RESEARCH ARTICLE Indian Journal of Agricultural Research, Volume 60 Issue 6: 891-897 (June 2026)

Effect of Zinc and Copper Loaded Alginate Beads on Growth, Yield and Nutrient Use Efficiency of Black Gram (*Vigna mungo* L.)

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10.18805/IJARe.A-6559

ABSTRACT

Background: Black gram (*Vigna mungo* L.) is a major pulse crop valued for its protein content, but its productivity is often constrained by micronutrient deficiencies, particularly zinc (Zn) and copper (Cu). These nutrients are essential for enzyme activity, photosynthesis and reproductive development. Conventional fertilizers show low efficiency due to leaching and fixation losses, necessitating improved delivery systems. The study aimed to evaluate alginate-based micronutrient delivery for improving black gram performance.

Methods: A pot experiment was conducted during winter 2024-25 and summer 2025 at VISTAS, Chennai. Zinc and copper-loaded alginate beads were synthesized using the ionotropic gelation technique and characterized by atomic absorption spectroscopy. Seven treatments, including soil, foliar and combined applications along with control, were evaluated in a completely randomized design with three replications. Growth, yield and physiological parameters were recorded.

Result: Soil + foliar application of Zn (T_4) recorded the highest plant height (27.30 and 28.38 cm), dry matter (20.35 and 22.65 g plant^{-1}), pods per plant (20.39 and 22.42) and yield (13.68 and 14.29 g plant^{-1}) during winter and summer, respectively. This treatment also improved reproductive efficiency and growth vigour index compared to other treatments. Foliar Zn (T_6) showed comparable performance, while Cu treatments exhibited moderate improvements over the control.

Key words: Alginate beads, Black gram, Controlled-release, Micronutrients, Nutrient use efficiency, Sustainability.

INTRODUCTION

Black gram (*Vigna mungo* L.) is an important pulse crop widely cultivated across South and Southeast Asia, serving as a major source of dietary protein and contributing significantly to soil fertility through biological nitrogen fixation. Despite its agronomic importance, the productivity of black gram remains low due to multiple constraints, among which micronutrient deficiencies, particularly zinc (Zn) and copper (Cu), are critical limiting factors (Dhaliwal *et al.,* 2023; Singh *et al.,* 2024). These micronutrients play indispensable roles in plant metabolism. Zinc acts as a structural and catalytic component of numerous enzymes involved in auxin synthesis, protein metabolism and chlorophyll stabilization, whereas copper participates in redox reactions, lignin biosynthesis and photosynthetic electron transport (Singh *et al.,* 2024; Kumar *et al.,* 2024). Deficiency of these nutrients often leads to poor germination, stunted growth, delayed flowering and reduced yield in pulse crops.

Conventional micronutrient fertilizers, typically applied as soluble salts such as zinc sulphate and copper sulphate, suffer from low nutrient use efficiency due to losses through leaching, volatilization and fixation in soil (De Francisco *et al.,* 2024). Such inefficiencies not only reduce nutrient availability to plants but also contribute to environmental concerns, including soil degradation and water contamination. Therefore, there is a growing need to develop innovative and sustainable approaches for efficient micronutrient delivery in agricultural systems (Anbarasu *et al.,* 2025).

In recent years, controlled-release fertilizer systems based on biodegradable polymers have gained considerable attention as a promising alternative to conventional fertilization methods. Among these, alginate, a naturally

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How to cite this article: Joyal, M., Mariyappillai, A., Perumal, A. and Srinivasarao, S. (2026). Effect of Zinc and Copper Loaded Alginate Beads on Growth, Yield and Nutrient Use Efficiency of Black Gram (*Vigna mungo* L.). *Indian Journal of Agricultural Research*. **60(6):** 891-897. doi: 10.18805/IJARe.A-6559.

Submitted: 17-04-2026 **Accepted:** 07-05-2026 **Online:** 13-05-2026

occurring polysaccharide derived from brown seaweed, has emerged as an effective carrier material due to its biocompatibility, biodegradability and ability to form hydrogels through ionotropic gelation with divalent cations (Chen *et al.,* 2020). The "egg-box" model of alginate cross-linking enables the encapsulation of micronutrients such as Zn^{2+} and Cu^{2+} within a three-dimensional network, facilitating their gradual release into the soil (Hood and Pensini, 2022). This controlled-release behavior enhances nutrient availability, reduces losses and improves nutrient uptake efficiency by plants.

