



RESEARCH ARTICLE

Dose-dependent effects of green-synthesised zinc oxide nanoparticles on growth and seed yield of black gram (*Vigna mungo* L.)

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Abstract

Black gram (*Vigna mungo* L., cv. Pant U-12) is an important pulse crop with nutritional and economic value, but its productivity is often constrained by poor seed vigour and low nutrient uptake. This study evaluated the potential of green-synthesised zinc oxide nanoparticles (ZnO NPs), derived from *Punica granatum* fruit peel extract, to enhance growth and yield in black gram. The biosynthesised ZnO NPs, with an average particle size of 65.73–81.52 nm, were characterised by Scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray Diffraction (XRD) and UV-Visible spectroscopy. Seeds were primed with five ZnO NP concentrations (5, 10, 15, 20 and 25 ppm) and tested in a randomised complete block design with three replicates during the rabi season (February–April). Growth parameters were recorded at 45 DAS and yield attributes were assessed at harvest. Among the treatments, 15 ppm ZnO NP seed priming produced the best overall response, increasing the number of leaves per plant (103 %), the number of pods per plant (113 %), seeds per pod (149 %) and seed yield per plant (168 %) compared with the control. The findings suggest that green-synthesised ZnO NP seed priming is an eco-friendly and effective approach for improving growth and yield in black gram, offering a sustainable alternative to conventional agrochemical inputs.

Keywords: black gram; green synthesis; nano particles; *Punica granatum*; seed priming; sustainability; yield parameters; zinc oxide nanoparticles

Introduction

A new emerging field of science and technology is nanotechnology, where phenomena take place at the nanometer scale to design and produce the materials or particles known as nanoparticles (1, 2). The materials with size ranges from 1–100 nm are considered as nanoparticles. In agriculture, the use of nanotechnology is rapidly increasing to enhance food values, improve nutrient contents, reduce agricultural inputs, increase shelf life and reduce the use of toxic chemicals. Development of a variety of nanomaterials is reported by using nanotechnology, such as nano-pesticides, nano-insecticides, nano-emulsions and nanoparticles (3). In the era of climatic changes, a constantly increasing human population with increased demand for food productivity, diminishing agricultural productivity, nutrient deficiency in food products that affect human health and loss of fertility of farm lands due to human activities are the serious issues facing the global agricultural system. In order to overcome these issues the agricultural system needs to adopt more advanced technology and nanotechnology is the most recent technology that holds an important role in agriculture and fulfils the demand in an efficient and cost-effective way (4–6). Nanotechnology has created great interest among agricultural scientists because it offers a cost-effective potential approach to enhance agricultural productivity with high efficiency and sustainability at a lower cost (7).

Nanoparticles also enhance soil fertility by increasing mineral N and P content and increasing the activity of phosphorus solubilizing enzyme in soil (8). Agro nanotechnology focuses on the use of nanoparticles to improve crop productivity and in all stages of agricultural production, such as crop improvement, plant protection (from stress, disease, pathogens and insects), soil management and seed germination (6). The ultimate goal for the application of nanomaterials in agriculture is to reduce hazardous chemicals, nutrient losses, pest control and increase crop yield (5). Zinc is one of the most important micronutrients required for the growth and metabolism of plants. To enhance plant growth and productivity, the utilisation of zinc nanoparticles is an effective strategy. Zinc is required for many enzymatic activities in plants and it is a cofactor for many enzymes such as carbonic anhydrase, alcohol dehydrogenase and RNA polymerase. Inadequate availability of zinc in soil results in the reduction of crop yield and growth (9). Deficiency of zinc (Zn) negatively affects plant functions such as reproduction and pollen development, also induces chlorosis, reduces leaf area and causes abnormal growth of plant structures. This deficiency can also result in higher susceptibility to biotic and abiotic stress. Zn-based nanoparticles influence plant temperature and temperature variations, which are useful indicators of stress response, plant transpiration and energy balance (10). Zinc improves the quality and increases the yield of the produce. Application of ZnO nanoparticles

in agriculture provides great benefits for plant growth, development, physiology and consequent production and also increases the content of total crude protein in zinc-deficient soil. Zn content is significantly varied in mung bean and urd bean varieties (11). In addition to their beneficial effects on plants, metal-based nanoparticles, such as ZnO nanoparticles, can enhance plant disease resistance activity and inhibit the growth of various plant pathogens that adversely affect the growth and yield of plants. ZnO nanoparticles have antimicrobial properties against phyto pathogens such as fungi that cause soil-borne disease (12). Due to their wide applications, zinc oxide nanoparticles are very important among other metal nanoparticles and also have great potential to enhance agriculture due to their remarkable optical, physical and antimicrobial properties (13). ZnO nanoparticles increase zinc bioaccumulation and translocation within plant tissues and modulate primary and secondary metabolism, thereby influencing zinc-mediated physiological responses under stress conditions. At optimum concentrations, ZnO-NPs can improve drought and salinity tolerance by reducing water loss, maintaining osmotic adjustment, enhancing ion homeostasis and improving the K/Na balance, thereby helping maintain turgor and water status under stress (14). Pulses are a major group of food crops and play an important role in the nutritional security of the vegetarian population of India. In India, pulses are generally produced in poor soils not suited to other crops, with a minimum use of resources and have a very low water footprint (14, 15). Pulses are a rich source of protein for the poor as well as for the vegetarians, mainly including chickpea, pigeon pea, lentil, mung bean, urd bean and field pea. India is the largest producer as well as consumer of pulses (16).

