



RESEARCH ARTICLE

Comparative effects of zinc oxide nanoparticles and conventional zinc on growth and yield attributes of cowpea

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Received: 26 March 2026; Accepted: 05 May 2026; Available online: Version 1.0: 15 June 2026

Cite this article: Preeti Y, Dhankhar SK, Neeraj, Ram M. Comparative effects of zinc oxide nanoparticles and conventional zinc on growth and yield attributes of cowpea. Plant Science Today. 2026; 13(sp2): 1-8. <https://doi.org/10.14719/pst.14710>

Abstract

Zinc deficiency is a widespread micronutrient constraint that limits growth, reproductive development and yield formation in legume crops, particularly under alkaline soil conditions. Nano-enabled fertilisers have recently emerged as a promising approach to enhance nutrient use efficiency and crop productivity due to their higher surface area and improved reactivity compared with conventional fertilisers. The present study evaluated the comparative effectiveness of zinc oxide nanoparticles (ZnO-NPs) and conventional bulk zinc on growth, yield attributes and seed productivity of cowpea. A pot experiment was conducted at Chaudhary Charan Singh Haryana Agricultural University, Hisar, during the summer season of 2023–24 using the variety Kashi Kanchan under a Completely randomised design with 13 treatments and 3 replications. Zinc was applied as a foliar spray at concentrations of 400, 500 and 600 ppm in both nanoparticle and bulk forms with one or two applications at critical growth stages. Zinc fertilisation significantly improved vegetative growth, reproductive traits and yield compared with the untreated control. Among the treatments, foliar application of 600 ppm ZnO nanoparticles applied twice (25 and 50 days after sowing) results in maximum plant height (61.70 cm), number of branches (7.89), pods per plant (23.22), seeds per pod (13.04) and seed yield per plant (20.32 g), which remained statistically at par with 500 ppm ZnO nanoparticles applied twice, a yield increase of approximately 26 % over the control. Nano-zinc treatments consistently outperformed bulk zinc fertilisers, indicating enhanced nutrient availability and physiological efficiency. Correlation and path coefficient analyses revealed that pod length, pod weight, seeds per pod and pods per plant were the principal determinants of seed yield. Quadratic regression analysis further indicated an optimum ZnO-NP concentration of approximately 550 ppm for maximising seed productivity. The findings highlight the agronomic potential of nano zinc fertilisation as an effective strategy for improving nutrient use efficiency, yield and sustainable production of cowpea.

Keywords: cowpea; foliar fertilisation; micronutrient management; nutrient use efficiency; yield attributes; zinc oxide nanoparticles

Introduction

Cowpea (*Vigna unguiculata* L.) is an important legume crop cultivated widely in tropical and subtropical regions due to its high nutritional value, adaptability to diverse environments and ability to fix atmospheric nitrogen (1). It serves as a significant source of dietary protein and contributes substantially to food and nutritional security, particularly in developing countries. Improving the productivity of cowpea through efficient nutrient management is therefore of considerable importance. Among essential micronutrients, zinc plays a critical role in plant growth and development. It is involved in enzyme activation, protein synthesis, auxin metabolism and photosynthetic processes. Zinc deficiency in soil often results in reduced plant growth, poor flowering and lower seed yield. Conventional zinc fertilisers such as zinc sulphate are widely used; however, their efficiency is often limited due to fixation in soil and low nutrient use efficiency (2). Recent advances in nanotechnology have opened new possibilities for improving nutrient delivery in crops. Zinc oxide nanoparticles (ZnO-NPs) possess unique physicochemical properties such as small particle size, high surface area and greater reactivity, which enhance nutrient absorption and utilisation by plants (3). Foliar application

of nanoparticles allows rapid nutrient uptake and efficient translocation within plant tissues. While several studies have reported the beneficial effects of nano-fertilisers on plant growth and productivity, comparative evaluation of foliar-applied zinc oxide nanoparticles and bulk zinc fertilisers on agronomic traits of cowpea under controlled conditions remains limited (4). Controlled experiments minimise environmental variability and provide reliable information for assessing the nutrient management techniques that improve yield and yield-attributing traits (5). This study provides a novel contribution by establishing a precise dose-response threshold for ZnO-NPs in cowpea under controlled conditions, filling a critical gap in standardised foliar application protocols. While previous research has broadly noted the benefits of nano-fertilisers, this investigation utilises quadratic regression analysis to mathematically define an optimum concentration for maximising seed productivity in the 'Kashi Kanchan' variety. Furthermore, by integrating correlation and path coefficient analyses, this research uniquely identifies pod length and pod weight as the primary physiological determinants of yield under nano-zinc enrichment. These findings offer a specific, data-driven framework for improving nutrient use efficiency that

distinguishes this work from more generalised comparative studies in legume agronomy.

