



Effect of Micronutrient Loaded Alginate Beads on the Growth and Yield of Black Gram (*Vigna mungo* L.)

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ABSTRACT

Background: Black gram (*Vigna mungo* L.) is an important pulse crop and a major source of protein in many tropical countries. However, its productivity is often constrained by micronutrient deficiencies such as iron (Fe), zinc (Zn) and copper (Cu). These micronutrients are essential for plant growth, photosynthesis and enzyme activity. Conventional fertilizers often show low efficiency due to nutrient losses in soil. Therefore, controlled-release nutrient delivery systems like alginate-based beads may improve micronutrient availability and crop productivity.

Methods: A pot culture experiment was conducted during Winter and Summer 2025 at Vels Institute of Science, Technology and Advanced Studies (VISTAS), Chennai. Micronutrient-loaded alginate beads containing Fe, Zn and Cu were synthesized using the ionotropic gelation method and analyzed using Atomic Absorption Spectroscopy. The experiment consisted of ten treatments including soil, foliar and combined applications along with a control. The treatments were arranged in a randomized block design with three replications. Growth and yield parameters were recorded at different stages of crop growth.

Result: Foliar application of Fe (T₇) recorded the highest plant height (28.40 and 29.38 cm), dry matter (20.86 and 23.46 g plant⁻¹), pods per plant (21.82 and 24.31) and yield (14.22 and 14.83 g) during Winter and Summer (2025). It also produced higher seeds per pod (6.99 and 7.67), pod length (6.68 and 6.62 cm) and test weight (7.61 and 8.10 g). Soil + foliar application of Fe (T₄) and Zn (T₆) also improved growth and yield compared to the control. These results indicate that alginate-based micronutrient delivery enhanced nutrient uptake and crop productivity.

Key words: Alginate beads, Black gram, Controlled-release fertilizer, Iron, Micronutrients, Sustainable agriculture, Zinc.

INTRODUCTION

Black gram (*Vigna mungo* L.) is one of the most important pulse crops cultivated in tropical and subtropical regions, particularly in India, where it serves as a major source of dietary protein for the predominantly vegetarian population. The crop is valued for its high nutritional content, including proteins, carbohydrates, vitamins and minerals and plays a crucial role in ensuring food and nutritional security (Anbarasu *et al.*, 2025). In addition to its dietary importance, black gram contributes to soil fertility through biological nitrogen fixation and fits well into diverse cropping systems, making it an important component of sustainable agriculture (Ali and Gupta, 2012).

Despite its importance, the productivity of black gram remains relatively low in many regions due to several agronomic and soil-related constraints. Among these factors, micronutrient deficiencies in soils have emerged as a major limitation to pulse crop production. Micronutrients such as iron (Fe), zinc (Zn) and copper (Cu) are essential for various physiological and biochemical processes in plants, including chlorophyll synthesis, enzyme activation, protein synthesis and nitrogen metabolism. Deficiency of these nutrients can lead to poor plant growth, reduced nodulation and lower yield in pulse crops (Alloway, 2008; Cakmak, 2008).

In recent decades, intensive cropping, imbalanced fertilizer application and depletion of soil organic matter have increased the incidence of micronutrient deficiencies in agricultural soils. Zinc deficiency, in particular, is considered

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one of the most widespread micronutrient disorders affecting crop productivity worldwide. Iron deficiency is also common in calcareous and alkaline soils, leading to chlorosis and reduced photosynthetic activity. Similarly, copper plays an important role in reproductive growth and enzyme functioning and its deficiency can negatively affect crop yield and quality (Marschner, 2012).

Conventional micronutrient fertilizers are usually applied through soil or foliar methods; however, their effectiveness is often limited by rapid nutrient release, leaching losses and fixation reactions in the soil. As a result, a significant portion of applied nutrients becomes unavailable to plants, reducing nutrient use efficiency. Therefore, the development of innovative and efficient nutrient delivery systems has become a key research priority in modern agriculture to enhance nutrient use efficiency and reduce environmental losses (Trenkel, 2010).