Black gram (*Vigna mungo* (L.) Hepper, Urd bean) is a widely grown short-duration pulse crop that belongs to the Fabaceae family. It is an important pulse from the point of food and nutritional security in the world. The production and yield of black gram have to be increased to meet the increasing demand. The crop improves the fertility of soil by fixing atmospheric nitrogen in soil because of its association with rhizobium bacteria present on root nodules and it is resistant to adverse climatic conditions. Black gram plays an important role in the Indian diet and economy (17). It is grown in tropical and subtropical parts of the world and cultivated in all three seasons, but mostly cultivated as a kharif crop. Black gram can be cultivated in a variety of soils, but the ideal soil for its cultivation is loam and clay loam soil with high water holding capacity, with a normal pH of 6.5-7.8 and cannot be cultivated in saline and alkaline soil (18, 19). Various biotic and abiotic stresses fluctuate the productivity of black gram and ultimately result in a decline in growth and productivity of black gram. The biotic stresses such as powdery mildew, yellow mosaic, cercospora leaf spot, leaf crinkle disease and web blight are major limiting factors for high yield (20). Major abiotic stresses are drought and salinity, which hamper the growth, development and yield of black gram (21).

Conventional Zn fertilisers suffer from low uptake efficiency and environmental losses, whereas green-synthesised ZnO NPs offer sustainable, targeted delivery. Prior studies demonstrate 20–80 % growth/yield gains in legumes, but field-level seed priming data for black gram remain limited, particularly using fruit waste extracts like pomegranate peel. This study aimed to synthesise and characterise ZnO NPs using *Punica granatum* peel extract, evaluate seed priming effects across concentrations (5–25 ppm) on growth parameters at 45 days after sowing (DAS) and yield at maturity (90 days after

sowing) and identify the optimal dose for sustainable black gram productivity under field conditions.

Materials and Methods

Experimental site and soil

Field trials conducted during rabi 2024–25 at Sardar Bhagwan Singh University, Balawala, Dehradun (30°19'17" N, 78°1'54" E). Clay loam soil (pH 7.4, N 0.18 %, P 29.58 ppm, K 59.5 ppm, OC 0.923 %, EC 0.07 dS/m). Soil samples were analysed for basic physicochemical parameters (pH, EC, organic carbon, available NPK) using standard laboratory protocols before sowing.

Plant material

Black gram (*Vigna mungo* L. cv. Pant U-12) seeds procured from G.B. Pant University, Pantnagar.

ZnO nanoparticle synthesis

ZnO nanoparticles were synthesised by adding 10 mL of 1 M NaOH dropwise to 25 mL of 0.1 M zinc nitrate solution, followed by dropwise addition of 50 mL of aqueous plant extract under continuous stirring at 400 rpm at 60 °C for 2 hr. The resulting mixture was centrifuged, washed, dried at 60°C and calcined at 400 °C for 2 hr. Characterised by Scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray Diffraction (XRD), UV-Vis size of synthesised nanoparticles were 65.73–81.52 nm confirmed by FE-SEM analysis, XRD confirmed crystallinity with average crystallite size 12.2 nm and FTIR analysis showed O-H, C-H, carbonyl/carboxyl and other phytochemical bands, along with a clear Zn-O stretching peak in the 400–600 cm⁻¹ region, indicating that extract biomolecules likely acted as reducing and stabilising agents (22).

Seed priming

ZnO NP suspensions were prepared freshly as 5, 10, 15, 20 and 25 ppm (T₁–T₅) concentrations. Black gram seeds were surface sterilised with ethanol, rinsed with distilled water and air-dried. The dried seeds were then soaked in respective NP suspensions in separate flasks and placed on a rotary shaker (30 min) for uniform NP coating. After shaking, the flasks remained undisturbed with seeds soaking in the same NP suspensions for 24 hr at room temperature. Seeds were then air-dried and used for sowing. Untreated seeds (T₀) were used as a control.

Field design

Randomised complete block design (RBD), 6 treatments × 3 replicates. Plot size 7.12 m² (30 × 10 cm spacing), ~24 plants/plot.

Field preparation

The land was prepared with deep ploughing by a tractor. The sowing was done by maintaining 3 replicates for each treatment, followed by immediate irrigation after sowing. The crop was raised by timely irrigation and weeding. The growth parameters of black gram were observed at 45 days after sowing and at maturity.

Parameter measurement

Morphological (45 DAS, maturity/90 DAS): 5 random plants/replicate uprooted gently; measured height, root/shoot length, leaves/plant.

Biomass: Fresh weights immediately; shade-dried (70 °C, 72 hr) for dry root/shoot/leaf/total weights.

Yield (maturity): Pods/plant, seeds/pod, pod length, seed yield/plant (g), 100-seed weight.

Statistical analysis

Data were analysed by one-way ANOVA in a Randomised complete block design (RCBD) with 6 treatments (control + 5 ZnO concentrations) and 3 replications per treatment. Treatment effects were tested at $p \leq 0.05$, followed by mean separation using critical difference (CD) at 5 % significance level. Summary statistics (GM, Sem, Sed, SD, CV) and complete ANOVA tables (SS, MS, DF, F-value, p -value) are presented in Tables 1–6.