Therefore, the present investigation was undertaken to assess the influence of different doses of ZnO-NPs and bulk zinc applied through a foliar spray on growth parameters, yield attributes and productivity of cowpea. ZnO-NPs used in this study pose negligible environmental and health risk under the experimental conditions. Zinc is an essential nutrient; foliar application at 400–600 ppm in a controlled pot setup results in minimal soil accumulation and negligible leaching. At low-to-moderate foliar doses, ZnO-NPs do not adversely affect soil microbiota or non-target organisms. ZnO is classified as GRAS (Generally Recognised as Safe) and widely used in food and pharma. Basic handling precautions (gloves, mask) are sufficient. Overall, risks are minimal and do not hinder sustainable agricultural adoption.

Materials and Methods

The present investigation was conducted as a pot experiment during the summer season of 2023–24 at the Research Farm of the Department of Vegetable Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, India, with the Kashi Kanchan variety of cowpea. The cowpea variety 'Kashi Kanchan' was selected due to its wide adaptability, stable performance in north India and responsiveness to nutrient management, making it suitable for evaluating the effects of nano- and bulk zinc fertilisation under controlled conditions. During the crop season, the average temperature ranged from 18–40 °C with relative humidity 21–48 %. Earthen pots of 30 cm diameter were used for raising the crop and each pot was filled with 17 kg of air-dried soil. The soil used for filling the pots was sandy loam in texture with pH 7.8, organic carbon 0.25 %, available nitrogen 132 kg/ha, phosphorus 13.80 kg/ha and potassium 238 kg/ha. The soil was collected from the surface layer (0–15 cm) of the research farm, air-dried, gently crushed and passed through a 2-mm sieve to ensure uniformity. Three doses of zinc oxide (400, 500 and 600 ppm) were applied in both nanoparticles and bulk form, along with a recommended dose of fertiliser, taking control (no zinc oxide application) as a check. The zinc concentrations (400, 500 and 600 ppm) were selected to capture the dose–response behaviour of foliar-applied Zn within a physiologically relevant range. These levels are anchored to the commonly recommended 0.5 % ZnSO₄, a foliar spray, which provides Zn in the order of ~1000–1100 ppm (as elemental Zn). The chosen concentrations therefore represent sub-recommended to near-recommended Zn levels, enabling precise evaluation of zinc use efficiency, especially for ZnO nanoparticles, which are expected to exhibit higher bioavailability

than bulk Zn. This range allows identification of the biological optimum concentration while also assessing the threshold for potential toxicity, leaf injury and nutrient antagonism under foliar application. Zinc oxide nanoparticles (ZnO-NPs; white powder, hexagonal crystal, 97 % purity, particle size < 50 nm, -30mv zeta potential and highly stable in solution) were procured from Sigma-Aldrich, USA, while bulk zinc was applied as zinc sulphate heptahydrate (ZnSO₄·7H₂O) of analytical grade.

Fresh spray solutions were prepared before each foliar application. For nano zinc treatments, the required quantity of ZnO-NP powder was dispersed in distilled water and subjected to ultrasonication for 25–30 min at 20 kHz using a probe sonicator to ensure uniform dispersion and minimise agglomeration. For bulk zinc treatments, the calculated amount of ZnSO₄·7H₂O was dissolved in distilled water and the solution was also ultrasonicated for the same duration to maintain uniformity in spray preparation. After sonication, the volume was adjusted to obtain the desired zinc concentrations as per treatment details. A non-ionic surfactant (Tween-20 at 0.05 %) was added to both nano ZnO suspension and bulk ZnSO₄ solution after sonication, followed by gentle mixing without further sonication. These fertilisers were applied as a foliar spray at two crop growth stages, i.e., 25 days after sowing (pre-flowering) and 50 days after sowing (flowering), using a fine mist hand sprayer during early morning hours. All recommended agronomic practices were followed promptly to successfully raise the crop. Recommended dose of fertilisers, i.e., 20 kg ha⁻¹ of nitrogen and 40 kg ha⁻¹ of phosphorus, was applied as a basal dose.

