

Research Article

Enhancing germination and seedling growth in vegetable soybean: The impact of seed coating with nitrogen, phosphorus and potassium

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Abstract - Vegetable soybean seeds often experience low germination rates and poor seedling growth after planting, likely due to nutrient-deficient soils resulting from frequent cultivation. This study aimed to identify the optimal types and concentrations of nutrients to enhance germination and seedling growth in vegetable soybeans. Seeds were coated with nitrogen (N), phosphorus (P), and potassium (K) at four different concentration levels. The results showed that coating with NH_4NO_3 at 3.0 g/L significantly improved ($P < 0.01$) emergence percentage, germination percentage and shoot length compared to non-coated seeds under sand conditions. In the top of paper covered with sand test, it was observed that coating with NH_4NO_3 at 3.0 g/L resulted in faster germination compared to other treatments. The results from both sand and top-of-paper covered with sand conditions indicated that seed coating with NH_4NO_3 at all four concentration levels did not result in significant differences in root length and root fresh weight when compared to non-coated seeds. In conclusion, seed coating with NH_4NO_3 at 3.0 g/L is recommended as the most effective type and concentration to enhance germination and seedling growth of vegetable soybean seedlings, providing an efficient approach to improving seed quality through nutrient-based coating.

Keywords: Seed enhancement, seed vigor, seed germination, legume, plant nutrient

1. Introduction

Vegetable soybean (*Glycine max* (L.) Merr.) is an economically and nutritionally significant crop due to its high protein content and essential amino acids, making it a primary raw material in the food industry for both human and animal consumption (Nair et al., 2023). However, in vegetable soybean cultivation, common issues include low germination rates, weak seedlings, and suboptimal growth. These issues are often due to nutrient depletion in soils from repeated cultivation, leading to nutrient deficiencies essential for seed germination and early seedling development. Consequently, seedlings may exhibit abnormal growth and increased vulnerability to diseases and pests (Desclaux & Roumet, 1996; Dubey et al., 2019; Poudel et al., 2023).

Seed coating technology offers a promising solution by using a polymer film to encase seeds, serving as a medium to deliver active ingredients that support seed germination and early seedling growth (Javed et al., 2022; Kangsopa & Atnaseo, 2022; Zaim et al., 2023). Essential nutrients are particularly crucial for enhancing the germination and growth of vegetable soybean seedlings. These nutrients also play a significant role in addressing nutrient deficiencies in soils often depleted by repeated cultivation, contributing to the healthy establishment of plants. Among these, the primary macronutrients nitrogen (N), phosphorus (P), and potassium (K) are vital for seedling development. Nitrogen is fundamental for protein and nucleic acid synthesis, both of which are essential for cell division and tissue growth (Osuna et al., 2015). Liu et al. (2023) demonstrated that applying nitrogen at a concentration of 15 kg/hm² improved nodule number, nodule dry weight, nitrogenase activity, and nitrogen fixation potential in peanut seedlings. Similarly, phosphorus plays a key role in ATP production, providing the primary energy source for metabolic processes that drive cell expansion, seed development,

and nodule formation in legumes (Yang, 2018). Naabe et al. (2021) demonstrated that phosphorus application at 60 kg P₂O₅/ha significantly improves peanut growth, nodulation, and yield. Potassium regulates water balance and maintains turgor pressure within plant cells, enabling roots to efficiently absorb water and nutrients. This strengthens seedling vigor and resilience under adverse environmental conditions (Sivanesan et al., 2011). Moreover, potassium application at 60 kg K₂O/ha has been shown to enhance peanut growth, germination, and quality, even under temporary water deficit conditions. Kangsopa et al. (2024) selected NH₄NO₃, NaH₂PO₄·2H₂O, and KCl for soybean seed encrusting because they serve as highly water-soluble and easily absorbable sources of N, P, and K, ensuring efficient nutrient uptake without interference from other elements and minimizing nutrient interaction effects. The results demonstrated that this formulation significantly improved the germination rate of soybean seeds compared to non-encrusted seeds. Additionally, studies on tomato seed coating with a plant nutrient formulation containing N, P, K, Ca, Mg, Fe, B, Mn, Cu, and Zn revealed increased germination rates in both low-quality (76%) and medium-quality (87%) seeds. The nutrient coating also enhanced tetrazolium dehydrogenase (TDH) activity 48 h after imbibition, further promoting shoot length (Klarod et al., 2021).

This study aims to investigate the effects of coating soybean seeds with varying concentrations of nitrogen, phosphorus, and potassium, assessing changes in germination quality, vigor, and seedling growth. Testing under sand and top of paper covered with sand conditions will provide insights into effective seed coating techniques that can enhance germination efficiency and seedling vigor, ultimately contributing to more robust vegetable soybean cultivation.