Several studies have demonstrated the potential of alginate-based systems in agriculture. Encapsulation of plant growth-promoting rhizobacteria in alginate beads has been shown to enhance seed germination and plant growth (Bashan *et al.,* 2014). Similarly, alginate matrices loaded with micronutrients or nanoparticles have improved nutrient delivery efficiency and plant performance under various environmental conditions (Raliya *et al.,* 2017; Jiménez-Arias *et al.,* 2025). However, most of these studies have primarily focused on single micronutrient delivery or microbial encapsulation, with limited attention to the combined delivery of essential micronutrients such as zinc and copper in pulse crops. In particular, there is a lack of systematic research on the synthesis, characterization and agronomic evaluation of zinc-copper alginate bead formulations in black gram under controlled conditions. This gap limits the understanding of their potential to enhance nutrient use efficiency, plant growth and yield performance in sustainable pulse production systems.

Considering the importance of micronutrient management in pulse crops and the advantages of controlled-release systems, the present study was undertaken to develop zinc and copper alginate beads using an ionotropic gelation technique. The synthesized beads were characterized using advanced analytical techniques and their effectiveness was evaluated through pot culture experiments in black gram. The study aims to assess the potential of alginate-based micronutrient delivery systems in enhancing plant growth, yield and overall crop performance while minimizing environmental impact.

MATERIALS AND METHODS

Study location and experimental design

The experiment was conducted during the winter and summer seasons of 2025 at the Vels Institute of Science, Technology and Advanced Studies (VISTAS), Pallavaram, Chennai, India. A pot culture experiment was carried out under controlled greenhouse conditions to evaluate the effect of zinc and copper-loaded alginate beads on the growth and yield of black gram (*Vigna mungo* L.). The experiment consisted of seven treatments, including soil application, foliar application and combined soil and foliar application of micronutrient-loaded alginate beads, along with an untreated control. The treatments were arranged in a completely randomized design (CRD) with three replications to ensure statistical validity (Gomez and Gomez, 1984). Each pot (30 cm diameter × 25 cm height) was filled with 5 kg of soil mixture and two plants were maintained per pot after thinning to ensure uniform plant population (Anbarasu *et al*., 2024).

Chemicals and materials

Sodium alginate, zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$) and copper sulphate pentahydrate ($CuSO_4 \cdot 5H_2O$) were used for the preparation of micronutrient-loaded alginate beads. All chemicals used in the study were of analytical grade and procured from standard chemical suppliers. Distilled water was used for preparing all solutions and reagents required for bead synthesis and experimental applications (Lee and Mooney, 2012).

Preparation of sodium alginate solution

A sodium alginate solution was prepared by dissolving 1 g of sodium alginate powder in 20 mL of distilled water at room temperature. The mixture was continuously stirred using a magnetic stirrer until a clear and homogeneous solution was obtained. This resulted in a 5.0% (w/v) sodium alginate solution, which served as the polymer matrix for micronutrient encapsulation (Lee and Mooney, 2012).

Synthesis of zinc and copper alginate beads

Micronutrient-loaded alginate beads were synthesized using the ionotropic gelation technique. Separate aqueous solutions of zinc sulphate and copper sulphate were prepared by dissolving the respective salts in distilled water. The prepared sodium alginate solution was added dropwise into each metal salt solution using a dropper. Immediate gel formation occurred due to ionic crosslinking between divalent metal ions (Zn^{2+} and Cu^{2+}) and the carboxyl groups of alginate, resulting in the formation of spherical hydrogel beads.

The formed beads were allowed to remain in the respective metal salt solutions for approximately 10 minutes to ensure complete crosslinking. Subsequently, the beads were collected by filtration, washed thoroughly with distilled water to remove excess ions and dried in a hot air oven at 50-70°C until complete removal of moisture (Shaviv, 2005).

Determination of micronutrient content

The concentration of zinc and copper in the synthesized alginate beads was determined using atomic absorption spectroscopy (AAS). A known quantity of dried beads was subjected to acid digestion to convert bound metal ions into soluble form. The digested samples were filtered and diluted appropriately before analysis. The concentrations of Zn and Cu were measured at their respective wavelengths using an atomic absorption spectrophotometer (Welz and Sperling, 1999).

