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Effect of green synthesized silver and copper nanoparticles on seed quality of greengram

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Abstract
Seed priming is a pre sowing technique aimed at enhancing germination per cent, root and shoot length by controlled seed hydration. In this investigation, the potential impact of silver (Ag) and copper (Cu) nanoparticles on seed quality improvement in greengram (*Vigna radiata* LR Wilczek) was explored. Greengram seeds were subjected to priming treatments utilizing various concentrations of Ag and Cu nanoparticles (50, 75, 100, 125 and 150 ppm) for distinct priming durations ranging from 1 to 3 hours. A control group of untreated seeds was incorporated for comparative analysis. Evaluation of primed seeds encompassed multiple seed quality parameters, such as germination (%), root length, shoot length and SVI (Seedling Vigour Index). The optimization of nanoparticle concentration emerged as a pivotal factor in establishing the most effective priming treatments for subsequent investigations. Equally significant was the standardization of soaking duration to determine the optimal time for promoting accelerated and uniform germination. Irrespective of priming durations and concentrations, all Nano primed seeds demonstrated higher germination per cent, root and shoot length and seedling vigor index in comparison to the control group. Particularly, seeds primed with 50 ppm copper nanoparticles, exhibited significantly higher germination percentage (99.33%), extended root length (26.09 cm), increased shoot length (16.91 cm) and elevated SVI (4271). This performance was on par with seeds primed using 150 ppm Ag nanoparticles. Among the different priming durations, 1 hour proved optimal for copper nanoparticles, displaying significant superiority over priming durations of 2 and 3 hours. Similarly, a priming duration of 3 hours exhibited optimal outcomes for silver nanoparticles, revealing substantial differentiation from other priming durations.

Keywords: Copper nanoparticles, green synthesis, seed quality, silver nanoparticles

Introduction
One of the extremely promising 21st-century technologies that can potentially meet the demands of agriculture is nanotechnology, or nanotech in brief. It would be worth mentioning here that the European Commission has revered this technology as one of six “key enabling technologies” for sustainability in different areas (EC, 2012). Advancements in nanotechnology research have the potential to enhance agricultural productivity, soil quality, efficient water utilization, food preservation, and food quality, all of which are fundamental factors in ensuring food security. The term "Nano" is derived from the Greek word for "dwarf." It signifies an incredibly small scale, where one nanometer equals 10^{-9} meters, approximately 250 millionth of an inch or roughly $8x10^{-4}$ times the diameter of a human hair. Nanotechnology is considered as "a scientific, engineering, and technological study to define the nanomaterial at the nanoscale level, where distinctive effects allow new and more effective utilization in a wide variety of fields, from biology to medicinal science, agriculture, chemistry, physics and electronics" (www.nano.gov). In essence, nanotechnology hinges on two fundamental aspects. The first is the consideration of scale, concentrating on the precise control of structures at nanometer dimensions. The second aspect revolves around novelty, emphasizing the strategic utilization of properties stemming from the nanoscale characteristics of these materials (Allhoff, 2007) [3].
Nanotechnology has the potential to significantly contribute to the transformation of agriculture through the development of creative solutions for sustainable food production. Nanotechnology offers various potential applications within the field of agriculture such as precision agriculture, targeted delivery of nutrients and pesticides, soil remediation, food safety and crop improvement. Overall, nanotechnology has the potential to transform agriculture by creating innovative solutions that are more sustainable, efficient and effective.

However, it is important to ensure that the application of nanotechnology in agriculture is safe and environmental friendly. The biological effectiveness of nanoparticles was shown to increase proportionally with an increase in their specific surface area. This phenomenon is attributable to the increase in their surface energy, amplified catalytic reactivity and consequential alterations in their physical, mechanical, optical and electromagnetic characteristics (Okuda *et al.*, 2005; Choi *et al.*, 2007 and Pradeep and Anshup, 2009) [25, 8, 27].