2. Materials and methods

2.1 Seed sources and experimental sites

This experiment utilized vegetable soybean seeds of the CK-024 variety, provided by Lanna Agro-Industry Co., Ltd., with an initial germination rate of 70% and a moisture content of 10%. The research was conducted in the Modern Seed Technology Laboratory, Faculty of Agricultural Production, Maejo University, from January to September 2024.

2.2 Coating vegetable soybean seeds

This experiment utilized a commercial seed coating formulation provided by the Modern Seed Technology Research Center, Faculty of Agricultural Production, Maejo University. The formulation was prepared with three plant nutrients: NH_4NO_3 , $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$, and KCl, each applied at four different concentration levels. The treatments were as follows: T1 = non-coated, T2 = coated with polymer (CP), T3–T6 = CP + NH_4NO_3 at 1.0, 2.0, 3.0, and 4.0 g/L, respectively; T7–T10 = CP + $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 1.0, 2.0, 3.0, and 4.0 g/L, respectively; and T11–T14 = CP + KCl at 1.0, 2.0, 3.0, and 4.0 g/L, respectively. Each treatment was applied to vegetable soybean seeds using a KSC-40 rotary seed coater. The seed coating process utilized the fertilizer formula at a volume of 15 mL per kg of seed. The coated seeds were then dried using a dry-air dehumidifier (model SKK 40-2) for 24 h or until the moisture content decreased to 10%.

2.3 Seed measurement

The evaluation of seed quality after coating with plant nutrients in each treatment was conducted using two methods: sand testing, which assesses seed germination quality under conditions that closely mimic natural environments, and top of paper covered with sand testing, which evaluates seed germination quality under controlled conditions with limited light exposure and moisture regulation to test

seed vigor. Both methods comply with the germination testing standards outlined by [International Seed Testing Association \(2023\)](#).

2.3.1 Sand testing

Use sand with a uniform particle size of <0.5 mm and sterilize it, followed by further sterilization in an autoclave at 121°C for 15 min. The sterilized sand served as a medium for assessing seed quality. Each treatment consisted of 4 replications, with 50 seeds per replication, using plastic containers (180 mm × 140 mm × 90 mm, L × W × H) for the germination test. The sand's moisture content was adjusted to approximately 60%, and the containers were filled with a 3 cm layer of sand. Seeds were evenly placed on the sand surface and then covered with an additional 2 cm layer of sand. The containers were maintained under greenhouse conditions at 25 °C ± 5 °C and 80% ± 5% relative humidity (AeroLab THB1S Hygrometer Thermometer). Each test box was watered daily with 50 mL of water. Emergence percentage was evaluated by counting seeds where cotyledons emerged above the sand on days 1 and 4 after sowing ([Kangsopa et al., 2024](#)). Speed of emergence was measured by recording cotyledons emerging above the sand daily from day 1 to day 4. Germination percentage was determined based on seeds that developed into normal seedlings, with the first count taken on day 5 and the final count on day 8 ([International Seed Testing Association, 2023](#)). Speed of germination was assessed by counting seeds that developed into normal seedlings from day 5 to day 8 ([Association of Official Seed Analysts, 1983](#)). Mean germination time was calculated by recording normal seedlings daily over 8 days ([Ellis & Roberts, 1980](#)). Additionally, shoot length, root length, shoot fresh weight, and root fresh weight were measured 8 days after sowing ([Jeephet et al., 2022](#)).

2.3.2 Top of paper covered with sand testing (TPS)

The TPS method followed the same sand and plastic box preparation as the sand test. In this procedure, a germination paper is placed at the base of the box, and 50 seeds are evenly spread on top. A 2 cm layer of sand was added to cover the seeds. The box was then sealed and kept under conditions identical to those in the sand test. Seed quality traits were assessed using the same criteria as in the sand testing method.

2.4 Statistical analysis

The germination percentage was arcsine-transformed to normalize the data before the statistical analysis. All data were analyzed by one-way analysis of variance (ANOVA, completely randomized design), and the difference between the treatments was tested using Duncan's multiple range test (DMRT).