Although the present study was conducted under controlled pot conditions to ensure precise evaluation of treatment effects, such conditions may not fully replicate field environments where factors such as soil heterogeneity, root expansion, nutrient leaching and climatic variability influence crop response. Therefore, the results should be considered indicative of the potential of ZnO nanoparticles rather than directly extrapolated to field-scale production. Further validation through multi-location field trials is required to confirm the agronomic efficiency and practical applicability of nano-zinc fertilisation under diverse agro-ecological conditions. Table 1 shows the details of the different treatment combinations utilised in the study as follows:

Statistical analysis

The experimental data were analysed under a completely randomised design with three replications and thirteen treatments to test the significance of treatment effects and analysis of variance, including correlation using OPSTAT software at 5 % ($p = 0.05$) level of significance. Path coefficient analysis was performed using KAU Grapes software and regression curves were

Table 1. Details of the different treatments

No. of treatment	Treatment details	Time of application
T ₁	Recommended dose of fertiliser (RDF)	As the basal dose
T ₂	RDF + 400 ppm ZnO NPs	1 spray - At 25 days after sowing (DAS)
T ₃	RDF + 400 ppm Bulk Zn	1 spray - At 25 DAS
T ₄	RDF + 400 ppm ZnO NPs	2 sprays - At 25 DAS + 50 DAS
T ₅	RDF + 400 ppm Bulk Zn	2 sprays - At 25 DAS + 50 DAS
T ₆	RDF + 500 ppm ZnO NPs	1 spray - At 25DAS
T ₇	RDF + 500 ppm Bulk Zn	1 spray - At 25DAS
T ₈	RDF + 500 ppm ZnO NPs	2 sprays - At 25 DAS + 50 DAS
T ₉	RDF + 500 ppm Bulk Zn	2 sprays - At 25 DAS + 50 DAS
T ₁₀	RDF + 600 ppm ZnO NPs	1 spray - At 25 DAS
T ₁₁	RDF + 600 ppm Bulk Zn	1 spray - At 25 DAS
T ₁₂	RDF + 600 ppm ZnO NPs	2 sprays - At 25 DAS + 50 DAS
T ₁₃	RDF + 600 ppm Bulk Zn	2 sprays - At 25DAS +50 DAS

plotted in Microsoft Excel 2021. A quadratic regression model ($Y = a + bX + cX^2$) was employed to determine the dose-response relationship and identify the optimum concentration of ZnO-NPs for maximum yield. Plant height, number of branches, number of pods per plant, number of seeds per pod, seed yield per plant, pod weight, pod length and pod yield per plant were recorded. Plant height was measured in centimetres from the soil surface to the apical meristem at maturity. The number of branches and pods per plant was counted manually. Pod length was measured in centimetres using a measuring scale, while pod weight (g), pod yield per plant (g) and seed yield per plant (g) were recorded using a digital electronic balance.

Results and Discussion

Effect of zinc oxide nanoparticles and bulk zinc on plant growth

Growth parameters of cowpea were significantly influenced by foliar application of zinc in both nanoparticle and bulk forms, highlighting the importance of micronutrient nutrition in regulating vegetative development. Plant height measured at different growth stages increased progressively under zinc treatments compared with the untreated control. At 30 DAS, plant height ranged from 18.72 cm in the control to 20.38 cm under 600 ppm ZnO nanoparticles with one spray, representing an increase of approximately 8–9 % over the control. At 60 DAS, the maximum plant height (49.30 cm) was recorded with 600 ppm ZnO nanoparticles with two sprays, which remained statistically comparable to 500 ppm ZnO nanoparticles with two sprays (49.32 cm). A similar trend was observed at harvest, where the tallest plants were recorded under 600 ppm ZnO nanoparticles with two sprays (61.68 cm), followed closely by 500 ppm ZnO nanoparticles with two sprays (61.70 cm), while the lowest plant height (54.10 cm) was observed in the control treatment. The enhancement in plant height under zinc fertilisation may be attributed to the essential role of zinc in several physiological and biochemical processes. Zinc functions as a structural and catalytic component of numerous enzymes involved in protein synthesis, carbohydrate metabolism and nucleic acid formation. In addition, zinc plays a critical role in auxin biosynthesis, which regulates cell division and elongation in meristematic tissues (6). Enhanced auxin production under adequate zinc supply promotes stem elongation and overall plant vigour. Similar improvements in

plant growth following zinc fertilisation have been reported in legumes and vegetable crops (7–9).