Silver nanoparticles (AgNPs) have garnered considerable attention owing to their robust surface plasmon resonance (SPR) characteristics. Because of their antimicrobial and antioxidant attributes, AgNPs have been employed as a seed coating to enhance seed quality properties (Nadagouda *et al.*, 2009) [22]. They hold immense promise for a diverse array of biological applications, including serving as antifungal agents, antibacterial agents effective against antibiotic-resistant bacteria, infection prevention, wound healing and anti-inflammatory treatments. Silver ions (Ag^+) and their compounds are profoundly detrimental to microorganisms, showcasing potent biocidal effects against a broad spectrum of bacteria, fungi and viruses.

Copper is undeniably one of the pivotal elements vital for the growth and development of plants. The utilization of copper nanoparticles (CuNPs) holds great promise in the realm of food packaging as a means to thwart the proliferation of food spoilage microorganisms. The incorporation of CuNP-infused agar materials into packaging has significant potential to prolong the shelf life of food products (Rai *et al.*, 2018) [28]. Furthermore, CuNPs have displayed potent fungicidal and insecticidal properties against crop pests, making them a compelling choice for the development of nano-pesticides, nano-herbicides and nano-fertilizers (El-Saadony *et al.*, 2020) [12].

Utilizing plant extracts for the bio-reduction of metal ions into nanoparticles has garnered significant attention. Plant-derived materials stand out as prime contenders for the synthesis of biocompatible nanoparticles, owing to the diverse biochemical makeup of plant extracts, the presence of non-toxic phytochemical components, lack of pathogenic attributes, cost-effectiveness, and the adaptable nature of reaction conditions when compared to conventional chemical synthesis approaches. Research has convincingly highlighted the pivotal role played by plant metabolites such as terpenoids, alkaloids, phenolic acids, sugars, polyphenols and proteins in the reduction of metal ions, subsequently ensuring the stability of the resultant nanoparticles. The synthesis of nanoparticles through plant extract-mediated routes not only ensures environmental safety but also promotes user well-being. By keeping in view-of the above-mentioned importance, the present research was designed with a novel, rapid and affordable route for bio-synthesis of AgNPs and CuNPs utilizing tulasi leaf extract. The synthesized AgNPs and CuNPs obtained by the green method was evaluated for their effect on seed quality enhancement in greengram.

Materials and Methods

The bio-synthesis of silver and copper nanoparticles took place at the Green Nanotechnology Laboratory, University of Agricultural Sciences (UAS), Dharwad. Analysis of seed quality parameters occurred at both the Department of Seed Science and Technology and the Seed Technology Research Unit, AICRP on Seed (Crops), Seed Unit. Seeds of greengram *var*. DGGV-2 used for the experiment was collected from the Seed Processing Unit of AICRP on Seed (Crops), University of Agricultural Sciences, Dharwad.

Green synthesis of silver nanoparticles through tulasi leaf extract

Usha *et al.* (2017) [34] reported that tulasi comprises components such as alkaloids, glycosides, tannins, saponins, and aromatic compounds. Additionally, it possesses minerals like calcium (Ca), manganese (Mn), copper (Cu), zinc (Zn), phosphorus (P), potassium (K), sodium (Na) and magnesium (Mg). Therefore, in the present research, aqueous extract of tulasi leaves (*Ocimum tenuiflorum* L.) acted as a source of bio-reduction and stabilizers for bio- synthesis of silver and copper nanoparticles.

Fresh tulasi leaves were collected from the campus of University of Agricultural Sciences, Dharwad. They were initially rinsed thoroughly with tap water to eliminate dust, followed by two washes with distilled water. Subsequently, the leaves were air-dried at room temperature to eliminate any residual moisture. For the extraction process, 25 grams of these dried tulasi leaves were combined with 500 milliliters of distilled water and subjected to boiling at 60 °C in a 1000 ml beaker for a duration of 30 minutes. The resulting leaf extract was allowed to cool down to room temperature, after which it was filtered through Whatman filter paper no. 1. The filtrate was then preserved by refrigerating it at 4 °C for future use. 0.3 grams of silver nitrate ($AgNO_3$) was dissolved in 1000 ml of distilled water to get 300 ppm of silver nitrate ($AgNO_3$) stock solution. For synthesis of silver nanoparticle, freshly prepared 50 ml of $AgNO_3$ stock solution was added drop wise to 50 ml of tulasi leaf extract in a 1:1 ratio by continuous stirring on magnetic stirrer at 60 ^oC for about 30 min. To confirm the formation of the AgNPs, bio-reduction of the silver ions in the medium was monitored by observing dark red colour (Fig. 1). The change in color serves as an indication of the silver nanoparticles' formation.