3. Results and discussion

3.1 Seed quality

The seed coating treatment using $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at a concentration of 1.0 g/L exhibited a high emergence rate, comparable to the performance of seeds coated with NH_4NO_3 at 2.0 g/L and 3.0 g/L, $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 2.0 g/L, and KCl at 4.0 g/L under sand test conditions. Under top-of-paper covered with sand conditions, the coatings of NH_4NO_3 at 3.0 g/L and KCl at 3.0 g/L resulted in a high emergence rate, which was significantly different compared to non-coated seeds. The seeds coated with $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at concentrations of 1.0 and 2.0 g/L and KCl at 3.0 g/L displayed a faster speed of emergence, which was significantly different from non-coated seeds under sand conditions. For the top of paper covered with sand test, seed coating with KCl at 3.0 g/L showed the fastest emergence rate, which was significantly higher compared to non-coated seeds (Table 1).

This experiment utilized commercially available seed coatings mixed with three essential nutrients—nitrogen (N), phosphorus (P), and potassium (K)—to assess their impact on seed emergence rate and speed of emergence (plants/day) under different test conditions. The sand test involves placing seeds in sand and covering them with another layer of sand to support seed germination, while the top of paper covered with sand test places seeds on moistened paper covered with a thin layer of sand to control moisture and simulate natural soil conditions ([International Seed Testing Association, 2023](#)). The results showed that seed coatings with NH_4NO_3 at 2.0 g/L, 3.0 g/L, and $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 1.0 g/L enhanced seed emergence under higher moisture levels provided by sand, as opposed to the top of paper covered test, where moisture is absorbed only from the sand layer covering the seeds. Phosphorus plays a crucial role in promoting seed germination by driving ATP production, which is vital for seedling emergence. When seeds receive adequate moisture, phosphorus dissolves and is absorbed more efficiently, boosting metabolic processes and energy utilization during seedling emergence ([Marschner, 2012](#); [Yang, 2018](#)). Nitrogen also promotes seed emergence under lower moisture conditions by stimulating the metabolism of stored proteins and nucleic acids, enabling seeds to release energy and essential nutrients quickly, even in low-moisture environments, thus facilitating efficient seedling growth ([Osuna et al., 2015](#)). Potassium supports seed germination in low-moisture conditions by regulating water balance within the seed cells and activating enzymes involved in protein synthesis and cell division. It enhances the seedling's tolerance to drought by improving water uptake and maintaining turgor pressure in plant cells ([Sivanesan et al., 2011](#); [Soares et al., 2016](#)). Therefore,

the seed coating with KCl at 3.0 g/L showed the most effective response across all concentrations. However, the experimental results indicated that the decrease in emergence percentage with increasing phosphorus concentration may be due to nutrient imbalance, osmotic stress, or toxicity caused by excess phosphorus. While lower concentrations of phosphorus supported metabolic

activities essential for germination, higher concentrations may disrupt nutrient uptake and the balance between nitrogen and potassium, thereby hindering water absorption and metabolic processes. These findings emphasized the importance of optimizing nutrient concentrations to maximize seed emergence and growth (Marschner, 2012; Soares et al., 2016; Yang, 2018).

Table 1. Emergence percentage and speed of emergence of vegetable soybean seeds after coating with different nitrogen, phosphorus, and potassium levels, tested under sand and top of paper covered with sand conditions.

Treatment ¹	Sand condition		Top of paper covered with sand condition	
	Emergence (%)	Speed of emergence (plant/day)	Emergence (%)	Speed of emergence (plant/day)
T1	37.58 ± 4 c-f	5.40 ± 1.96 c-e	5.46 ± 6 de	0.63 ± 0.80 e
T2	43.11 ± 6 b-d	6.35 ± 2.24 b-d	27.51 ± 5 a-c	3.31 ± 1.74 a-e
T3	30.21 ± 6 d-f	3.98 ± 2.18 de	33.20 ± 6 ab	4.13 ± 2.92 a-c
T4	62.47 ± 2 ab	2.98 ± 1.01 e	23.74 ± 4 a-d	4.56 ± 2.71 ab
T5	64.50 ± 6 ab	8.67 ± 2.49 ab	37.56 ± 3 a	2.88 ± 1.82 a-e
T6	42.74 ± 3 b-e	6.27 ± 1.97 b-d	32.12 ± 3 ab	3.96 ± 1.57 a-c
T7	68.52 ± 3 a	10.15 ± 2.13 a	8.30 ± 1 c-e	1.00 ± 0.73 de
T8	52.82 ± 2 a-c	9.60 ± 1.02 a	4.77 ± 1 e	0.50 ± 0.73 e
T9	37.04 ± 6 c-f	7.29 ± 2.77 a-c	29.34 ± 2 a-c	3.56 ± 1.36 a-d
T10	21.41 ± 4 d-f	5.23 ± 0.53 c-e	4.45 ± 4 de	0.50 ± 0.47 e
T11	20.38 ± 1 ef	2.75 ± 0.13 e	11.30 ± 3 b-e	1.31 ± 0.92 c-e
T12	17.22 ± 4 f	2.23 ± 1.01 e	16.95 ± 2 a-e	1.94 ± 1.16 a-e
T13	28.35 ± 5 d-f	3.79 ± 0.85 de	38.38 ± 2 a	4.75 ± 1.16 a
T14	59.46 ± 3 a-c	9.71 ± 1.65 a	14.63 ± 2 a-e	1.69 ± 1.07 b-e
F-test	**	**	**	**
CV.%	20.11	33.48	14.02	71.69

