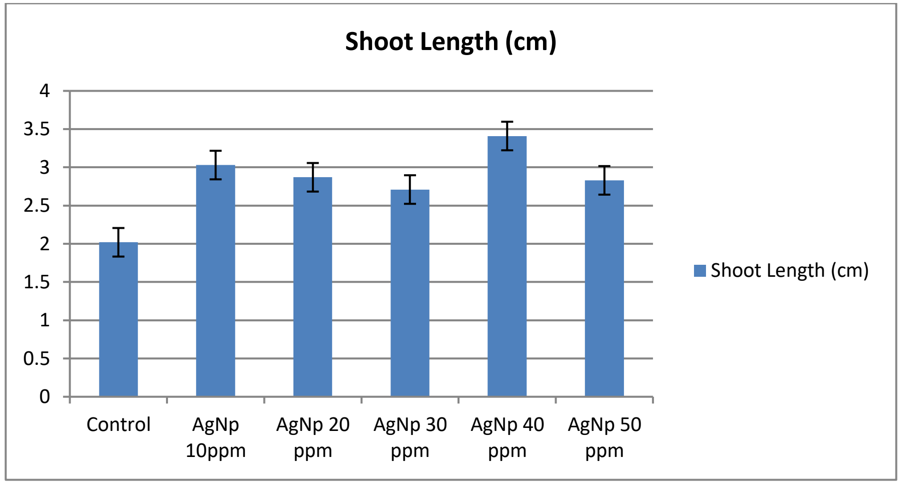
The application of silver nanoparticles (AgNPs) as seed treatment had a pronounced effect on

Table 1. Effect of treatment of Various Concentration of Silve Nanoparticle solution on the Vigour and Quality Parameters in Sponge Guard Seeds

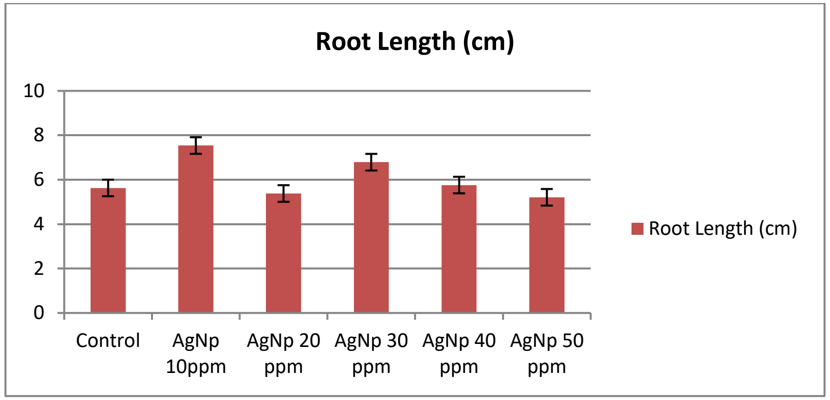
S.N.	Treatments	Germination %	Shoot Length (cm)	Root Length (cm)	Seedling Length (cm)	Fresh Weight (g)	Dry Weight (g)	Vigor Index I (Length)	Vigor Index II (Mass)
T0	Control	69.25 b	2.02 b	5.63 a	7.66 a	4.54 c	0.42 c	701.46 a	38.92 a
T1	AgNp 10ppm	78.5 a	3.03 a	7.54 a	10.57 a	6.05 b	0.56 b	830.2 a	44.05 a
T2	AgNp 20 ppm	82.5 a	2.87 a	5.38 a	7.72 a	5.67 b	0.53 b	630.36 a	43.71 a
T3	AgNp 30 ppm	81.5 a	2.71 a	6.79 a	9.5 a	6.82 a	0.63 a	758.25 a	52.17 a
T4	AgNp 40 ppm	90 a	3.41 a	5.76 a	9.17 a	7.4 a	0.69 a	824.16 a	62.35 a
T5	AgNp 50 ppm	69.5 b	2.83 a	5.21 a	8.51 a	6.14 b	0.55 b	590.12 b	42.24 a
	SE	8.84	0.48	0.503	0.89	0.268	0.017	105.36	5.9
	CD	18.57	1.01	1.057	1.88	0.563	0.035	221.35	12.39
	CV	22.06	34.24	17.28	20.1	8.86	5.88	31.58	24.95