Green synthesis of copper nanoparticles through tulasi leaf extract

20 grams of Tulasi leaves were combined with 200 ml of distilled water and boiled for 30 minutes at 60 °C in a 500 ml beaker. The resulting leaf extract was allowed to cool to room temperature and then filtered through Whatman filter paper no. 1. The filtrate was stored in a refrigerator at 4 °C for future use. To create a 300 ppm copper sulfate stock solution, 0.3 grams of $CuSO_4.5H_2O$ was dissolved in 1000 ml of distilled water. A mixture containing $CuSO_4.5H_2O$ and the tulasi leaf extract in a 1.5:1 ratio was incubated in darkness at room temperature for approximately 60 minutes. A noticeable change in color, shifting from light green to dark green, served as an indicator of the formation of copper nanoparticles (Fig 1).

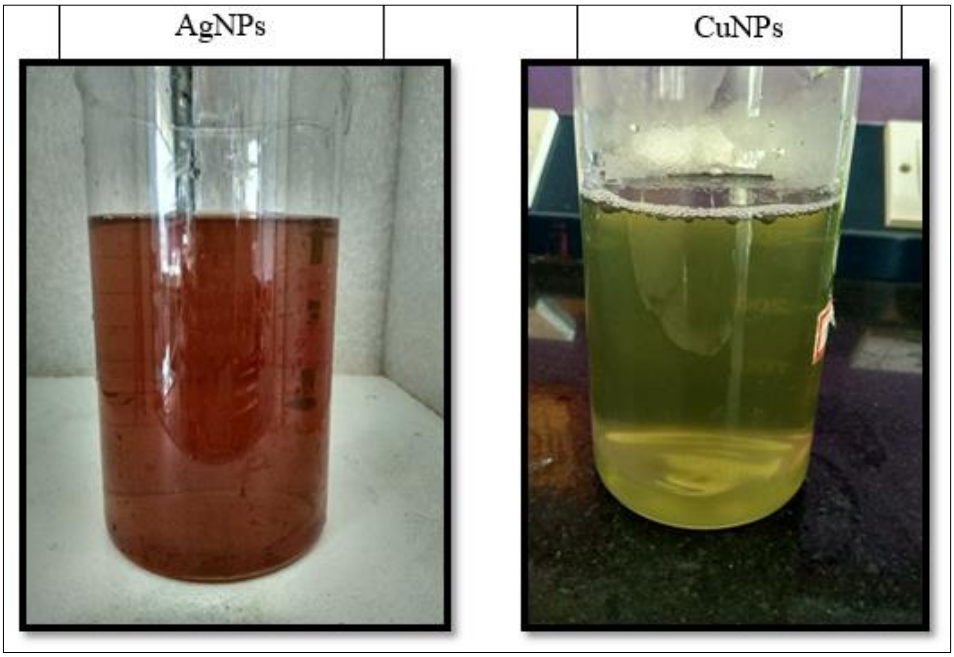

Fig 1: Colour change indicates formation of silver and copper nanoparticles

Seed priming

Seeds were subjected to priming in silver and copper nanosolutions at a seed-to-solution ratio of 1:2 (volume/volume). This process involved various durations, ranging from 1 to 3 hours, and concentrations, spanning from 50 to 150 ppm. Each experiment was conducted in triplicate using 100 seeds per replication. Once the priming period concluded, the nanosolution was drained from the seeds, which were then dried to their optimal moisture content. Subsequently, these treated seeds were employed for further assessment of various seed quality parameters.