Controlled-release fertilizer technologies have gained considerable attention as a promising strategy for improving nutrient management in crop production systems. Among these approaches, polymer-based encapsulation systems have shown potential for regulating nutrient release according to crop demand. Natural biopolymers such as alginate are particularly attractive for this purpose due to their biodegradability, non-toxicity and excellent gel-forming ability. Alginate is a naturally occurring polysaccharide derived from brown seaweeds and forms stable hydrogels when crosslinked with multivalent cations such as calcium, iron, or zinc (Lee and Mooney, 2012).

Alginate-based beads can encapsulate micronutrients and release them gradually into the soil solution, thereby improving nutrient availability and reducing nutrient losses. In addition, the hydrogel matrix of alginate beads can enhance soil moisture retention and create a favorable microenvironment in the rhizosphere for plant growth. Previous studies have reported that controlled-release fertilizers and encapsulated nutrient formulations can significantly improve nutrient use efficiency and crop productivity compared with conventional fertilizer application methods (Shaviv, 2005).

Considering the importance of micronutrients in pulse crop production and the advantages of controlled-release nutrient delivery systems, the use of micronutrient-loaded alginate beads may provide an innovative approach to improve the growth and yield of black gram. However, limited research has been conducted on the application of alginate-based micronutrient formulations in pulse crops. Therefore, the present study was undertaken to evaluate the effect of micronutrient-loaded alginate beads on the growth and yield of black gram (*Vigna mungo* L.) and to assess their potential as a sustainable micronutrient management strategy.

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 open environmental conditions to evaluate the effect of micronutrient-loaded alginate beads on the growth and yield of black gram (*Vigna mungo* L.) variety VBN 8. The experiment consisted of ten treatments including soil

application, foliar application and combined soil and foliar application of micronutrient-loaded alginate beads, along with a control without micronutrient application. The treatments were arranged in a randomized block design (RBD) with three replications to ensure statistical reliability of the results (Gomez and Gomez, 1984).

Chemicals and materials

Sodium alginate, copper sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$), zinc sulfate heptahydrate ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$) and ferric chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) were used for the preparation of micronutrient-loaded alginate beads. All chemicals used in the study were of analytical grade and obtained from standard chemical suppliers. Distilled water was used for preparing all solutions and reagents required for bead synthesis and experimental applications (Mohanambal *et al.*, 2026).

Preparation of sodium alginate solution

A sodium alginate solution was prepared by dissolving 0.5 g of sodium alginate powder in 50 mL of distilled water at room temperature. The solution was stirred continuously using a magnetic stirrer until a clear and homogeneous solution was obtained. This process produced a 1.0% (w/v) sodium alginate solution, which served as the base polymer matrix for encapsulating micronutrients (Lee and Mooney, 2012).

Synthesis of micronutrient alginate beads

Micronutrient-loaded alginate beads were synthesized using the ionotropic gelation technique. Separate aqueous solutions of copper sulfate, zinc sulfate and ferric chloride were prepared by dissolving the respective salts in distilled water. The prepared sodium alginate solution was added dropwise into the metal salt solutions using a dropper. Immediate gel formation occurred due to ionic crosslinking between the metal ions (Cu^{2+} , Zn^{2+} , Fe^{3+}) and the carboxyl groups of alginate, resulting in the formation of spherical hydrogel beads with micronutrient availability (Table 1). The formed beads were allowed to remain in the metal salt solution 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 micronutrients 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 the bound metal ions into soluble form. The digested samples were filtered and diluted appropriately before analysis (Table 2). The concentrations of copper, iron and zinc were then measured using an atomic absorption spectrophotometer at their respective wavelengths, following standard analytical procedures (Welz and Sperling, 1999).

Crop establishment and treatment application

Black gram seeds of variety VBN 8 were sown in pots containing well-prepared soil. A total of ten treatments were evaluated: T₁- Soil application of Fe, T₂- Soil application of Cu, T₃- Soil application of Zn, T₄- Soil + foliar application of Fe, T₅- Soil + foliar application of Cu, T₆- Soil + foliar application of Zn, T₇- Foliar application of Fe, T₈- Foliar application of Cu, T₉ - Foliar application of Zn and T₁₀- Control (without micronutrient application). A 2% suspension of micronutrient alginate beads was used for both soil and foliar applications. Foliar spraying was carried out at 25 and 45 days after sowing using a hand-operated sprayer (Fig 1).