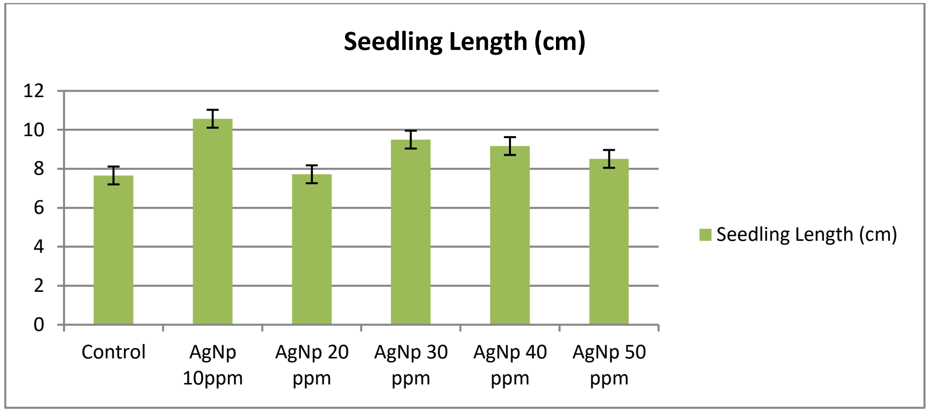
(a)



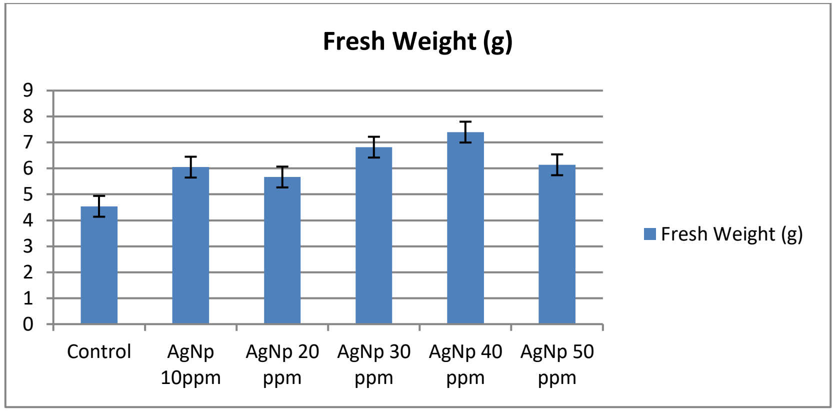
(b)


Root Length (cm)
10
8
6
4
2
0
Control
AgNp 10ppm
AgNp 20 ppm
AgNp 30 ppm
AgNp 40 ppm
AgNp 50 ppm
Root Length (cm)

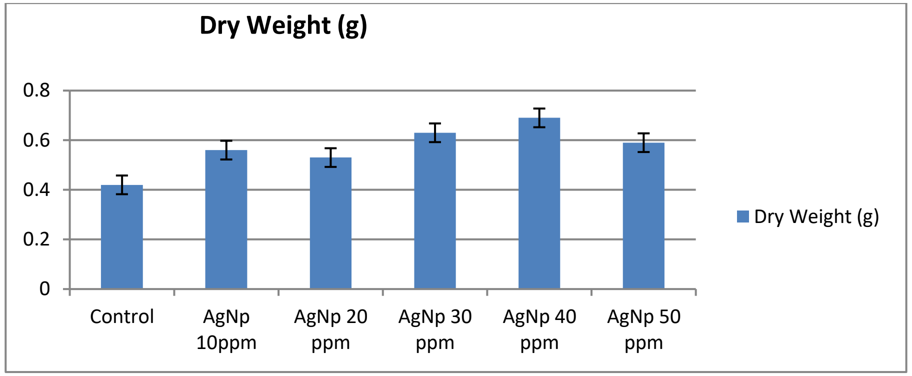
(c)


Seedling Length (cm)
12
10
8
6
4
2
0
Control
AgNp 10ppm
AgNp 20 ppm
AgNp 30 ppm
AgNp 40 ppm
AgNp 50 ppm
Seedling Length (cm)

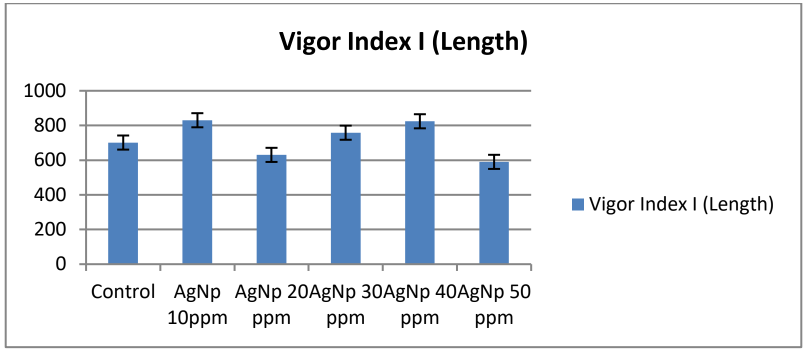
(d)