Crop establishment and treatment application

Black gram seeds (*Vigna mungo* L.) were sown in pots filled with a well-prepared soil mixture consisting of red soil, sand and farmyard manure (FYM) in a 1:1:1 ratio. The experimental soil had a pH of approximately 6.2 with adequate moisture and nutrient status suitable for crop growth. The treatments included: Soil application of Cu (T_1), Soil application of Zn (T_2), Soil + Foliar application of Cu (T_3), Soil + Foliar application of Zn (T_4), Foliar application of Cu (T_5), Foliar application of Zn (T_6) and an untreated control (T_7).

A 2% (w/v) suspension of micronutrient alginate beads (2 g beads per 100 mL water) was prepared for both soil and foliar applications and applied as soil placement near the root zone and as foliar spray at 25 and 45 days after sowing (DAS).

Data collection and statistical analysis

Observations on growth parameters such as plant height, leaf length, leaf width, root traits and dry matter production were recorded at different growth stages. Yield attributes including number of pods per plant, pod length, number of seeds per pod, seed yield per plant, 100-seed weight and yield (g plant^{-1}) were recorded at harvest.

The following indices were computed:

$$\text{Biomass efficiency (BE)} = \frac{\text{Seed yield (g plant}^{-1}\text{)}}{\text{Dry matter production (g plant}^{-1}\text{)}}$$

Reproductive efficiency (RE) =

$$\frac{\text{Number of pods per plant}}{\text{Dry matter production (g plant}^{-1}\text{)}}$$

Growth vigour index (GVI) =

$$\frac{\text{Plant height (cm)} \times \text{Leaf area index (LAI)} \times \text{Dry matter production (g plant}^{-1}\text{)}}{100}$$

The experimental data were subjected to analysis of variance (ANOVA) appropriate for a completely randomized design (CRD) to determine the significance of treatment effects at the 5% probability level. Statistical analysis was performed using SPSS (Version 25.0) following standard procedures described by Gomez and Gomez (1984). Treatment means were compared using the Critical Difference (CD) test at P = 0.05.

RESULTS AND DISCUSSION

Micronutrient content of alginate beads

The atomic absorption spectroscopy (AAS) analysis confirmed the successful incorporation of micronutrients into the alginate matrix (Table 1). The zinc alginate beads recorded a significantly higher metal concentration (40.3%) compared to copper alginate beads (18.2%). This higher loading capacity of zinc may be attributed to its stronger affinity towards alginate carboxyl groups and better coordination behavior. The results indicate that alginate beads are efficient carriers for micronutrient encapsulation and controlled delivery.

Effect of micronutrient loaded alginate beads on growth parameters of black gram

The application of micronutrient-loaded alginate beads significantly influenced the growth attributes of black gram during both winter 2024-25 and summer 2025 seasons (Table 2). Among the treatments, soil + foliar application of Zn (T_4) recorded the highest plant height of 27.30 cm and 28.38 cm during winter and summer, respectively, followed by foliar application of Zn (T_6) (26.90 cm and 27.88 cm) and soil application of Zn (T_2) (25.67 cm and 26.65 cm). The lowest plant height was observed in the control treatment (T7) with 19.67 cm and 20.45 cm.

The number of branches per plant was highest under soil + foliar application of Zn (T_4) with 6.58 and 6.63 branches during winter and summer, respectively, followed

Table 1: Micronutrient content of synthesized alginate beads determined by AAS.

Alginate bead type	Micronutrient element	Concentration (%)
Zinc alginate beads	Zn	40.3
Copper alginate beads	Cu	18.2

Table 2: Effect of zinc and copper loaded alginate beads on growth parameters of black gram (*Vigna mungo* L.).

Treatments	Winter- 2024-25				Summer- 2025			
	Plant height (cm)	No. of branches	LAI	DMP (g plant^{-1})	Plant height (cm)	No. of branches	LAI	DMP (g plant^{-1})
T_1- Soil application of Cu	21.23	4.78	3.37	15.77	22.21	5.23	3.43	18.17
T_2- Soil application of Zn	25.67	5.91	4.17	18.84	26.65	6.15	4.13	21.44
T_3- Soil + foliar application of Cu	24.90	5.75	3.75	18.48	25.68	5.58	4.21	20.88
T_4- Soil + foliar application of Zn	27.30	6.58	4.38	20.35	28.38	6.63	4.49	22.65
T_5- Foliar application of Cu	22.47	5.10	3.67	16.98	23.75	5.22	3.83	18.88
T_6- Foliar application of Zn	26.90	6.12	4.37	19.75	27.88	6.74	4.46	22.35
T_7- Control	19.67	4.42	3.22	14.55	20.45	4.27	3.29	16.81
SEd	1.42	0.38	0.21	1.18	1.56	0.44	0.24	1.36
CD (P=0.05)	3.09	0.83	0.46	2.57	3.39	0.96	0.52	2.96