Note:** : significantly different at $P \leq 0.01$. Data were arcsine-transformed before analysis, and the back-transformed data are presented. Means within a column followed by the same letter are not significantly different at $P > 0.05$ according to DMRT. ¹ T1-T14 were different treatments specified in the materials and methods section.

In the sand condition, seed coating with NH_4NO_3 at 3.0 g/L resulted in a 14% increase in germination compared to non-coated seeds. For seed coating with NH_4NO_3 at all four concentrations (T3-T6), the speed of germination was not significantly different ($P > 0.01$) from that of non-coated seeds and seeds coated with other materials. Coating seeds with $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 2.0 g/L led to faster germination compared to non-coated

seeds. In the top of paper covered with sand condition, the germination percentage was not statistically different ($P > 0.01$) among treatments when compared to non-coated seeds, except for $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 1.0 g/L and KCl at 4.0 g/L, which exhibited reduced germination percentages and were statistically distinct ($P < 0.01$) from other treatments. Seed coating with NH_4NO_3 at 3.0 g/L and $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 4.0 g/L demonstrated

an increase in the speed of germination. For KCl at 3.0 g/L, seeds showed a reduction in the mean germination time to emergence, though this difference was not statistically significant compared to non-coated seeds (Table 2).

The results from both test methods, which evaluated seed quality, clearly showed differences in seed performance. Coating with NH_4NO_3 at 3.0 g/L resulted in the highest germination rate and speed of germination under both conditions, as this concentration optimally promotes these processes by providing a balanced source of nitrogen. NH_4NO_3 enhances seed germination more effectively than $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ and KCl due to nitrogen's crucial role in initiating germination. Nitrogen from NH_4NO_3 , in the form of NH_4^+ and NO_3^- , is absorbed immediately after imbibition, with NO_3^- acting as a signaling molecule that triggers gene expression and enzyme activity like nitrate reductase, which in turn boosts

ATP production necessary for rapid seedling growth (Lyu et al., 2022). This immediate availability of nitrogen accelerates the early stages of germination. In contrast, $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ provides phosphorus, essential for ATP and nucleic acid synthesis, which supports cell division and growth (Soares et al., 2016; Lambers, 2022), but its slower absorption compared to nitrogen limits its overall efficiency in promoting speed of germination. KCl, on the other hand, primarily regulates water balance within the seed and supports root growth and turgor pressure, but its impact on early germination is less pronounced. $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 2.0 g/L in sand shortens MGT by promoting early growth through efficient ATP production, while KCl at 3.0 g/L enhances osmotic regulation and cell expansion, allowing for faster germination in specific conditions compared to NH_4NO_3 (Taiz & Zeiger, 2010; Oosterhuis et al., 2014).

Table 2. Germination percentage (GE), speed of germination (SGE), and mean germination time (MGT) of vegetable soybean seeds after coating with different nitrogen, phosphorus, and potassium levels, tested under sand and top of paper covered with sand conditions.