The number of primary branches per plant also showed a significant response to zinc treatments. The maximum number of branches (7.89) was recorded with 600 ppm ZnO nanoparticles with two sprays, which remained statistically comparable with 500 ppm ZnO nanoparticles with two sprays (7.88), whereas the control treatment recorded the lowest value (6.53). Increased branching under zinc fertilisation may be associated with improved hormonal balance and enhanced photosynthetic efficiency. A higher number of branches contributes to the development of a larger canopy and increased leaf area, thereby improving light interception and photosynthetic capacity. Consequently, increased assimilate production supports both vegetative growth and reproductive development. The superior performance of ZnO nanoparticles compared with bulk zinc fertilisers may be attributed to their nanoscale properties. Nanoparticles possess a larger surface area-to-volume ratio and enhanced reactivity, which improve nutrient solubility and facilitate efficient penetration through leaf tissues during foliar application. As a result, nano-zinc fertilisers enhance nutrient uptake and metabolic activity more effectively than conventional zinc fertilisers (10).

Effect of zinc fertilisation on yield attributes

Yield attributes such as number of pods per plant, seeds per pod, pod length and pod weight were significantly influenced by zinc fertilisation as illustrated in Fig. 1. These yield components are important determinants of final crop productivity as they directly influence seed yield formation during the reproductive stage. The number of pods per plant ranged from 18.90 in the control to 23.22 under 600 ppm ZnO nanoparticles with two sprays, which is statistically at par with 23.20, obtained on application of 500 ppm ZnO nanoparticles applied twice, a substantial improvement in reproductive performance under nano-zinc fertilisation. The increase in pod number suggests enhanced flowering and pod setting under adequate zinc nutrition. Zinc plays a key role in enzyme activation and carbohydrate metabolism, which improves reproductive growth and pod development. Bulk zinc treatments also improved pod formation compared with the control, but their response remained lower than that observed under ZnO nanoparticle treatments. Similarly, the number of seeds per pod

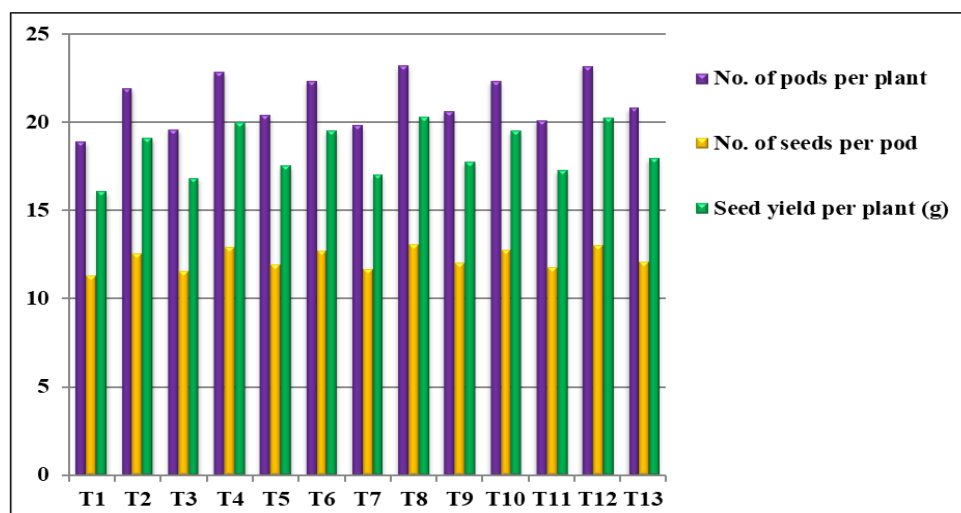


Fig. 1. Effect of foliar application of zinc oxide nanoparticles and bulk zinc on seed yield and major yield attributes (number of pods per plant and seeds per pod) of cowpea.

varied from 11.28 in the control to 13.04 under 600 ppm ZnO nanoparticles with two sprays, which is statistically at par with 500 ppm ZnO nanoparticles (13.01), representing an increase of approximately 15–16 %. Zinc plays a crucial role in pollen formation, fertilisation and seed development. Adequate zinc availability improves pollen viability and fertilisation efficiency, leading to improved seed formation and higher seed numbers per pod (11). Similar findings have been reported in legumes under zinc fertilisation (12, 13).

Pod length and pod weight also showed significant improvement under ZnO nanoparticle treatments. The maximum pod length (22.80 cm) and higher pod weight (10.68 g) were recorded under 500–600 ppm ZnO nanoparticles with two sprays, whereas the lowest values were recorded in the control treatment. The increase in pod size may be attributed to enhanced photosynthetic efficiency and improved assimilate translocation from leaves to developing pods. Zinc regulates enzymes involved in carbohydrate metabolism and energy transfer, thereby promoting biomass accumulation and efficient seed filling during the reproductive stage (14). Similar enhancement in pod length and weight following zinc fertilisation has been reported in cowpea and other legumes (15, 16). Two sprays at 25 and 50 DAS are more effective than a single spray at 25 DAS because they synchronise zinc supply with the plants' two peak demand stages, i.e. vegetative and reproductive growth phases. Thus, ensure uninterrupted enzymatic activity, pollen viability, pod setting and seed filling, which together translate into higher yield.