Data collection and statistical analysis

Observations on growth parameters such as plant height, number of branches, leaf area index (LAI) and dry matter production were recorded at appropriate growth stages. Yield attributes including number of pods per plant, number of seeds per pod, pod length, test weight and yield per plant were recorded at harvest. The experimental data were statistically analyzed using analysis of variance (ANOVA) appropriate for a randomized block design to determine the significance of treatment effects at the 5% probability level (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

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-2025 and Summer-2025 seasons (Table 3). Among the treatments, foliar application of Fe (T₇) recorded the highest plant height of 28.40 cm and 29.38 cm during Winter and Summer, respectively, followed by soil + foliar application of Fe (T₄) (27.98 cm and 28.76 cm) and soil + foliar application of Zn (T₆) (27.30 cm and 28.38 cm). The lowest plant height was observed in the control treatment (T₁₀) with 19.67 cm and 20.45 cm.

The number of branches per plant was highest under soil + foliar application of Zn (T₆) with 6.58 and 6.63 branches during Winter and Summer, respectively, followed by foliar application of Fe (T₇) (6.51 and 6.78). Leaf area index (LAI) was maximum in soil + foliar application of Fe (T₄) with 4.64 and 4.50, while the control recorded the lowest LAI (3.22 and 3.29). Dry matter production (DMP) was also significantly higher under foliar application of Fe (T₇), registering 20.86 g plant⁻¹ and 23.46 g plant⁻¹ during Winter and Summer, respectively.

Table 1: Micronutrient alginate beads synthesized using the ionotropic gelation method.

Bead type	Metal salt used	Chemical formula	Metal Ion involved	Role in bead formation
Copper alginate beads	Copper sulfate	CuSO ₄ ·5H ₂ O	Cu ²⁺	Crosslinks with alginate carboxyl groups to form Cu-alginate hydrogel beads.
Ferric alginate beads	Ferric chloride hexahydrate	FeCl ₃ ·6H ₂ O	Fe ³⁺	Forms ferric-alginate network through ionic interaction with alginate chains.
Zinc alginate beads	Zinc sulfate heptahydrate	ZnSO ₄ ·7H ₂ O	Zn ²⁺	Produces Zn-alginate hydrogel beads via ionic crosslinking.



Fig 1: Pot culture experiment on the micronutrient loaded alginate beads on the black gram.

The improvement in growth parameters may be attributed to the role of Fe and Zn in chlorophyll synthesis, enzyme activation and metabolic activities, which enhance photosynthesis and biomass accumulation (Marschner, 2012; Alloway, 2008). Seasonal comparison indicated that growth parameters were slightly higher during Summer-2025 than Winter-2025 across most treatments. Higher temperature, increased solar radiation and favorable 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 vigor.

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-2025 and Summer-2025 seasons (Table 4). Among the treatments, foliar application of Fe (T_7) recorded the highest number of pods per plant (21.82 and 24.31), number of seeds per pod (6.99 and 7.67), pod length (6.68 cm and 6.62 cm), test weight (7.61 g and 8.10 g) and yield per plant (14.22 g and 14.83 g) during Winter and Summer, respectively. This was followed by soil + foliar application of Fe (T_4) (21.31 and 23.53 pods plant⁻¹, 6.76 and 7.77

seeds pod⁻¹, 6.29 and 6.53 cm pod length, 7.50 and 7.39 g test weight, 13.98 and 14.62 g plant⁻¹ yield) and soil + foliar application of Zn (T_6) (20.39 and 22.42 pods plant⁻¹, 6.67 and 7.40 seeds pod⁻¹, 6.24 and 6.38 cm pod length, 7.32 and 7.81 g test weight, 13.68 and 14.29 g plant⁻¹ yield), which also recorded superior yield parameters compared to other treatments. In contrast, the control treatment (T_{10}) 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.

The improvement in yield attributes under Fe and Zn treatments may be attributed to enhanced photosynthetic efficiency, increased enzyme activity and improved translocation of assimilates from source to sink during the reproductive stage (Meena *et al.*, 2013). Iron plays a vital role in chlorophyll formation and energy transfer, while zinc is crucial for auxin synthesis and protein metabolism, contributing to better pod formation and seed development (Marschner, 2012; Cakmak, 2008; Anbarasu *et al.*, 2025). Additionally, the controlled-release nature of alginate beads likely maintained micronutrient availability over an extended period, enhancing nutrient uptake efficiency and crop productivity (Choudhary *et al.*, 2017). Similar trends have been reported with controlled-release fertilizer technologies that improve nutrient use efficiency and yield compared with conventional fertilizer applications (Shaviv, 2005).