Results

Green-synthesised zinc oxide nanoparticles significantly enhanced growth and yield parameters of *V. mungo* (Pant U-12) in a concentration-dependent manner, with 15 ppm (T_3) consistently optimal across all measurements at 45 days after sowing (DAS) and maturity (Fig. 1–8, Table 1–3).

Morphological parameters

Plant height increased progressively from T_1 (5 ppm) to T_3 (15 ppm) at both 45 DAS and maturity, then declined slightly at higher concentrations (20–25 ppm). Maximum root and shoot lengths also occurred at 15 ppm across both growth stages, with minimum values recorded at 5 ppm and control. This indicates that plants respond better to 15 ppm, which is the optimum concentration beyond which (20–25 ppm) nanoparticle toxicity results in declined growth. Treatment effects were highly significant for most growth parameters ($p < 0.05$), with the clearest improvements observed in plant height and shoot length (Table 4).

Biomass assessment

Root and shoot dry weights were maximum at 15 ppm at both 45 DAS and maturity, followed by 10 ppm and 20 ppm treatments. Total dry matter accumulation and leaf fresh/dry weights also peaked at 15 ppm, while control and 5 ppm showed minimum biomass across all stages. The shift toward higher shoot allocation and improved leaf biomass at 15 ppm may indicate enhanced photosynthetic capacity and nutrient use efficiency compared to control treatments. Treatment effects were highly significant for

Table 1. Effect of green-synthesised ZnO Nanoparticle treatment on plant growth parameters at 45 DAS

Treatments (T)	Plant height (cm)	Root length (cm)	Shoot length (cm)	No. of leaf/plant	Root dry weight (g)	Shoot dry weight (g)	Total dry weight (g)	Leaf fresh weight (g)	Leaf dry weight (g)	Root/Shoot ratio
T0	23.17	7.9	6.54	18	0.21	0.20	0.41	1.28	0.58	1.05
T1	23.75	8.30	7.4	20	0.25	0.24	0.49	1.44	0.60	1.04
T2	27.3	9.76	9.10	24	0.26	0.28	0.54	2.27	0.91	0.93
T3	31.15	11.56	10.68	32	0.32	0.41	0.73	2.50	1.43	0.78
T4	28.7	11.24	10.40	26	0.31	0.30	0.61	2.41	0.92	1.03
T5	26.9	10.88	10.20	25	0.30	0.27	0.57	2.26	0.89	1.11
GM	26.83	9.94	9.05	24.2	0.27	0.283	0.558	2.027	0.89	0.990
SD	3.01	1.55	1.72	4.92	0.042	0.071	0.109	0.527	0.31	0.118
SEm(±)	1.23	0.63	0.70	2.01	0.017	0.029	0.044	0.215	0.126	0.048
SEd	1.74	0.90	0.99	2.84	0.024	0.041	0.063	0.304	0.178	0.068
CV	11.22 %	15.64 %	19.02 %	20.3 %	15.4 %	25.1 %	19.5 %	25.98 %	34.6 %	11.9 %
CD	4.01	2.03	2.25	6.54	0.056	0.095	0.145	0.701	0.411	0.157

Table 2. Effect of green-synthesised ZnO Nanoparticle treatment on plant growth parameters at Maturity (90 DAS)

Treatment (T)	Plant height (cm)	Root length (cm)	Shoot length (cm)	Root dry weight (g)	Shoot dry weight (g)	Total dry weight (g)	Root/Shoot ratio	No. of leaf/Plant	Leaf fresh weight (g)	Leaf dry weight (g)
T0	33.84	12.44	17.26	0.57	1.12	1.70	0.51	32	4.35	0.70
T1	37.40	13.3	17.1	0.67	1.76	2.43	0.61	39.4	9.8	1.36
T2	40.80	14.1	19.5	0.84	1.65	2.52	0.742	40.8	10.52	1.43
T3	51.90	16.56	25	1.13	4.62	5.76	0.41	65	17.2	2.27
T4	46.04	11.74	22.6	0.53	2.60	2.64	0.35	53.2	13.56	1.86
T5	41.46	14.88	19.4	1.50	1.12	1.62	0.46	45.6	11.22	1.60
GM	41.51	13.75	19.95	0.81	1.88	2.52	0.50	44.82	10.27	1.45
SD	6.38	1.74	3.10	0.38	1.33	1.52	0.14	11.66	4.26	0.53
SEm(±)	1.443	1.02	0.49	0.14	0.34	0.44	0.04	1.15	0.24	0.04
SEd	2.041	3.23	0.69	0.44	1.08	1.39	0.11	1.63	0.34	0.06
CV	14.66	16.33	12.19	21.1	12.1	13.4	14.5	14.5	15.1	14.9
CD (5%)	3.212	3.23	1.43	0.58	1.13	1.43	0.12	2.35	0.49	0.08

Table 3. Influence of different treatments on pod yield parameters, seed yield per plant and 100-seed weight in plants treated with green-synthesised zinc oxide nanoparticles