Effect of zinc fertilisation on yield and harvest index

Pod yield and seed yield per plant represent the cumulative outcome of various yield-contributing traits and therefore serve as reliable indicators of crop productivity. In the present investigation, pod yield ranged from 131.59 g in the control to 160.35 g under 600 ppm ZnO nanoparticles with two sprays. Similarly, seed yield per plant varied from 16.12 g in the control to 20.32 g under 600 ppm ZnO nanoparticles with two sprays, as shown in Fig. 2. Yield improvement analysis further indicated that zinc fertilisation significantly enhanced seed yield compared with the control. The highest yield increase (26.05 %) was recorded under 500 ppm ZnO nanoparticles applied through two foliar sprays, followed closely by 600 ppm ZnO nanoparticles with two sprays (25.93 %). In contrast, bulk zinc treatments resulted in comparatively lower yield improvement, ranging from 4.34 % to 11.66 %, as shown in Table 2. These findings may be attributed to improved photosynthetic efficiency, better nutrient uptake and efficient

translocation of assimilates to reproductive organs, which ultimately increase yield attributes, viz., number of pods, size of pods, number and size of seeds. Harvest index also showed a significant response to zinc fertilisation, increasing from 37.08 % in the control to 41.42 % with 500 ppm ZnO nanoparticles with two sprays. The increase in harvest index indicates improved partitioning of assimilates toward economic yield under nano-zinc fertilisation. Zinc enhances photosynthetic activity and nutrient assimilation, thereby increasing the proportion of biomass allocated to reproductive organs (9). Similar results regarding improvement in seed and pod yield of legumes with zinc fertilisation were reported (17–19).

Quadratic regression analysis revealed a curvilinear dose–response relationship between zinc application and seed yield, which is typical for micronutrient fertilisation as shown in Fig. 3. Seed yield increased sharply with increasing ZnO nanoparticle concentration up to approximately 500–550 ppm, beyond which the response tended to stabilise. The quadratic model predicted an optimum ZnO nanoparticle dose of approximately 554 ppm, corresponding to a maximum predicted seed yield of about 20.34 g/plant. In contrast, bulk zinc treatments exhibited a weaker dose–response relationship, suggesting lower nutrient use efficiency.

Agronomic efficiency analysis further supported these results. Agronomic efficiency was calculated as the increase in seed yield per unit of zinc applied. Agronomic efficiency decreased with increasing zinc dose for both sources, indicating diminishing marginal returns at higher nutrient levels. Although higher zinc doses produced slightly greater seed yield, the additional nutrient input reduced the yield increase per unit of zinc applied. This response is commonly observed in fertiliser studies where nutrient use efficiency declines as application rates increase. The highest agronomic efficiency was recorded at ZnO nanoparticles, while bulk zinc treatments exhibited substantially lower efficiency values across all application levels, as depicted in Fig. 4. The higher agronomic efficiency of ZnO nanoparticles may be attributed to their greater surface area and enhanced reactivity, which facilitate improved nutrient absorption and metabolic utilisation within plant tissues.

$$\text{Agronomic efficiency} = \frac{\text{Yield of treated plot} - \text{Yield of control plot}}{\text{Zinc applied}} \quad (\text{Eqn.1})$$

Overall, the results clearly demonstrate that foliar application of

Table 2. Effect of foliar application of zinc oxide nanoparticles and bulk zinc on growth and yield parameters of cowpea

Treatments	Plant height at 30DAS (cm)	Plant height at 60 DAS (cm)	Plant height at harvest (cm)	No. of branches	No. of pods/plant	No. of seeds/pod	Pod weight (g)	Pod length (cm)	Pod yield per plant (g)	Seed yield per plant (g)	Harvest index (%)
T ₁	18.72	42.58	54.10	6.53	18.90	11.28	8.83	20.19	131.59	16.12	37.08
T ₂	20.05	47.42	59.76	7.51	21.95	12.53	10.15	22.08	152.83	19.15	40.23
T ₃	19.12	43.69	55.25	6.72	19.60	11.55	9.13	20.64	136.40	16.82	37.83
T ₄	20.06	48.80	61.20	7.79	22.85	12.90	10.54	22.59	158.06	20.00	41.16
T ₅	19.13	44.87	56.40	7.05	20.42	11.88	9.51	21.09	141.26	17.57	38.61
T ₆	20.24	48.02	60.34	7.64	22.33	12.70	10.32	22.30	155.15	19.53	40.60
T ₇	19.25	44.07	55.63	6.83	19.87	11.66	9.25	20.78	137.97	17.06	38.08
T ₈	20.24	49.30	61.68	7.88	23.20	13.01	10.66	22.78	160.20	20.28	41.41
T ₉	19.25	45.25	56.74	7.15	20.64	11.98	9.61	21.21	142.75	17.79	38.83
T ₁₀	20.38	48.05	60.35	7.64	22.36	12.71	10.33	22.32	155.28	19.55	40.61
T ₁₁	19.37	44.41	55.98	6.92	20.10	11.75	9.36	21.91	139.46	17.29	38.31
T ₁₂	20.37	49.32	61.70	7.89	23.22	13.04	10.68	22.80	160.35	20.32	41.42
T ₁₃	19.38	45.60	57.06	7.23	20.85	12.05	9.70	21.33	144.18	18.00	39.03
C,D at 5 %	0.12	0.32	0.30	0.09	0.20	0.11	0.08	0.12	1.41	0.18	0.19