by foliar application of Zn (T_6) (6.12 and 6.74). Leaf area index (LAI) was maximum in soil + foliar application of Zn (T_4) with 4.38 and 4.49, while the control recorded the lowest LAI (3.22 and 3.29). Dry matter production (DMP) was also significantly higher under soil + foliar application of Zn (T_4), registering 20.35 g plant^{-1} and 22.65 g plant^{-1} during winter and summer, respectively.

Compared with the control, T_4 increased plant height by 38.8% and 38.8%, number of branches by 48.9% and 55.3%, LAI by 36.0% and 36.5% and dry matter production by 39.9% and 34.7% during winter and summer, respectively. Similarly, T_6 enhanced the number of branches per plant by 38.5% and 57.9% over the control.

The superior performance of combined soil and foliar application of Zn (T_4) compared with soil or foliar application alone suggests that integrated nutrient delivery ensured continuous availability of micronutrients throughout the crop growth period. Soil application supplied nutrients for sustained uptake, while foliar feeding enabled rapid absorption during critical growth stages, thereby minimizing losses due to fixation.

The improvement in growth parameters may be attributed to the role of zinc in chlorophyll synthesis, enzyme activation, auxin metabolism and protein synthesis, which collectively enhance photosynthesis and biomass accumulation (Marschner, 2012; Cakmak, 2008). Copper treatments showed moderate improvements but were inferior to zinc treatments, possibly due to their comparatively limited role in vegetative growth processes.

Seasonal comparison indicated that growth parameters were slightly higher during Summer 2025 than Winter 2024-25 across most treatments. Higher temperature, increased solar radiation and favourable environmental conditions during summer may have enhanced photosynthetic activity and nutrient uptake, resulting in improved plant growth (Taiz and Zeiger, 2015). Overall, the results indicate that micronutrient-loaded alginate bead formulations improved nutrient availability and uptake efficiency, thereby promoting vegetative growth and plant vigour.

Effect of micronutrient loaded alginate beads on yield parameters of black gram

Micronutrient-loaded alginate bead treatments significantly influenced the yield attributes and yield of black gram during both winter 2024-25 and summer 2025 seasons (Table 3). Among the treatments, soil + foliar application of Zn (T_4) recorded the highest number of pods per plant (20.39 and 22.42), number of seeds per pod (6.67 and 7.40), pod length (6.24 cm and 6.38 cm), test weight (7.32 g and 7.81 g) and yield per plant (13.68 g and 14.29 g) during winter and summer, respectively. This was followed by foliar application of Zn (T_6) (19.71 and 21.87 pods plant^{-1}, 6.89 and 7.18 seeds pod^{-1}, 5.85 and 6.29 cm pod length, 7.16 and 7.81 g test weight, 13.58 and 13.90 g plant^{-1} yield) and soil application of Zn (T_2), which also recorded superior yield parameters compared to other treatments.

In contrast, the control treatment (T_7) recorded the lowest values for all yield attributes, with 9.53 and 9.98 pods plant^{-1}, 4.92 and 5.83 seeds pod^{-1}, 4.55 and 4.69 cm pod length, 5.28 and 5.79 g test weight and yield per plant of 9.88 g and 10.39 g during winter and summer, respectively.

Relative to the control, T_2 increased the number of pods per plant by 113.9% and 124.6%, seeds per pod by 35.6% and 26.9%, pod length by 37.1% and 36.0%, test weight by 38.6% and 34.9% and yield per plant by 38.5% and 37.5% during winter and summer, respectively.

The higher yield under T_2 compared with other treatments suggests that combined soil and foliar application of Zn was more effective in meeting crop nutrient demand throughout the growth cycle. Since zinc plays a crucial role in reproductive development, its continuous availability may have improved flower retention, pod formation and seed filling.