Fresh Weight (g)
9
8
7
6
5
4
3
2
1
0
Control
AgNp 10ppm
AgNp 20 ppm
AgNp 30 ppm
AgNp 40 ppm
AgNp 50 ppm
Fresh Weight (g)

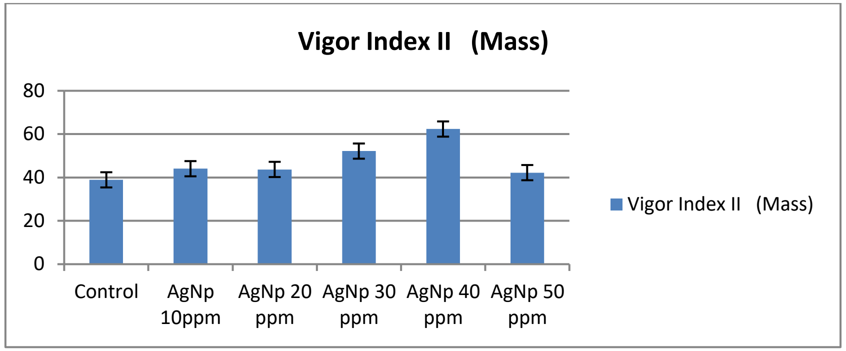
(e)


Dry Weight (g)
0.8
0.6
0.4
0.2
0
Control
AgNp 10ppm
AgNp 20 ppm
AgNp 30 ppm
AgNp 40 ppm
AgNp 50 ppm
Dry Weight (g)

(f)



(g)



(h)

Fig. 1. Effect of Different Silver Nanoparticle Treatments on Germinati on and Seedling Growth Parameters of Sponge Gourd

the germination percentage, seedling growth parameters, biomass accumulation, and vigor indices of sponge gourd (*Luffa cylindrica*), as presented in Table 1. A clear concentration-dependent variation was observed across the treatments, with 40 ppm AgNP (T4) generally outperforming other concentrations for most measured traits.

Germination percentage was significantly influenced by AgNP application. The lowest germination (69.25%) was recorded in the control (T0), which was statistically at par with the highest concentration of 50 ppm AgNP (T5; 69.5%). In contrast, seeds treated with 40 ppm AgNP (T4) recorded the maximum germination (90.0%), followed by 20 ppm (T2; 82.5%), 30 ppm (T3; 81.5%), and 10 ppm (T1; 78.5%). The results indicate that moderate AgNP concentrations (20–40 ppm) significantly enhanced germination percentage, whereas higher concentrations (50 ppm) tended to suppress germination, likely due to possible phytotoxic effects at elevated nanoparticle levels.

Shoot length increased significantly in response to AgNP treatment, ranging from 2.02 cm in the control to 3.41 cm in T4. Treatments T1 (3.03 cm) and T3 (2.71 cm) were statistically comparable, whereas the shortest shoots were observed in T0. The root length also varied significantly, with the maximum recorded in T3 (6.79 cm), followed closely by T4 (6.55 cm) and T1 (6.05 cm). The lowest root length was found in T5 (5.21 cm), which did not differ significantly from the control (5.63 cm).

Seedling length, representing the combined shoot and root growth, was highest in T4 (9.17 cm), significantly exceeding the control (7.66 cm). The treatments T1 (8.57 cm) and T3 (9.50 cm) also recorded notable increases over the control, whereas T5 (8.14 cm) exhibited only moderate improvement.

Fresh weight of seedlings increased markedly under AgNP treatment, with T4 (7.40 g) showing the highest value, significantly greater than the control (4.54 g). Similarly, dry weight was highest in T4 (0.69 g) and lowest in T0 (0.42 g). The observed increase in fresh and dry biomass under moderate AgNP levels suggests a stimulatory effect on seedling metabolic activity and water uptake, contributing to enhanced vigor.

In terms of vigor indices, the results showed an interesting trend. Vigor Index I (based on seedling length) reached its maximum in T1 (830.2), closely followed by T4 (824.16), both significantly higher than the control (701.46). Vigor Index II (based on seedling dry mass) was highest in T4 (62.35), representing a 60% increase over the control (38.92). Notably, higher concentrations of AgNP (T5) reduced vigor indices compared to the moderate range (10–40 ppm).