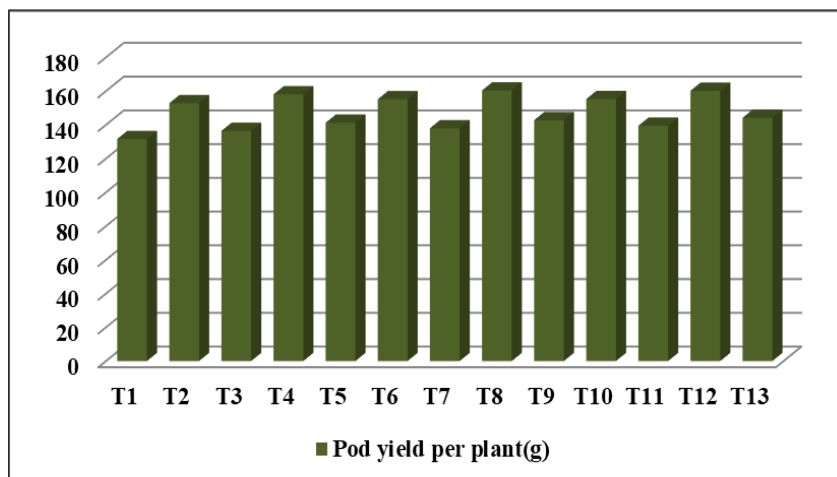


Fig. 2. Effect of foliar application of zinc oxide nanoparticles and bulk zinc on the pod yield of cowpea.

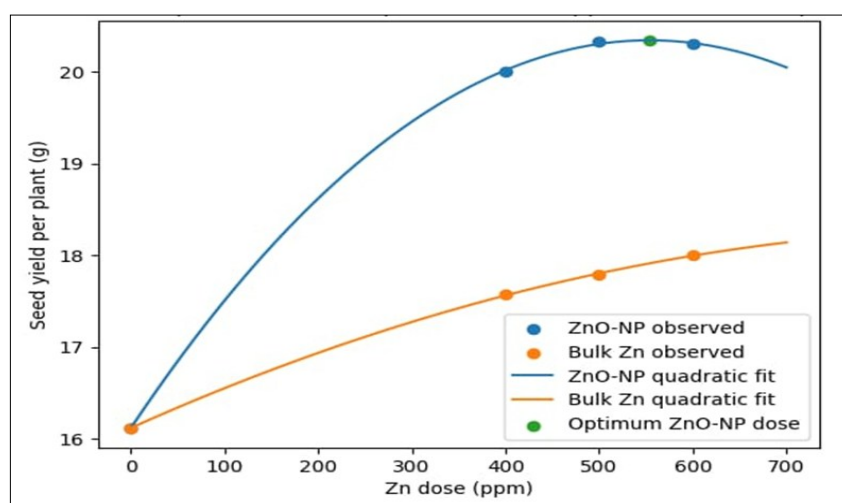


Fig. 3. Quadratic dose response relationship between Zn-application and cowpea seed yield.