Treatments (T)	No. of Pod/Plant	Pod length (cm)	No. of seed/Pod	Seed Yield/Plant	100 seed weight (g)
T0	14	3.00	2.88	57.2	3.03
T1	18	3.23	4.04	77.8	3.61
T2	21.6	3.36	4.89	88.2	4.00
T3	29.8	3.86	7.16	153	5.0
T4	17.4	3.84	6.9	123.4	4.83
T5	14.4	3.37	5.78	99.6	4.10
GM	18.54	3.43	5.03	95.06	4.04
SD	5.88	0.34	1.66	34.12	0.74
SEm(±)	1.23	0.11	0.44	6.23	0.11
SEd	1.74	0.16	0.62	8.81	0.16
CV	14.5	12.1	15.6	18.3	10.5
CD (5 %)	2.48	0.23	0.88	12.51	0.23

Table 4. Analysis of variance (ANOVA) for vegetative growth parameters of black gram (*Vigna mungo* cv. Pant U-12) under ZnO nanoparticle seed priming treatments

Parameters	Source	SS	MS	DF	F-Value	p- Value
Plant height	Between group	1014.6		5		
	Within group	124	202.92	12	39.17	0.0001
	Total	1139	5.18	17		
Root length	Between group	63.6	12.72	5		
	Within group	72.4	3.02	12	4.32	0.007
	Total	136		17		
Shoot length	Between group	114.1	22.84	5		
	Within group	24.19	1.23	12	18.57	0.0001
	Total	138.38		17		

Table 5. Analysis of variance (ANOVA) for biomass parameters of black gram (*Vigna mungo* cv. Pant U-12) under ZnO nanoparticle seed priming treatments

Parameters	Source	SS	MS	DF	F-Value	P- Value
Root dry weight	Between group	1.775	0.355	5		
	Within group	2.354	0.098	12	3.62	0.014
	Total	4.129		17		
Shoot Dry weight	Between group	41.45	8.29	5		
	Within group	14.19	0.59	12	14.05	0.0001
	Total	55.64		17		
Total Dry weight	Between group	54.25	10.85	5		
	Within group	23.19	0.97	12	11.19	0.0001
	Total	77.44		17		
Root/Shoot ratio	Between group	0.43	0.086	5		
	Within group	0.41	0.034	12	2.51	0.062
	Total	0.84		17		
No.of leaf/ Plant	Between group	1234.56	246.91	5		
	Within group	345.67	14.40	12	15.23	<0.001
	Total	1580.23		17		
Leaf fresh weight	Between group	2345.67	469.13	5		
	Within group	456.78	19.03	17	20.56	<0.001
	Total	2802.45		12		
Leaf dry weight	Between group	12.34	2.47	5		
	Within group	3.21	0.13	12	18.42	<0.001
	Total	15.55		17		

Table 6. Analysis of variance (ANOVA) for yield parameters of black gram (*Vigna mungo* cv. Pant U-12) under ZnO nanoparticle seed priming treatment

Parameters	Source	SS	MS	DF	F-Value	P- Value
No. of pods/plant	Between group	234.56	46.91	5	5.23	
	Within group	123.45	5.14	12		0.001
	Total	358.01		17		
Pod length(cm)	Between group	0.73 12.34		5		
	Within group	6.78	2.47 2.47	12		0.005
	Total	19.12	0.28	17	4.23	
No. of seed/pod	Between group	6.78		5		
	Within group	1		12		
	Total	1.12		17		
Seed yield/plant	Between group	56.78	11.36	5		
	Within group	23.45	0.98	12	6.15	0.0003
	Total	80.23		17		
100 seed weight (g)	Between group	1234.56	1691.34	5		
	Within group	456.78	19.03	12	8.42	< 0.0001
	Total	1691.34		17		

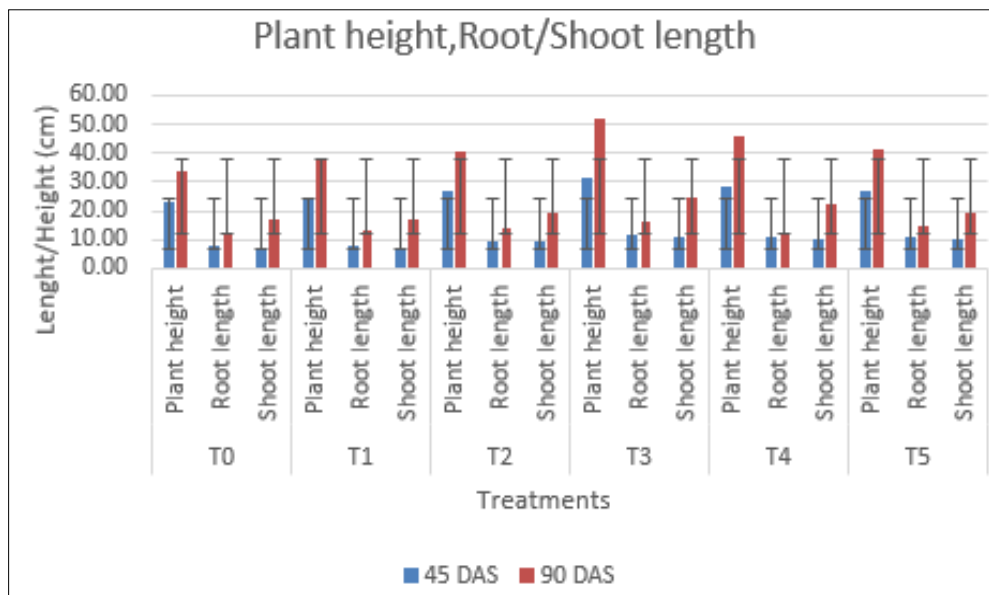


Fig. 1. Effects of different concentrations of zinc oxide nanoparticles on plant growth parameters. Plant height, root length and shoot length at both stages of growth (45 DAS and maturity (90 DAS)).