Observations recorded

Seed Germination

A germination test was carried out using four separate replicates, each consisting of 100 seeds. The seeds were placed in rolled paper towels and placed inside a walk-in seed germination room maintained at a temperature of 25 ± 2 °C and a relative humidity of 90 ± 5 per cent. Seedling evaluation took place when the seedlings had reached a stage where all essential structures were fully developed. Sufficient time was allotted for the seeds to germinate and exhibit all the necessary structures indicating their potential to grow into healthy plants under favorable conditions. Seedlings meeting these criteria were considered normal seedlings, and their count was used to calculate the germination percentage. The number of normal seedlings in each replication was tallied at the end of the 7th day, and the germination percentage was calculated and expressed as a percentage, following the guidelines provided by ISTA (Anon, 2011) [6].

$$\text{Normal seedlings \%} = \frac{\text{Number of normal seedlings}}{\text{Total number of seeds}} \times 100$$

Root Length

From the germination test, ten random normal seedlings were chosen from each treatment in each replication on the 7th day. The measurement involved determining the length of the primary root, starting from its tip to the base of the hypocotyl. The average root length was then quantified and expressed in centimeters.

Shoot Length

From the germination test, ten randomly selected normal seedlings from each treatment within each replication were chosen on the 7th day. The measurement involved determining the length of the shoot, starting from the base of the primary leaf to the base of the hypocotyl. The average shoot length was then quantified and expressed in centimeters.

Seedling Vigour Index (SVI)

The vigour index was calculated by using the following formula and the result was expressed in number (Abdul-Baki and Anderson, 1973) [1].

Seedling vigour index = Germination % × [Shoot length (cm) + Root length (cm)].

Results

Effect of varied soaking durations and concentrations on seed nano-priming of Greengram

Seed germination

The impact of nano priming with silver and copper nanoparticles, synthesized using tulasi leaf extract, on the germination of greengram seeds was evaluated, and the results are presented in Table 1. The germination percentage of greengram seeds was significantly influenced by the concentrations of green-synthesized silver and copper nanoparticles as well as the duration of seed priming.

Significant variations in germination percentage was observed in greengram seeds nano primed with AgNPs at all tested concentrations (50, 75, 100, 125 and 150 ppm) compared to the control. Notably, the highest significant difference was found in seeds nano primed at 150 ppm for a duration of 3 hours (T_{15}-99%), which was on par to seeds primed with 125 ppm (T_{12}-98%) for 3 hours duration, when compared to control (T_{31}-90%). Similarly, greengram seeds nano primed with CuNPs at all concentrations (50, 75, 100, 125 and 150 ppm) exhibited significant variations in germination

percentage compared to the control. But, numerically highest significant difference was observed in seeds nano primed at 50 ppm for a duration of 1 hour (T_{16}-99.33%), which was on par with seeds primed with 75 ppm (T_{19}-98.67%) for about 1 hour duration, in comparison to control (T_{31}-90%).
Comparing seed germination between AgNPs and CuNPs priming, numerically higher per cent was recorded in seeds primed with CuNPs at 50 ppm for 1 hour soaking duration (T_{16}-99.33%), when compared to AgNPs 150 ppm for a duration of 3 hours (T_{15}-99%).

Shoot length
The data on effect of silver and copper nanoparticles bio-synthesized through tulasi leaf extract on shoot length is given in Table 1. The shoot length of greengram seeds was significantly influenced by the concentrations of green-synthesized silver and copper nanoparticles as well as the duration of seed priming.
Shoot length showed significant difference in seeds treated with silver nanoparticles, where the highest significant difference was found in seeds primed with 150 ppm for a duration of 3 hours (T_{15}-26.21 cm), which was on par with seeds primed with 125 ppm for 3 hours (T_{12}-26.19 cm) compared to control (T_{31}-23.40 cm). Similarly, seeds primed with CuNPs showed significant variation in shoot length. The highest significant difference was observed in seeds primed with 50 ppm for a duration of 1 hour (T_{16}-26.09 cm), which was on par with seeds primed at 75 ppm for 1 hour (T_{19}-26.03 cm) when compared to control (T_{31}-23.40 cm).
In comparing the effects of AgNPs and CuNPs, highest shoot length was observed numerically, in seeds primed with AgNPs at 150 ppm concentration for a soaking duration of 3 hours (T_{15}-26.21 cm), when compared to seeds primed with CuNPs at 50 ppm for 1 hour (T_{16}-26.09 cm).