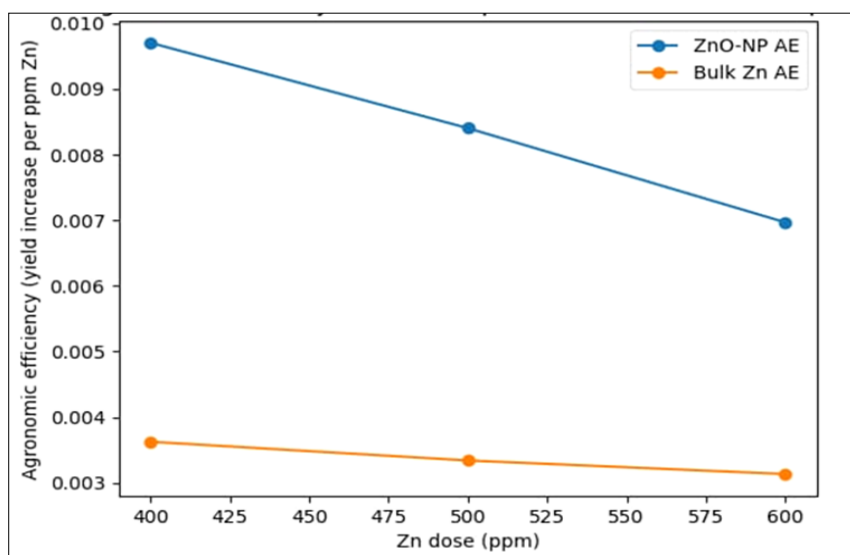


Fig. 4. Comparison of agronomic efficiency of bulk and nano zinc on cowpea yield.

zinc significantly improved growth, yield attributes and productivity of cowpea. Zinc oxide nanoparticles proved more effective than bulk zinc fertilisers in enhancing agronomic performance, likely due to their higher bioavailability, improved nutrient uptake and greater metabolic efficiency. Among the treatments evaluated, 500 ppm ZnO nanoparticles applied through two foliar sprays emerged as the most effective treatment, producing the highest values for plant growth, yield attributes, pod yield, seed yield and harvest index. While zinc uptake and translocation were not directly measured, the

significantly higher growth, yield attributes and agronomic efficiency observed under ZnO nanoparticle treatments compared to bulk zinc strongly indicate enhanced nutrient availability and utilisation. The comparative experimental design, where both sources were applied at identical concentrations, isolates the effect of nanoparticle form. Furthermore, the observed dose-response relationship and improved reproductive performance processes highly dependent on zinc, provide functional evidence of improved zinc uptake. These findings highlight the potential of nano-enabled

micronutrient fertilisation as an effective strategy for improving nutrient use efficiency and crop productivity in cowpea.

Relationship among yield components and seed yield

Understanding the interrelationships among yield components is fundamental for identifying the traits that most strongly influence crop productivity. In the present investigation, correlation analysis revealed pronounced positive associations among several agronomic traits and the seed yield of cowpea. Seed yield per plant exhibited strong positive correlations with pod length ($r = 0.878$), pod weight ($r = 0.872$), number of seeds per pod ($r = 0.826$) and number of pods per plant ($r = 0.821$) as illustrated in Table 3. These strong correlations clearly indicate that reproductive traits associated with pod development and seed formation play a dominant role in determining yield potential in cowpea. In leguminous crops, yield is largely governed by the combined influence of pod formation, seed development and assimilate partitioning; therefore, strong relationships between these traits and seed yield are physiologically expected (20).

Pod length displayed strong positive correlations with number of seeds per pod ($r = 0.792$), pod weight ($r = 0.841$) and number of pods per plant ($r = 0.795$), indicating that longer pods tend to accommodate more seeds and accumulate greater pod biomass. This relationship reflects the close physiological linkage between pod development and seed formation. Likewise, pod weight exhibited strong positive associations with the number of pods per plant and seeds per pod, highlighting the importance of efficient assimilate translocation and reproductive growth in determining crop productivity. In contrast, the number of branches per plant showed comparatively weaker correlations with yield attributes and seed yield ($r = 0.164$), suggesting that vegetative branching contributes to productivity primarily through indirect effects mediated by reproductive structures rather than exerting direct influences on yield (21).

Although correlation analysis provides useful insights into the strength and direction of associations among traits, it does not distinguish between direct and indirect effects. Therefore, path coefficient analysis was performed to partition the correlation coefficients into their direct and indirect components and to identify the most influential yield-determining traits. The results of path analysis indicated that pod length exerted the highest positive direct effect on seed yield (0.389), followed by pod weight (0.278), number of seeds per pod (0.185) and number of pods per plant (0.148), as

shown in Table 4. These findings demonstrate that pod morphological characteristics and seed development traits are the primary determinants of yield formation in cowpea.

Pod length not only exhibited the strongest direct effect on seed yield but also contributed substantially through indirect effects via seeds per pod and pod weight. This suggests that longer pods enhance yield both by directly contributing to seed production and by facilitating improved seed filling and pod biomass accumulation. Similarly, pod weight exerted considerable indirect effects through pod length and seeds per pod, further strengthening its role as a key yield component. The number of seeds per pod also showed a positive direct influence on seed yield and contributed indirectly through its association with pod length and pod weight, indicating that efficient seed set and seed filling are critical processes governing yield formation (22).