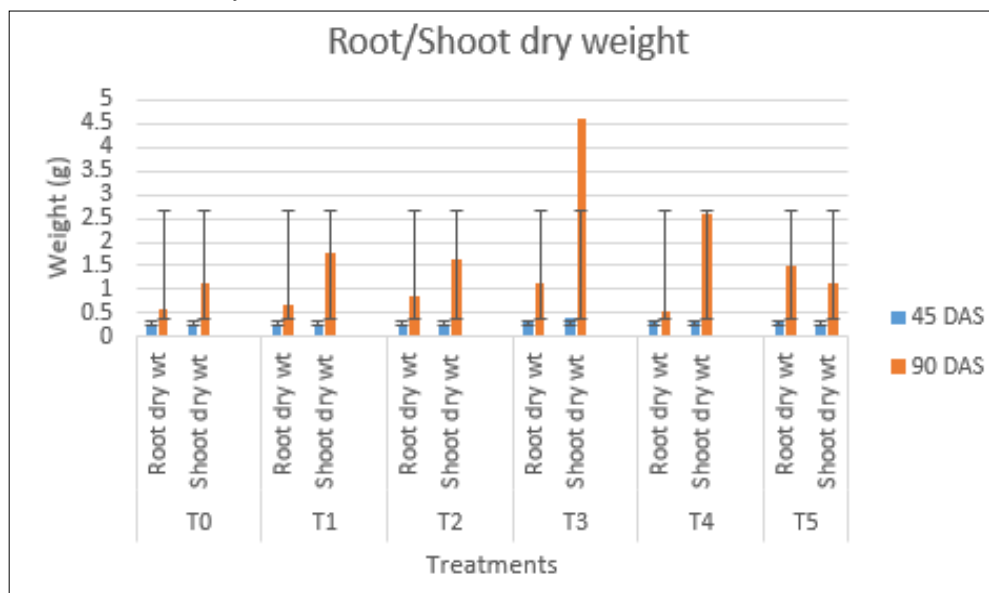


Fig. 2. Effects of different concentrations of green-synthesised zinc oxide nanoparticles on root and shoot dry weight at both stages of growth, 45 DAS and maturity (90 DAS).

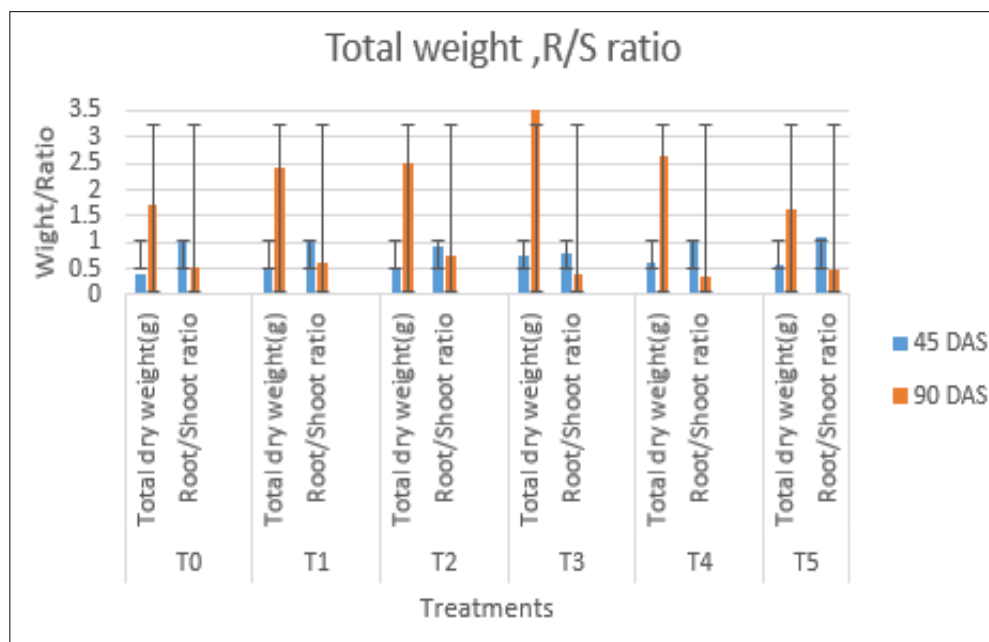


Fig. 3. Total dry weight and root/shoot ratio under green-synthesised ZnO nanoparticle treatments T₀ to T₅ at 45 DAS and 90 DAS.