Root length
The results on effect of silver and copper nanoparticles bio-synthesized through tulasi leaf extract on root length are represented in Table 1. The root length of greengram seeds was significantly influenced by the concentrations of green-synthesized silver and copper nanoparticles as well as the duration of seed priming.
Significant effect was observed on root development when seeds were nanoprimed with silver nanoparticles. The highest significant difference was found in seeds primed with 150 ppm for a duration of 3 hours (T_{15}-16.82 cm), which was on par with seeds primed with 125 ppm for 3 hours (T_{12}-16.79 cm) when compared to control (T_{31}-14.15 cm). Likewise, significant difference was observed on root length in seeds primed with 50 ppm for a duration of 1 hour (T_{16}-16.91 cm), which was on par with seeds primed at 75 ppm for 1 hour (T_{19}-16.85 cm), when compared to control (T_{31}-14.15 cm).
There was no significant difference on root length in seeds primed with AgNPs at 150 ppm for a soaking duration of 3 hours (T_{15}-16.82 cm) and seeds primed with CuNPs at 50 ppm for 1 hour (T_{16}-16.91 cm).

Seedling vigour index–I
Data on seedling vigour index-I as influenced by the seed nano priming with silver and copper nanoparticles bio-synthesized through tulasi leaf extract is presented in Table 1.
The seedling vigour index-I of greengram seeds was significantly influenced by the concentrations of green-synthesized silver and copper nanoparticles as well as the duration of seed priming.
Nano priming of seeds with silver nanoparticles showed significant difference on seedling vigour index-I, where numerically highest seedling vigour index-I was recorded in seeds primed with AgNPs at 150 ppm for a duration of 3 hours (T_{15}-4260), being on par with seeds primed with 125 ppm for 3 hours (T_{12}-4212) when compared to control (T_{31}-3379). Similarly, seeds nanoprimed with CuNPs showed significant variation in seedling vigour index-I. The highest significant difference was observed in seeds primed with 50 ppm for a duration of 1 hour (T_{16}-4271), which was on par with seeds primed at 75 ppm for 1 hour (T_{19}-4231) when compared to control (T_{31}-3379).
No significant difference was observed on seedling vigour-I in seeds primed with AgNPs at 150 ppm for a soaking duration of 3 hours (T_{15}-4260) and seeds primed with CuNPs at 50 ppm for 1 hour (T_{16}-4271).

Discussion
In recent decades, nanotechnology has emerged as a promising and versatile field, finding applications in diverse sectors, including agriculture. Among the cutting-edge applications, Nano priming has gained significant importance for enhancing seed performance and overall crop productivity. Nano priming, an innovative seed priming technology, offers remarkable benefits, including improved seed germination, seedling growth, and higher yields by conferring resistance to various stresses in plants. In comparison to conventional seed priming methods, Nano priming stands out as a considerably more effective approach (Nile *et al.*, 2022). This efficacy can be attributed to its ability to activate enzymes responsible for nutrient mobilization during germination, thereby promoting seed vigor and early growth (Acharya *et al.*, 2020).

Table 1: Effect of seed priming with AgNPs and CuNPs on seed quality parameters of greengram cv. DGGV-2

Treatments	Germination (%)	Shoot length (cm)	Root length (cm)	SVI-I
T_1: Seed priming with AgNPs at 50 ppm for 1 hour	94.00(75.82)	24.41	14.79	3685
T_2: Seed priming with AgNPs at 50 ppm for 2 hour	94.33(76.24)	24.45	14.81	3704
T_3: Seed priming with AgNPs at 50 ppm for 3 hour	95.00(77.08)	25.29	15.48	3873
T_4: Seed priming with AgNPs at 75 ppm for 1 hour	94.67(76.66)	24.38	15.13	3740
T_5: Seed priming with AgNPs at 75 ppm for 2 hour	95.33(77.54)	24.43	15.20	3778
T_6: Seed priming with AgNPs at 75 ppm for 3 hour	96.00(78.46)	25.30	15.87	3952
T_7: Seed priming with AgNPs at 100 ppm for 1 hour	95.33(77.54)	24.41	15.39	3794
T_8: Seed priming with AgNPs at 100 ppm for 2 hour	96.00(78.52)	24.48	15.47	3835
T_9: Seed priming with AgNPs at 100 ppm for 3 hour	96.33(78.98)	25.37	16.13	3998
T_{10}: Seed priming with AgNPs at 125 ppm for 1 hour	95.67(77.99)	25.20	16.00	3942
T_{11}: Seed priming with AgNPs at 125 ppm for 2 hour	96.33(78.98)	25.31	16.15	3994
T_{12}: Seed priming with AgNPs at 125 ppm for 3 hour	98.00(81.87)	26.19	16.79	4212
T_{13}: Seed priming with AgNPs at 150 ppm for 1 hour	96.33(78.98)	25.33	16.00	3982