Treatment ¹	Sand condition			Top of paper covered with sand condition		
	GE (%)	SGE (plant/day)	MGT (day)	GE (%)	SGE (plant/day)	MGT (day)
T1	70.25 ± 3 b-d ^{1,2}	4.19 ± 0.91 ab	6.19 ± 0.26 b-e	63.75 ± 6 ab	3.65 ± 0.54 b-d	6.4 ± 0.23 cd
T2	78.20 ± 8 a-c	4.21 ± 0.33 ab	6.21 ± 0.27 b-e	62.34 ± 4 ab	3.61 ± 0.34 b-d	7.07 ± 0.25 a
T3	71.41 ± 5 b-d	4.77 ± 0.69 a	6.47 ± 0.33 a-c	64.12 ± 6 ab	3.69 ± 0.53 b-d	6.32 ± 0.38 cd
T4	77.35 ± 4 a-c	4.32 ± 0.28 a	6.59 ± 0.48 ab	63.25 ± 10 ab	3.64 ± 0.22 b-d	6.52 ± 0.27 b-d
T5	84.70 ± 4 a	4.63 ± 0.89 a	5.94 ± 0.35 d-f	70.40 ± 6 a	4.70 ± 0.56 a	6.48 ± 0.32 b-d
T6	81.39 ± 6 ab	4.55 ± 0.72 a	6.00 ± 0.22 c-f	68.28 ± 8 a	4.23 ± 0.40 a-c	6.41 ± 0.27 cd
T7	76.56 ± 6 a-c	2.63 ± 0.38 c	5.77 ± 0.22 ef	46.72 ± 7 c	3.01 ± 0.53 d	7.19 ± 0.23 a
T8	67.47 ± 7 cd	2.52 ± 0.71 c	5.67 ± 0.26 f	62.56 ± 6 ab	4.48 ± 0.29 a-c	6.98 ± 0.23 ab
T9	62.33 ± 8 de	3.23 ± 0.45 bc	6.16 ± 0.28 b-f	62.51 ± 5 ab	3.94 ± 0.51 a-d	6.49 ± 0.36 b-d
T10	53.48 ± 7 ef	3.04 ± 0.48 c	6.40 ± 0.16 a-d	68.23 ± 7 a	4.72 ± 0.57 a	7.12 ± 0.33 a
T11	37.30 ± 4 g	2.43 ± 0.23 c	6.54 ± 0.05 ab	56.12 ± 6 a-c	3.74 ± 0.52 a-d	6.95 ± 0.29 ab
T12	42.45 ± 7 fg	2.73 ± 0.52 c	6.77 ± 0.09 a	69.45 ± 5 a	4.64 ± 0.16 ab	6.82 ± 0.18 a-c
T13	42.82 ± 4 fg	2.80 ± 0.46 c	6.58 ± 0.31 ab	66.23 ± 10 a	3.87 ± 0.75 a-d	6.24 ± 0.31 d
T14	70.54 ± 5 b-d	2.48 ± 0.42 c	5.90 ± 0.06 d-f	51.45 ± 13 bc	3.63 ± 0.82 cd	6.80 ± 0.24 a-c
F-test	**	**	**	*	**	**
CV.%	7.50	19.13	4.93	8.75	14.59	4.90

Note: *, **: significantly different at $P \leq 0.05$ and $P \leq 0.01$, respectively. Data were arcsine-transformed before analysis, and the back-transformed data are presented. Means within a column followed by the same letter are not significantly different at $P > 0.05$ by DMRT. ¹ T1-T14 were different treatments specified in the materials and methods section.

3.2 Seedling growth

Under sand conditions, seed coating with NH_4NO_3 at 3.0 g/L resulted in a statistically significant ($P < 0.01$) increase in shoot length compared to non-coated seeds. For root length, not significantly different ($P > 0.01$) were observed among treatments compared to non-coated seeds, except for seed coatings with KCl at concentrations of 1.0, 2.0, and 3.0 g/L, which exhibited shorter root lengths than other treatments. Under top of paper covered with sand conditions, NH_4NO_3 at 3.0 g/L produced greater shoot and root lengths compared to other treatments, although these differences were not statistically significant when compared to non-coated seeds (Table 3).

In the sand test, NH_4NO_3 promoted shoot length growth more effectively than $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ and KCl due to the availability of nitrogen in NH_4NO_3 in the form of NH_4^+ and NO_3^- . Nitrogen plays a crucial role in protein and nucleic acid (DNA and RNA) synthesis, which are essential for cell division and shoot elongation. Additionally, NO_3^- stimulates the activity of nitrate reductase, an enzyme involved in ATP production (Coskun et al., 2016; Lyu et al., 2022), which is necessary for shoot growth, resulting in superior shoot length in soybean seedlings compared to other treatments. Under top of paper covered

with sand conditions, NH_4NO_3 continued to promote superior shoot and root growth compared to $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ and KCl. Nitrogen in NH_4NO_3 supports balanced growth in both shoots and roots, as it enables the rapid expansion of root cells and triggers the elongation of shoots via NO_3^- signaling. The quick absorption of nitrogen allows seedlings to grow efficiently, even in the lower moisture conditions associated with the top of the paper-covered sand test. In contrast, phosphorus from $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ primarily supports ATP production and cell division (Marschner, 2012; Oosterhuis et al., 2014), but its absorption is slower than nitrogen. KCl, which supplies potassium, primarily contributes to osmotic regulation and the maintenance of cellular turgor. Under sand-test conditions, the lower KCl concentrations, particularly 2.0 and 3.0 g/L, resulted in shorter roots than the NH_4NO_3 and $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ -based treatments. These differences may be associated with the roles of nitrogen and phosphorus in protein synthesis, energy metabolism, and cell division, which are essential for root development (Marschner, 2012). In comparison, potassium in KCl mainly regulated water balance and did not directly influence early root growth as effectively as phosphorus and nitrogen.