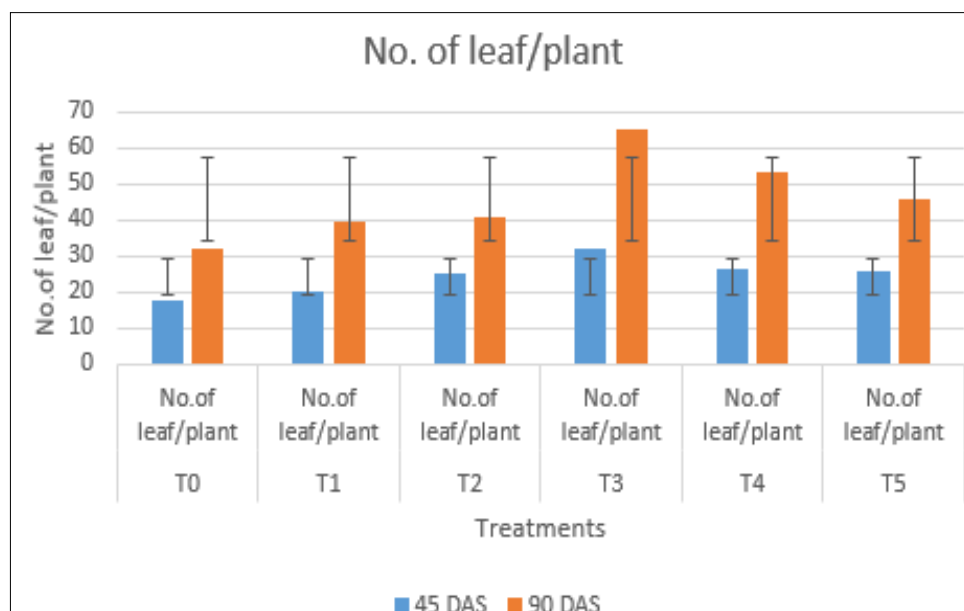


Fig. 4. Temporal changes in leaf number per plant across green synthesised ZnO nanoparticle treatments (T₀–T₅) at 45 and 90 days after sowing (DAS).

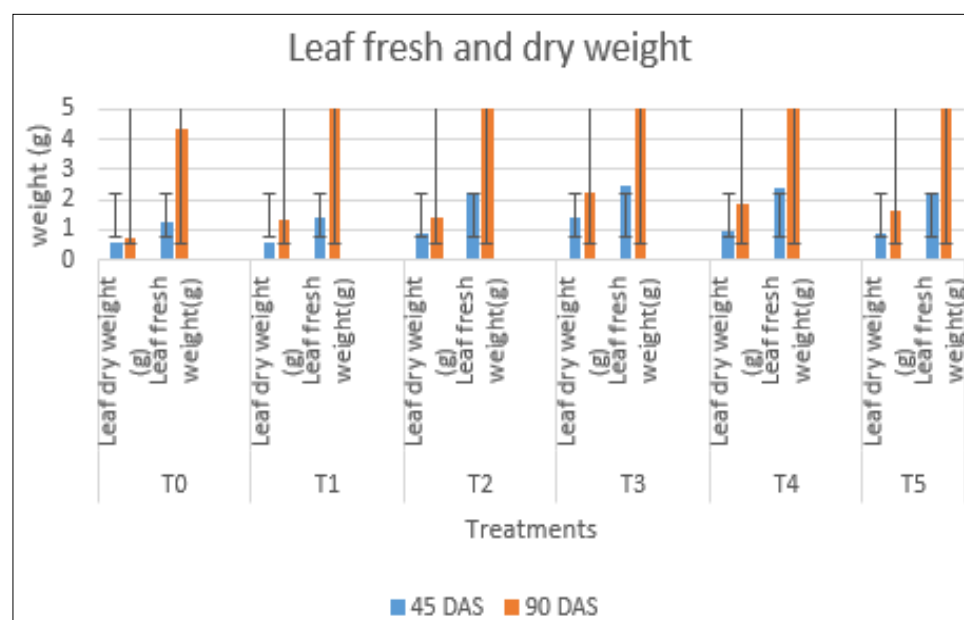


Fig. 5. Leaf fresh weight and dry weight under green-synthesised ZnO nanoparticle treatments T₀ to T₅ at 45 DAS and 90 DAS.

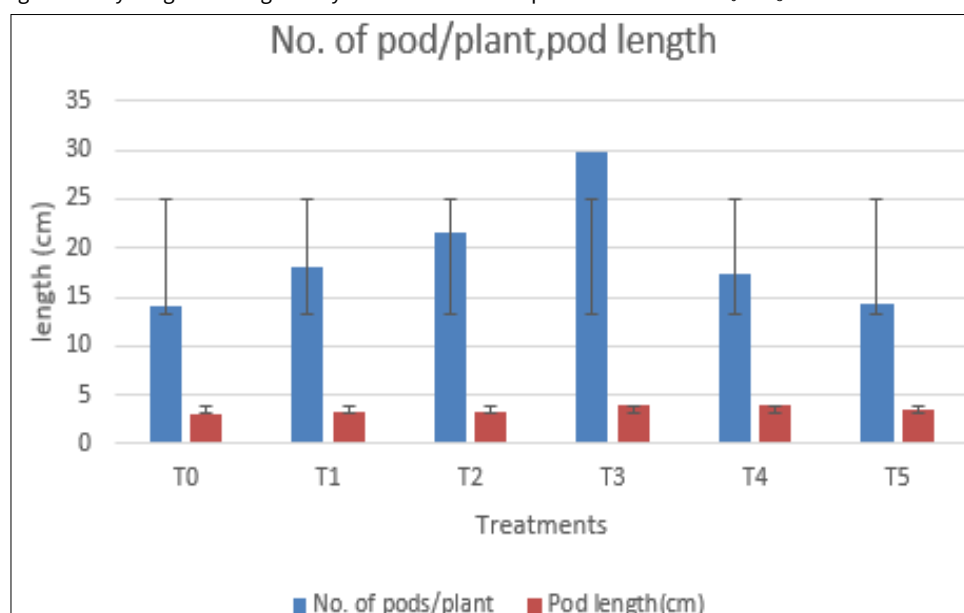


Fig. 6. Number of pods per plant and pod length under green-synthesised ZnO nanoparticle treatments T₀ (control) to T₅ at maturity (90 DAS).