T_{14}: Seed priming with AgNPs at 150 ppm for 2 hour	98.00(81.87)	25.35	16.14	4066
T_{15}: Seed priming with AgNPs at 150 ppm for 3 hour	99.00(84.26)	26.21	16.82	4260
T_{16}: Seed priming with CuNPs at 50 ppm for 1 hour	99.33(85.32)	26.09	16.91	4271
T_{17}: Seed priming with CuNPs at 50 ppm for 2 hour	98.67(83.46)	25.25	16.27	4096
T_{18}: Seed priming with CuNPs at 50 ppm for 3 hour	96.67(79.50)	25.21	16.23	4006
T_{19}: Seed priming with CuNPs at 75 ppm for 1 hour	98.67(83.46)	26.03	16.85	4231
T_{20}: Seed priming with CuNPs at 75 ppm for 2 hour	97.00(80.12)	25.19	16.22	4017
T_{21}: Seed priming with CuNPs at 75 ppm for 3 hour	96.00(78.46)	25.10	16.19	3964
T_{22}: Seed priming with CuNPs at 100 ppm for 1 hour	96.67(79.50)	25.21	16.20	4003
T_{23}: Seed priming with CuNPs at 100 ppm for 2 hour	96.00(78.46)	24.33	15.57	3830
T_{24}: Seed priming with CuNPs at 100 ppm for 3 hour	95.67(78.06)	24.30	15.50	3807
T_{25}: Seed priming with CuNPs at 125 ppm for 1 hour	96.67(79.66)	25.17	16.10	3989
T_{26}: Seed priming with CuNPs at 125 ppm for 2 hour	95.33(77.54)	24.32	15.45	3791
T_{27}: Seed priming with CuNPs at 125 ppm for 3 hour	95.00(77.12)	24.29	15.39	3770
T_{28}: Seed priming with CuNPs at 150 ppm for 1 hour	95.00(77.08)	25.09	15.53	3859
T_{29}: Seed priming with CuNPs at 150 ppm for 2 hour	95.00(77.12)	24.30	14.79	3714
T_{30}: Seed priming with CuNPs at 150 ppm for 3 hour	93.67(75.43)	24.25	14.80	3657
T_{31}: Control (untreated)	90.00(71.58)	23.40	14.15	3379
S.EM (±)	0.67	0.22	0.16	32.94
C.D (1%)	2.52	0.81	0.62	123.81

*Figures in the parentheses indicate arcsine root transformed values

The color of the AgNP colloid generated is contingent on the concentration of the added $AgNO_3$ solution (Badiah *et al.*, 2019) [7]. The color change is attributed to the surface plasmon resonance of AgNPs in the visible region (Mukherjee *et al.*, 2008) [21], and surface active molecules present in the leaf extract, such as carbohydrates, flavonoids, and polyphenols, which also act as stabilizing agents during the synthesis (Tailor *et al.*, 2020 and Liaqat *et al.*, 2022) [31, 18]. Similarly, for CuNPs synthesis the change in color from light green to dark green indicated successful formation of copper nanoparticles, in line with previous studies (Thakur *et al.*, 2014; Mekala *et al.*, 2016; Altikatoglu *et al.*, 2017; Usha *et al.*, 2017 [34] and Dagar *et al.*, 2020) [33, 20, 4, 34, 9]. The active compounds present in the tulasi leaf extract functioned as both reducing and capping agents in the synthesis process.