Table 3. Shoot length and root length of vegetable soybean seeds after coating with different nitrogen, phosphorus, and potassium levels, tested under sand and top of paper covered with sand conditions.

Treatment ¹	Sand condition		Top of paper covered with sand condition	
	Shoot length (cm)	Root length (cm)	Shoot length (cm)	Root length (cm)
T1	12.82 ± 0.71 de	19.15 ± 1.98 ab	12.77 ± 1.07 a-c	15.34 ± 1.92 ab
T2	14.44 ± 0.80 cd	19.84 ± 2.54 ab	10.20 ± 3.06 a-d	14.29 ± 1.51 a-c
T3	11.53 ± 1.85 e	20.33 ± 3.31 ab	13.05 ± 1.96 ab	14.97 ± 0.92 a-c
T4	11.91 ± 1.81 e	20.84 ± 0.75 a	12.87 ± 2.77 ab	14.71 ± 1.73 a-c
T5	18.00 ± 1.43 a	20.85 ± 2.98 a	13.96 ± 1.94 a	17.42 ± 3.21 a
T6	16.23 ± 1.26 a-c	21.65 ± 1.34 a	12.82 ± 3.54 ab	16.17 ± 2.51 ab
T7	16.45 ± 0.93 a-c	21.03 ± 1.31 a	8.58 ± 1.60 d	11.57 ± 1.77 c
T8	17.07 ± 0.68 ab	21.51 ± 1.58 a	8.76 ± 1.32 d	13.37 ± 1.75 bc
T9	14.48 ± 1.24 cd	19.33 ± 2.26 ab	11.91 ± 1.46 a-d	15.88 ± 2.56 ab
T10	15.29 ± 0.62 bc	17.93 ± 0.85 a-c	9.05 ± 1.91 cd	15.29 ± 1.31 ab
T11	11.05 ± 0.68 e	16.75 ± 0.67 b-d	9.05 ± 0.84 cd	12.97 ± 0.86 bc
T12	11.17 ± 0.86 e	14.49 ± 1.00 cd	10.39 ± 0.81 a-d	16.14 ± 1.85 ab
T13	10.92 ± 1.65 e	13.14 ± 2.59 d	11.52 ± 1.53 a-d	16.30 ± 2.33 ab
T14	16.62 ± 1.29 a-c	17.86 ± 3.60 a-c	9.67 ± 1.26 b-d	13.40 ± 1.20 bc
F-test	**	**	**	*
CV.%	9.82	13.03	20.48	14.97

Note: *, **: significantly different at $P \leq 0.05$ and $P \leq 0.01$, respectively. Means within a column followed by the same letter are not significantly different at $P > 0.05$ by DMRT. ¹ T1-T14 were different treatments specified in the materials and methods section.