In contrast, the number of branches per plant exhibited a small negative direct effect (-0.042) on seed yield, although it contributed indirectly through other yield components. This suggests that vegetative growth alone does not necessarily translate into higher productivity unless it supports the development of reproductive organs such as pods and seeds. The relatively low residual effect obtained from path analysis further indicates that the selected traits collectively explain a large proportion of variability in seed yield, confirming their relevance in determining crop productivity (23).

Contribution analysis further emphasised the relative importance of individual yield components in explaining yield variability. Pod length contributed the largest proportion to seed yield variation (37.16 %), followed by pod weight (26.99 %), number of seeds per pod (17.67 %) and number of pods per plant (14.14 %). In contrast, the number of branches per plant accounted for the smallest contribution (4.04 %). These results clearly demonstrate that reproductive traits associated with pod development and seed formation exert a substantially greater influence on yield than vegetative growth traits.

Overall, the combined results of correlation, path coefficient and contribution analyses indicate that pod length, pod weight, number of seeds per pod and number of pods per plant are the most critical determinants of seed yield in cowpea. These traits, therefore, represent reliable selection criteria for improving productivity and may serve as key targets for agronomic management and crop improvement strategies under zinc-enriched production systems. Similar relationships between seed yield and its component traits have been reported in cowpea and other grain legumes, where pod

Table 3. Phenotypic correlation matrix among yield and yield attributing traits

	No. of branches	No. of pods Per plant	Pod length (cm)	No. of seeds per pod	Pod weight (g)	Seed yield per plant (g)
No. of branches	1	0.421	0.206	0.063	0.188	0.164
No. of pods per plant	0.421	1	0.795*	0.770*	0.861**	0.821*
Pod length (cm)	0.206	0.795*	1	0.792*	0.841**	0.878**
No. of seeds per	0.063	0.770*	0.792*	1	0.798*	0.826*
Pod weight (g)	0.188	0.861**	0.841**	0.798*	1	0.872**
Seed yield per plant (g)	0.164	0.821*	0.878**	0.826*	0.872**	1

** Correlation is significant at the 0.01 level (two-tailed), * Correlation is significant at the 0.05 level (two-tailed).

Table 4. Direct and indirect effects of yield components on seed yield in cowpea

Traits	Branches	Pods/plant	Pod length	Seeds/pod	Pod weight	Total correlation (r)	Contribution (%)
Branches	-0.042	0.062	0.080	0.012	0.052	0.164	4.04
Pods/plant	-0.081	0.148	0.309	0.142	0.239	0.821	14.14
Pod length	-0.009	0.118	0.389	0.147	0.234	0.878	37.16
Seeds/pod	-0.003	0.114	0.308	0.185	0.222	0.826	17.67
Pod weight	-0.008	0.127	0.327	0.148	0.278	0.872	26.99

Residual effect = 0.32, Diagonal bold values represent direct effect.

number, seed number and pod characteristics were identified as the primary contributors to yield formation (24–26). The consistency of these findings with previous studies further confirms the importance of reproductive traits in determining yield potential in cowpea.

Conclusion

The study concludes that foliar application of zinc oxide nanoparticles (ZnO-NPs) is significantly more effective than conventional bulk zinc in enhancing the growth and productivity of cowpea. The superior performance of ZnO-NPs is attributed to their higher surface area and reactivity, which leads to improved nutrient uptake and metabolic efficiency compared to bulk fertilisers. The most effective results for plant growth, seed yield and harvest index were achieved using 500 ppm ZnO nanoparticles applied twice (at 25 and 50 days after sowing). Nano-zinc treatments consistently outperformed bulk zinc, with the 500 ppm double-spray treatment resulting in a yield increase of approximately 26 % over the control. Correlation and path coefficient analyses identified pod length, pod weight, number of seeds per pod and number of pods per plant as the primary factors determining seed yield.

Acknowledgements

The authors wish to thank the staff and technicians of the Chaudhary Charan Singh Haryana Agricultural University, Hisar, Department of Vegetable Science, for their assistance with laboratory and analytical activities related to this research.

Authors' contributions

PY contributed to laboratory experiments, methodology, original draft writing, review and editing. SKD contributed to conceptualisation, methodology, review and supervision. N contributed to the visualisation, review and editing of the manuscript. RM contributed to formal analysis and investigation. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process:

During the preparation of this work, the author(s) used Claude AI in order to language refinement and grammatical correction. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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