The role of alginate beads in improving yield extends beyond micronutrient supply. The encapsulated formulation likely released nutrients in a gradual and synchronized manner, ensuring continuous availability during the crop growth period. This slow-release mechanism would have reduced nutrient losses through leaching and fixation,

Table 3: Effect of zinc and copper loaded alginate beads on yield attributes and yield of black gram (*Vigna mungo* L.).

Treatments	Winter- 2024-25					Summer- 2025				
	No. of pods plant^{-1}	No. of seeds Pod^{-1}	Pod length (cm)	Test weight (g)	Yield (g plant^{-1})	No. of pods Plant^{-1}	No. of seeds Pod^{-1}	Pod length (cm)	Test weight (g)	Yield (g plant^{-1})
T_1- Soil application of Cu	11.34	5.80	4.73	5.72	10.56	12.67	5.81	4.97	6.31	11.27
T_2- Soil application of Zn	17.89	6.79	5.58	6.89	12.86	19.77	6.90	5.98	7.38	13.47
T_3- Soil + foliar application of Cu	16.76	6.20	5.61	6.69	12.28	18.53	6.71	5.85	7.28	12.99
T_4- Soil + foliar application of Zn	20.39	6.67	6.24	7.32	13.68	22.42	7.40	6.38	7.81	14.29
T_5- Foliar application of Cu	13.17	5.60	4.99	5.84	11.27	14.37	6.51	5.41	6.53	11.68
T_6- Foliar application of Zn	19.71	6.89	5.85	7.16	13.58	21.87	7.18	6.29	7.81	13.9
T_7- Control	9.53	4.92	4.55	5.28	9.88	9.98	5.83	4.69	5.79	10.39
SEd	1.12	0.46	0.38	0.52	0.96	1.28	0.58	0.44	0.61	1.12
CD (P=0.05)	2.44	1.00	0.83	1.13	2.09	2.79	1.26	0.96	1.33	2.44

resulting in more efficient utilization of micronutrients (Shaviv, 2005).

Furthermore, the biodegradable alginate matrix may have enhanced rhizosphere microbial activity, indirectly improving nutrient mobilization and uptake. Compared with conventional micronutrient fertilizers, the alginate-based encapsulated formulation appears to provide superior efficiency due to its prolonged nutrient release and reduced losses. Similar findings have been reported in legumes, where encapsulated micronutrient fertilizers increased yield and nutrient use efficiency significantly (Subramanian *et al.,* 2015).

The improvement in yield attributes under zinc treatments may be attributed to enhanced photosynthetic efficiency, enzyme activity and translocation of assimilates from source to sink during reproductive stages. Zinc plays a key role in auxin synthesis and protein metabolism, which contribute to better pod formation and seed development (Marschner, 2012; Cakmak, 2008).

Effect of micronutrient application on biomass efficiency, reproductive efficiency and growth vigour index of black gram

Micronutrient application significantly influenced biomass efficiency (BE), reproductive efficiency (RE) and growth vigour index (GVI) of black gram during both winter 2024-25 and summer 2025 seasons (Table 4). Among the treatments, soil + foliar application of Zn (T_4) recorded superior performance with higher reproductive efficiency (1.00 and 0.99) and growth vigour index (24.33 and 28.86) during winter and summer, respectively. This was followed by foliar application of Zn (T_6), which also registered higher RE (1.00 and 0.98) and GVI (23.22 and 27.79). Soil application of Zn (T_2) and combined application of Cu (T_3) showed moderate improvement over individual Cu treatments. Biomass efficiency exhibited relatively narrow variation across treatments, with slightly higher values observed under Zn treatments, particularly T_6 (0.69) during winter, while in summer all treatments ranged between 0.62 and 0.63. The limited variation in BE across treatments indicates that total biomass production and its conversion into economic yield were relatively stable, suggesting that micronutrient application had a more pronounced effect on reproductive traits than on overall biomass accumulation.

In contrast, the control treatment (T_7) recorded the lowest values for all indices, with BE (0.68 and 0.62), RE (0.65 and 0.59) and GVI (9.22 and 11.31) during winter and summer, respectively. Compared to control, T_4 showed a substantial increase in reproductive efficiency and growth vigour index, indicating improved biomass partitioning and reproductive success. The higher performance of Zn-treated plants, particularly under combined soil and foliar application, suggests better nutrient availability throughout the crop growth period, leading to enhanced physiological efficiency.