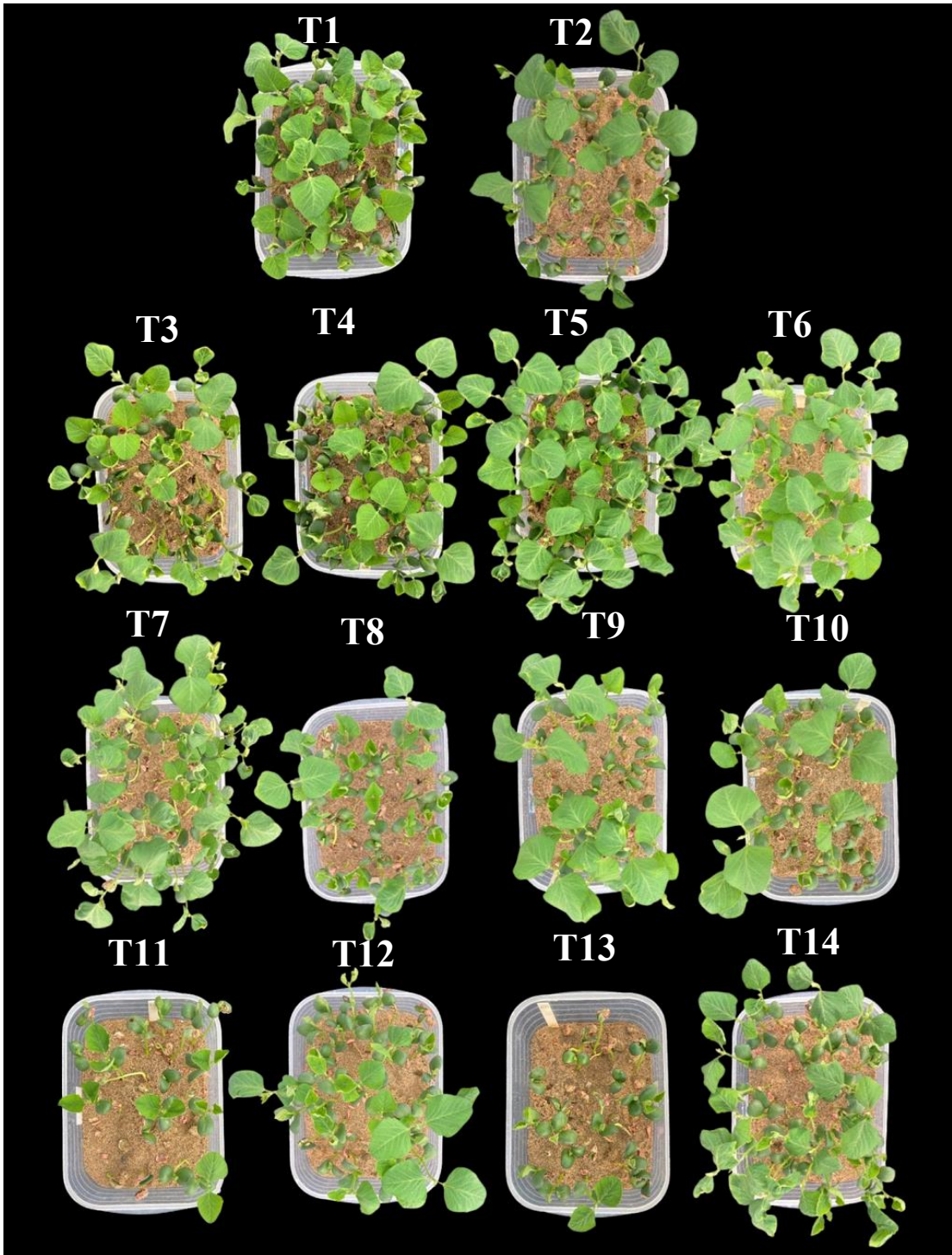


Figure 1. Normal vegetable soybean seedlings at 8 days after sowing following seed coating with different concentrations of nitrogen, phosphorus, and potassium under sand-test conditions. T1–T14 represent the treatments described in the Materials and methods section.

Under sand conditions, seed coating with NH_4NO_3 at 3.0 g/L, $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 4.0 g/L, and KCl at 4.0 g/L resulted in a statistically significant increase ($P < 0.05$) in shoot fresh weight ($P < 0.01$) compared to non-coated seeds. For root fresh weight, non-coated seeds and those coated with NH_4NO_3 or $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at all four concentrations had significantly greater root fresh weight ($P < 0.01$) compared to seeds coated with KCl at all concentrations. Under top of paper covered with sand conditions, the results showed no significant differences in shoot fresh weight among all treatments and non-coated seeds, except for $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 1.0 g/L and 4.0 g/L, as well as KCl at 1.0 g/L and 4.0 g/L, which exhibited reduced shoot fresh weight. Similarly, not significantly different ($P > 0.01$) in root fresh weight were observed among most treatments and non-coated seeds, except for $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ at 1.0 g/L, 2.0 g/L, and 4.0 g/L, and KCl at 1.0 g/L, which resulted in reduced root fresh weight (Table 4).

The test under sand conditions showed that seedlings had a higher shoot fresh weight compared to the top of paper covered with sand condition. This is because sand provides a porous and well-drained medium that facilitates better root aeration and water movement, allowing seeds to absorb nutrients more effectively. In contrast, the top of paper covered with sand condition creates a less uniform environment for water and nutrient availability, potentially leading to reduced nutrient uptake by the seedlings. Furthermore, nitrogen (NH_4^+ and NO_3^-) in NH_4NO_3 is a nutrient that plants can rapidly absorb, playing a crucial role in protein synthesis, an essential component of stem cells. Nitrogen also promotes nucleic acid synthesis and cell division, which are necessary for seedling growth, leading to increased accumulation of fresh weight in the shoots. The porous nature of sand also helped distribute nitrogen