The aim of this study was to identify the most effective concentration and duration for seed priming based on seed germination, root length, and shoot length for both Ag and Cu nanoparticles. The results indicated that seeds nanoprimed with AgNPs at 150 ppm exhibited the highest improvement in germination percentage (99 %), root length (16.82 cm), shoot length (26.21 cm), and seedling vigour index-I (4260) compared to all other treatments of AgNPs and the control. Increasing the priming duration also led to improved seed quality for AgNPs, with three hours of soaking showing the best results (Fig. 2). This finding is supported by Mahakham *et al.* (2017) [19], who found that priming rice seeds with silver nanopriming solutions accelerated early seed germination and germination percentage, attributing it to various mechanisms, including enhanced water uptake, rebooting of ROS/antioxidant systems, generation of hydroxyl radicals for cell wall loosening, and nanocatalyst effects on starch hydrolysis.

On the other hand, seeds treated with 50 ppm of CuNPs exhibited the highest germination percentage (99.33 %), root length (16.91 cm), shoot length (26.09 cm), and seedling vigour index-I (4271) compared to all other treatments of copper nanoparticles and the control (Fig. 2). One hour of priming duration was found to be optimal for enhancing seed quality parameters for CuNPs. Similar results were reported by Faraz *et al.* (2023) [13], where CuO NPs priming for 30 minutes at 4 mg/L proved to be the most effective in increasing shoot length and root length in *Brassica juncea* seeds. Other studies by Kausar *et al.* (2022) [15] and Ortega-Ortiz *et al.* (2022) [26] also demonstrated the positive effects of CuNPs on seed germination and seedling development.

Fig 2: Seedling length (cm) observed in seeds primed with CuNPs and AgNPs compared to control (unprimed)

The observed enhancements in seed quality can be attributed to the ability of nanoparticles to come into contact with seed coats, penetrate seeds, and promote favorable physiological processes, leading to improved seed performance and seedling growth (Khodakovskaya *et al.*, 2012) [16]. The enhanced germination can be attributed to the nano size of particles, allowing them to easily penetrate the seed coat and facilitate better absorption and utilization by the seeds (Dangi Sandeep *et al.*, 2019) [10]. Another study conducted on onion storage by Anandaraj and Natarajan (2017) [5] revealed that nanoparticles have a beneficial effect on improving seed quality. This effect can be ascribed to nanoparticles triggering oxidation-reduction reactions through the superoxide ion radical during germination, leading to the suppression of free radicals in germinating seeds. Thakur *et al.* (2021) [32] reported that copper nanoparticles can enhance seed germination and growth for certain plants at lower concentrations. However, at higher concentrations, these nanoparticles have negative impacts, such as retarded growth. But, in my study it was observed that the lower concentrations for both the nanoparticles till 150 ppm were found to be enhancing seed quality in greengram when compared to control. Enhancement in seedling length can be attributed to the activation of various metabolic pathways essential for seed germination, root and shoot growth, triggered by the nanoparticles accumulated within the seeds. Additionally, the efficient utilization of accessible food reserves within the seeds led to the early emergence and growth of the seedlings, consequently contributing to heightened seedling growth and the production of dry matter (Lakshmi *et al.*, 2017) [17]. Rani *et al.* (2019) [29] studied the quality parameters of sorghum seeds and found that AgNPs (100 mg) positively influenced seedling length, vigour index, and biomass. Studies by Harish and Rame Gowda (2017) [14] and Sowjanya and Prasad (2023) [30] have also reported that the incorporation of nanoparticles enhances seed vigour by increasing cell division within the apical meristem of seedlings.

Conclusion

In conclusion, this study demonstrates the efficacy of green-synthesized copper nanoparticles (CuNPs) at 50 ppm and silver nanoparticles (AgNPs) at 150 ppm in significantly enhancing seed quality attributes of greengram through seed priming. CuNPs, when applied for 1-hour priming, and AgNPs, during a 3-hour priming, exhibited notable improvements in germination, root and shoot lengths, and seedling vigor index. These findings underscore the potential of nanomaterial-based seed priming as a promising and environmental friendly approach to promote early seedling growth and offer insights for optimizing priming strategies in crop production.

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