Although RE values approaching 1.00 may appear unusually high, this can be attributed to efficient biomass partitioning under optimal micronutrient supply, where a greater proportion of assimilates is directed towards pod formation rather than vegetative growth. Additionally, the calculation of RE as a ratio of number of pods to dry matter production may result in values close to unity under conditions of high reproductive output and relatively moderate biomass accumulation.

The superior performance under Zn treatments can be attributed to its essential role in enzymatic activation, chlorophyll synthesis and auxin production, which collectively enhance vegetative growth and reproductive development (Joyal *et al.,* 2026). The increased reproductive efficiency indicates improved flower retention and pod formation, while higher GVI reflects enhanced plant growth through increased plant height, leaf area index and dry matter accumulation. The comparatively lower performance of Cu treatments may be due to its limited requirement and mobility in plants compared to Zn.

Furthermore, combined soil and foliar application ensured continuous nutrient supply, improving nutrient uptake efficiency and minimizing losses. These findings are in agreement with earlier reports that zinc fertilization enhances physiological efficiency, biomass production and yield attributes in legumes by improving metabolic activities and assimilate translocation (Marschner, 2012; Cakmak, 2008; Hafeez *et al.,* 2013). The results clearly indicate that integrated micronutrient management, particularly with zinc, plays a crucial role in improving crop performance under varying seasonal conditions.

Table 4: Effect of zinc and copper loaded alginate beads on biomass efficiency, reproductive efficiency and growth vigour index of black gram (*Vigna mungo* L.).

Treatments	Winter- 2024-25			Summer- 2025		
	Biomass efficiency	Reproductive efficiency	Growth vigour index	Biomass efficiency	Reproductive efficiency	Growth vigour index
T_1- Soil application of Cu	0.67	0.72	11.28	0.62	0.70	13.84
T_2- Soil application of Zn	0.68	0.95	20.17	0.63	0.92	23.60
T_3- Soil + foliar application of Cu	0.66	0.91	17.26	0.62	0.89	22.57
T_4- Soil + foliar application of Zn	0.67	1.00	24.33	0.63	0.99	28.86
T_5- Foliar application of Cu	0.66	0.78	14.00	0.62	0.76	17.17
T_6- Foliar application of Zn	0.69	1.00	23.22	0.62	0.98	27.79
T_7- Control	0.68	0.65	9.22	0.62	0.59	11.31

Overall, the results clearly demonstrate that micronutrient-loaded alginate bead formulations, particularly zinc-based treatments, significantly enhanced growth, yield and physiological efficiency of black gram across both seasons. The superior performance of combined soil and foliar application (T_4) highlights the importance of continuous and balanced nutrient supply throughout the crop growth period. The improved biomass efficiency, reproductive efficiency and growth vigour index indicate better assimilate partitioning and enhanced plant metabolic activity. The slow-release nature of alginate beads likely reduced nutrient losses and ensured sustained availability, contributing to higher nutrient use efficiency. Zinc played a crucial role in promoting photosynthesis, enzyme activation and reproductive development, resulting in improved yield attributes. Seasonal variations further supported the effectiveness of treatments under favourable environmental conditions. Thus, alginate-based micronutrient delivery systems can be considered an efficient and sustainable approach for enhancing crop productivity.

CONCLUSION

The present study clearly establishes that micronutrient-loaded alginate bead formulations are effective and sustainable carriers for enhancing nutrient use efficiency and productivity in black gram. The higher encapsulation efficiency of zinc and its gradual release from the alginate matrix ensured continuous nutrient availability, resulting in significant improvements in growth parameters, yield attributes and physiological indices such as biomass efficiency, reproductive efficiency and growth vigour index. Among the treatments, combined soil and foliar application of zinc (T_4) consistently outperformed all other treatments across both seasons, highlighting the importance of integrated nutrient management.

The superior performance of zinc-loaded treatments underscores the role of controlled-release nutrient delivery in improving crop efficiency by minimizing losses and ensuring sustained availability during critical growth stages. Seasonal variations further indicated the stability of the treatment under different environmental conditions. Overall, the findings suggest that zinc-loaded alginate bead technology, coupled with integrated application methods, offers a promising approach for improving crop productivity, nutrient efficiency and sustainability in pulse-based cropping systems.

Future research should focus on validating these results under field conditions, evaluating long-term effects on soil health and optimizing dosage and application timing for different agro-climatic regions. Additionally, economic analysis and large-scale field trials are essential to assess the feasibility of adopting this technology in practical farming systems.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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