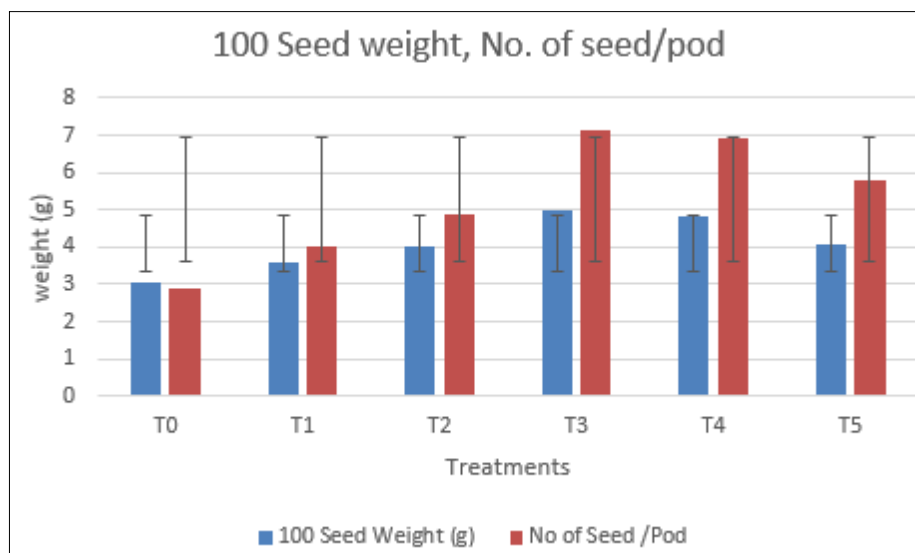


Fig. 7. Comparative effects of green-synthesised ZnO nanoparticle treatments on 100-seed weight and number of seeds per pod at maturity (90 DAS).

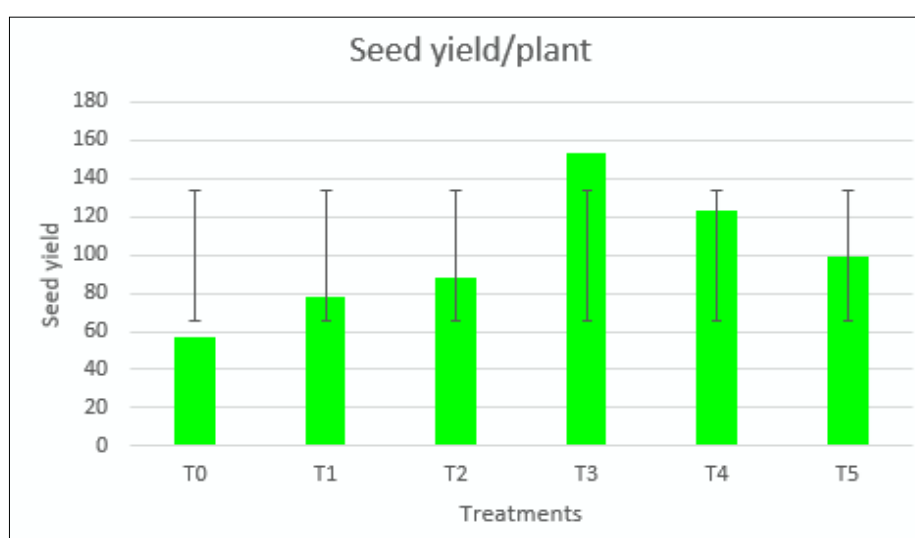


Fig. 8. Seed yield per plant (g) in response to green-synthesised ZnO nanoparticle treatments, T₀(control) to T₅ at maturity (90 DAS). These concentration-dependent enhancements reflect zinc oxide nanoparticles' roles in auxin signalling, photosynthesis and antioxidant defence, consistent with prior nanoprimer studies in legumes. The optimal 15 ppm dose balances bioavailability against potential phytotoxicity at higher levels (> 20 ppm).

most biomass parameters ($p < 0.05$), with the clearest improvements observed in dry matter accumulation and leaf number, while root:shoot ratio was not significant ($p > 0.05$) (Table 5).

Yield parameters

Seed yield per plant was highest at 15 ppm (T₃), followed by T₅ and T₂, with the control recording the lowest yield. All yield attributes (pods/plant, pod length, seeds/pod, seed yield/plant) showed maximum values at 15 ppm compared to other treatments. The identical treatment ranking from vegetative growth through reproductive success demonstrates that early ZnO priming benefits were effectively translated into final productivity under field conditions. Yield traits also showed highly significant treatment effects ($p < 0.05$), particularly for pods per plant, seeds per pod and seed yield per plant (Table 6).