Overall, the results suggest that micronutrient-loaded alginate beads, particularly foliar application of Fe and combined soil + foliar application of Zn, significantly enhanced yield attributes and productivity of black gram (Kumar *et al.*, 2018). The gradual release of micronutrients from the alginate matrix improved nutrient availability and utilization by plants, ultimately leading to higher yield and better crop performance.

Table 2: Micronutrient content of synthesized alginate beads determined by AAS.

Alginate bead type	Micronutrient element	Concentration (%)
Copper alginate beads	Cu	18.2
Ferric alginate beads	Fe	14.6
Zinc alginate beads	Zn	40.3

Table 3: Effect of micronutrient-loaded alginate beads on growth attributes of blackgram.

Treatments	Winter - 2025				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 Fe	26.93	6.18	4.23	19.88	27.51	6.38	4.33	22.38
T_2 - Soil application of Cu	21.23	4.78	3.37	15.77	22.21	5.23	3.43	18.17
T_3 - Soil application of Zn	25.67	5.91	4.17	18.84	26.65	6.15	4.13	21.44
T_4 - Soil + foliar application of Fe	27.98	6.34	4.64	20.75	28.76	6.39	4.50	23.15
T_5 - Soil + foliar application of Cu	24.90	5.75	3.75	18.48	25.68	5.58	4.21	20.88
T_6 - Soil + foliar application of Zn	27.30	6.58	4.38	20.35	28.38	6.63	4.49	22.65
T_7 - Foliar application of Fe	28.40	6.51	4.56	20.86	29.38	6.78	4.57	23.46
T_8 - Foliar application of Cu	22.47	5.10	3.67	16.98	23.75	5.22	3.83	18.88
T_9 - Foliar application of Zn	26.90	6.12	4.37	19.75	27.88	6.74	4.46	22.35
T_{10} - Control	19.67	4.42	3.22	14.55	20.45	4.27	3.29	16.81
SEd	4.86	1.1	0.77	3.58	5.74	1.27	0.93	5.98
CD (P=0.05)	10.56	2.43	1.68	7.79	11.44	2.58	1.84	10.19

Table 4: Effect of micronutrient-loaded alginate beads on yield attributes of blackgram.

Treatments	Winter - 2025					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 Fe	19.65	6.80	5.98	7.22	13.49	21.83	7.21	6.30	7.71	14.30
T ₂ - 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 ₃ - 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 ₄ - Soil + foliar application of Fe	21.31	6.76	6.29	7.50	13.98	23.53	7.77	6.53	7.39	14.62
T ₅ - 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 ₆ - 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 ₇ - Foliar application of Fe	21.82	6.99	6.68	7.61	14.22	24.31	7.67	6.62	8.10	14.83
T ₈ - 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 ₉ - 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 ₁₀ - Control	9.53	4.92	4.55	5.28	9.88	9.98	5.83	4.69	5.79	10.39
SEd	3.31	1.19	1.07	1.28	2.42	3.64	1.70	1.31	1.77	3.03
CD (P=0.05)	7.19	2.59	2.34	2.79	5.25	7.91	3.10	2.58	3.28	5.86

CONCLUSION

The present study demonstrated that the application of micronutrient-loaded alginate beads significantly improved the growth and yield attributes of black gram (*Vigna mungo* L.) during both Winter and Summer seasons. Among the treatments, foliar application of iron (Fe) recorded the highest plant height, dry matter production, number of pods per plant, seeds per pod, test weight and yield per plant compared to other treatments and the control. Soil + foliar application of zinc (Zn) and soil + foliar application of Fe also showed considerable improvement in growth and yield parameters. The enhanced performance may be attributed to improved micronutrient availability, better chlorophyll synthesis, increased enzymatic activity and efficient translocation of photosynthates resulting from the gradual release of nutrients from alginate bead formulations. Seasonal comparison indicated slightly higher growth and yield during the Summer season due to favorable environmental conditions. Overall, the findings suggest that micronutrient-loaded alginate bead technology can serve as an effective and sustainable nutrient management strategy for improving the productivity of black gram.

Disclaimers

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or

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