uniformly around the seed, enhancing its absorption efficiency compared to the uneven distribution in the top-of-paper setup. Additionally, nitrogen in the form of NO_3^- acts as a signal that stimulates the activity of the enzyme nitrate reductase, which aids in the production of ATP, a critical energy source for stem cell expansion (Chen et al., 2018). These factors collectively result in higher shoot fresh weight under sand conditions than those observed with $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ and KCl treatments or in the top-of-paper covered with sand condition. For root fresh weight, seed coatings with NH_4NO_3 and $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ enhanced root growth more effectively than KCl in the sand test. Phosphorus in $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ plays a key role in ATP production, which is essential for root development. ATP provides the primary energy required for cell division and root cell expansion (Oosterhuis et al., 2014), while phosphorus promotes the formation of a robust root system, resulting in increased root fresh weight. NH_4NO_3 , on the other hand, boosts root growth through rapid protein synthesis and nitrogen metabolism. Potassium in KCl, although essential for water regulation, does not support cell division and root growth as effectively as phosphorus and nitrogen. Under top of paper covered with sand test conditions, seed coatings with NH_4NO_3 and $\text{NaH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ continued to promote higher root fresh weight than treatment with KCl. Both nitrogen and phosphorus play crucial roles in root development and expansion, even in low moisture conditions. Phosphorus continues to support ATP production, essential for root development, while nitrogen allows rapid nutrient uptake and stimulates root growth, even under limited moisture conditions. Potassium in KCl, although aiding in water balance (Hu et al., 2016), did not significantly promote root growth compared to non-coated seeds.

Table 4. Shoot fresh weight and root fresh weight of vegetable soybean seeds after coating with different nitrogen, phosphorus, and potassium levels, tested under sand and top of paper covered with sand conditions.

Treatment ¹	Sand condition		Top of paper covered with sand condition	
	Shoot fresh weight (g)	Root fresh weight (g)	Shoot fresh weight (g)	Root fresh weight (g)
T1	22.02 ± 1.96 d	13.07 ± 0.88 a-d	20.91 ± 2.82 a-c	8.88 ± 1.22 a-d
T2	23.94 ± 0.18 a-d	14.01 ± 1.67 ab	21.51 ± 1.04 a-c	8.00 ± 1.09 a-d
T3	22.17 ± 1.79 cd	12.99 ± 1.32 a-d	21.46 ± 1.34 a-c	8.64 ± 0.96 a-d
T4	22.42 ± 2.08 b-d	12.65 ± 2.33 a-d	21.82 ± 1.10 a-c	8.12 ± 0.50 a-d
T5	26.18 ± 1.41 a	14.84 ± 0.86 a	22.75 ± 1.09 a	9.15 ± 1.35 a-c
T6	24.96 ± 1.16 a-c	13.57 ± 0.86 a-c	20.36 ± 1.86 a-c	9.48 ± 0.51 ab
T7	24.87 ± 1.88 a-d	12.90 ± 1.53 a-d	16.92 ± 1.51 d	6.75 ± 1.30 d
T8	25.13 ± 2.31 ab	15.03 ± 1.64 a	22.05 ± 1.15 ab	7.04 ± 0.80 cd
T9	24.43 ± 0.72 a-d	14.54 ± 1.02 a	22.35 ± 1.22 a	9.72 ± 1.49 a
T10	25.79 ± 1.41 a	13.75 ± 2.19 a-c	18.83 ± 1.39 cd	7.38 ± 1.20 b-d
T11	22.36 ± 1.28 b-d	10.98 ± 1.86 c-e	19.03 ± 1.79 cd	7.33 ± 0.32 b-d
T12	25.23 ± 1.63 ab	10.47 ± 0.88 de	20.87 ± 1.66 a-c	8.40 ± 0.48 a-d
T13	22.70 ± 0.76 b-d	9.77 ± 1.79 e	20.53 ± 1.98 a-c	8.39 ± 1.48 a-d
T14	26.20 ± 0.97 a	11.28 ± 1.81 b-d	19.16 ± 0.66 b-d	8.97 ± 1.67 a-c
F-test	**	**	**	*
CV.%	7.21	13.97	8.73	15.45

Note: *,** : significantly different at $P \leq 0.05$ and $P \leq 0.01$, respectively. Means within a column followed by the same letter are not significantly different at $P > 0.05$ by DMRT. ¹ T1-T14 were different treatments specified in the materials and methods section.

4. Conclusion

Coating seeds with NH_4NO_3 at 3.0 g/L significantly increased ($P < 0.01$) emergence percentage, germination percentage and shoot length compared to non-coated seeds under sand conditions. Therefore, NH_4NO_3 at 3.0 g/L is recommended as the optimal concentration for promoting the germination of vegetable soybean seedlings.

Further studies are warranted to evaluate the storability of nutrient-coated seeds and to determine whether the improvements in germination, seedling vigor, and early seedling growth observed in this study can be maintained during prolonged storage under different storage conditions.

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