Discussion

Growth response

The concentration-dependent improvement in growth and yield

traits of black gram (*V. mungo* cv. Pant U-12) shows that green-synthesised ZnO NP seed priming was effective, with 15 ppm (T₃) giving the best response across morphological, biomass and reproductive traits. Plant height (+ 53 %) compared to untreated control (28.3 vs 43.2 cm), root and shoot length (+33 % and +45 %) and leaf number (+ 103 %) at T₃ are in line with earlier studies which reports better seed germination and vigour in black gram through biogenic ZnO/Cu NP priming using *C. sativum* and *N. oleander* extracts (23). During seed priming, ZnO NPs may support early seedling growth by supplying readily available zinc, improving enzyme activity, helping chlorophyll formation and allowing better water and nutrient uptake during germination and early development (24–26). These findings also match the 30–60 % gains reported from microwave ZnO priming and the pod improvement observed with MgO nanoparticles in lentil, suggesting that nanoparticle-driven changes in early physiology can later support stronger vegetative growth and better productivity (27,28).

Biomass accumulation

Shoot biomass was maximised at 15 ppm, indicating that this

concentration provided an optimal balance between nutrient availability and physiological stimulation. The decline in root:shoot ratio from 1.23 to 1.02 suggests a shift in assimilate partitioning toward shoot development, which is often associated with improved nutrient sufficiency and enhanced photosynthetic capacity (29). In the present study, the pronounced increases in shoot dry weight (+ 312 %) and total biomass (+ 239 %) may reflect ZnO-mediated antioxidant upregulation and chlorophyll stabilisation, which could reduce oxidative constraints during early development. These responses are consistent with reports in mung bean and other legumes, where low ZnO exposure enhanced shoot biomass and vegetative growth (29). The pronounced increase in shoot dry weight and total biomass in the present study may also reflect the role of pomegranate-mediated ZnO nanoparticles in gradual nutrient release, possibly due to polyphenol-zinc interactions that improve particle stability and uptake efficiency. Such a pattern suggests that ZnO nanoparticles may have supported more efficient vegetative growth by promoting chlorophyll stability and reducing oxidative constraints during early development. Zinc is known to act as a structural and catalytic cofactor in several enzymes, including carbonic anhydrase and superoxide dismutase, which can improve CO₂ assimilation and antioxidant defence, thereby supporting biomass accumulation under nanoprimer conditions (27).

Yield enhancement

The marked improvement in reproductive traits at 15 ppm indicates that this concentration optimally supported the transition from vegetative growth to effective sink development. Increased pods per plant, seeds per pod and seed yield suggest improved floral retention, better pollen function and more efficient translocation of photo assimilates to developing reproductive structures. This response may be linked to ZnO-mediated enhancement of enzyme activity, membrane integrity and antioxidant protection during flowering and pod filling, when reproductive tissues are especially sensitive to oxidative stress. In addition, zinc availability is known to influence auxin metabolism and carbohydrate partitioning, which can favour pod initiation and seed development. The superior performance of *P. granatum*-mediated ZnO nanoparticles may further reflect improved particle uniformity and bioavailability, as polyphenol capping can enhance stability and controlled Zn release. Overall, the present findings align with earlier reports showing increased pod formation and yield under ZnO nanoprimer in legumes, supporting the role of ZnO nanoparticles in reproductive success and final productivity (27–30).

Dose response and phytotoxicity

Punica granatum peel-mediated synthesis provides eco-advantages over chemical methods. Optimal 15 ppm balances bioavailability against phytotoxicity (>20 ppm), aligning with pulse nanoprimer. At higher concentrations, ZnO NPs may become phytotoxic by generating oxidative stress, disturbing membrane integrity, or interfering with nutrient homeostasis, which can explain the reduced response at 25 ppm (31, 32). Previous studies reported a 76.04 % increase in shoot biomass in mung bean at 20 ppm nano ZnO, while biomass reduction at higher concentrations indicated toxicity beyond the optimum dose (29).

Conclusion

Green-synthesised ZnO nanoparticles from pomegranate peel extract, applied via seed priming, significantly enhanced growth, biomass accumulation and yield parameters in black gram (*V. mungo* cv. Pant U-12) under field conditions. The 15 ppm treatment (T₃) proved optimal, delivering 53 % plant height increase, 33–45 % root/shoot length gains, 312 % shoot dry weight, 103 % more leaves/plant and 168 % seed yield (153 g/plant vs. 57.2 g control). These improvements reflect ZnO NPs' multifaceted roles in nutrient delivery, photosynthesis enhancement and stress alleviation, validated across 45 DAS morphological and maturity yield assessments. This study establishes pomegranate peel-derived ZnO NPs as sustainable nanofertilizers, converting agro-waste into high-value biostimulants while minimizing chemical inputs. The concentration-dependent optima (decline > 20 ppm) highlight bioavailability-phytotoxicity balance critical for field application. Future research directions: Multi-location trials validate agro-climatic robustness, Biochemical assays (chlorophyll, antioxidants) elucidate mechanisms, Long-term soil microbial studies assess sustainability and Scale-up cost-benefit analysis for farmer adoption. These nano-priming strategies offer actionable pathways to boost pulse productivity amid climate challenges.

Authors' contributions

KB carried out the design and drafting of the research, performed the experiments and analysed the data and results. NN carried out the design of the research and supervised the whole research. MFS provided important technical, methodological and intellectual input in the study design and manuscript revision. 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

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