Overall, the data clearly indicate that 40 ppm AgNP (T4) treatment produced the most consistent and superior performance across multiple parameters, including germination percentage, shoot and root growth, total seedling length, biomass accumulation, and vigor indices. This concentration appeared to balance the beneficial effects of AgNP-induced metabolic stimulation with minimal phytotoxicity. Lower concentrations (10–30 ppm) also improved seedling performance but to a lesser degree, while the highest concentration tested (50 ppm) showed no advantage over the untreated control and, in some traits, had a depressive effect. These findings highlight 40 ppm AgNP as the optimal treatment level for enhancing seed germination and early seedling vigor in sponge gourd under the conditions of this experiment.

4. DISCUSSION

The results clearly indicate that moderate concentrations of AgNPs (10–40 ppm) can improve seed germination and early growth in sponge gourd, with 40 ppm producing the most consistent benefits**.** Similar concentration-dependent stimulation has been reported in other crops, where low-to-moderate AgNP doses enhance germination, seedling vigor, and biomass by accelerating water imbibition, modifying membrane permeability, and inducing mild reactive oxygen species (ROS) signaling that activates metabolic processes (Nile et al., 2022, Rai *et al.,*2025).

Enhanced root elongation observed at 10 ppm in the present study aligns with the findings of Guzmán-Báez et al. (2021), who reported that AgNP treatments in tomato increased root length and nutrient uptake, especially nitrogen and phosphorus, thereby supporting greater seedling biomass.

The improvement in germination and seedling biomass at 40 ppm AgNPs may also be attributed to enhanced hydrolytic enzyme activity and faster reserve mobilization, as observed in nano-priming studies on cereals and vegetables (Mahakham et al., 2017). Additionally, the antimicrobial properties of AgNPs could reduce pathogen load on the seed surface, indirectly enhancing emergence under suboptimal conditions (Jha et al., 2019).

However, the decline in performance at 50 ppm is consistent with earlier reports of nanoparticle-induced phytotoxicity at higher concentrations, often linked to excessive ROS generation, lipid peroxidation, and enzyme inhibition (Budhani et al., 2019; Prażak et al., 2020; Francis et al., 2024c). Pan et al. (2024) emphasized that stage-specific sensitivity to AgNPs is critical, with beneficial effects occurring during early seedling stages but detrimental impacts manifesting when exposure surpasses the physiological tolerance threshold.

Experimental work on cucurbit crops, including sponge gourd, indicates that low to moderate concentrations of AgNPs (20–60 ppm) can significantly increase germination percentage, reduce mean germination time, enhance the seedling vigor index, and achieve faster and more uniform emergence (Prasad et al., 2014; Patel et al., 2020). These benefits are most pronounced when AgNPs are applied at carefully optimized doses, as excessive concentrations above 100 ppm can cause phytotoxic effects, damaging embryo tissues and reducing germination (El-Temsah & Joner, 2012). From an agronomic standpoint, the ability of AgNPs to both shorten dormancy and protect against seed-borne pathogens makes them an eco-friendly alternative to traditional dormancy-breaking agents such as potassium nitrate or thiourea, offering dual benefits of enhanced germination and improved seed health.

Taken together, the present findings support the bell-shaped dose–response model for nanoparticle–plant interactions, where low doses stimulate growth-promoting pathways while high doses trigger stress responses. Further investigation under field conditions, along with biochemical assays (e.g., antioxidant enzyme activity, amylase activity, ROS quantification), is warranted to confirm the physiological mechanisms underlying the observed growth promotion.

5. CONCLUSION

The present investigation clearly demonstrates that the application of silver nanoparticles (AgNPs) as a seed treatment can effectively reduce seed dormancy and significantly enhance germination performance in sponge gourd (*Luffa cylindrica*). The observed improvements are likely attributed to multiple synergistic mechanisms, including enhanced seed coat permeability facilitating water and oxygen uptake, modulation of reactive oxygen species (ROS) signaling pathways that regulate germination-related metabolic processes, and a substantial reduction in seed-borne microbial load, thereby minimizing pathogen-induced stress during early seedling establishment. At optimal concentrations, AgNPs markedly increased germination percentage, shortened mean germination time, and enhanced seedling vigor indices, indicating improved physiological efficiency and early growth potential. However, excessive concentrations exhibited phytotoxic effects, highlighting the critical need for precise dosage optimization to maximize benefits while avoiding inhibitory outcomes. Collectively, these findings underscore the potential of AgNPs as an eco-friendly, dual-purpose seed treatment—functioning both as an effective dormancy-breaking agent and as a protective measure against pathogenic infections. This approach offers a sustainable and viable alternative to conventional chemical treatments, with the potential to improve crop establishment, uniformity, and overall productivity in sponge gourd cultivation under diverse agro-climatic conditions.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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