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Seed Encrusting with Plant Nutrients Enhances Germination, Plant Growth and Yield of Soybean (*Glycine max*)

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ABSTRACT

Background: Encrusted seeds receive a thinner coating than encrusted seeds and the coating process is halted before full roundness is achieved. This is beneficial for soybean seeds and enhances water-use efficiency during germination. Additionally, adding essential nutrients to seeds promotes germination and growth, enabling soybean plants to grow faster and to have a higher yield.

Methods: Soybean seeds were encrusted with 3.45 g/kg NH_4NO_3, 4.60 g/kg $NaH_2PO_4.H_2O$ and 1.87 g/kg KCl, using vermiculite as the encrusting material and 0.4% w/w aqueous-carboxymethyl cellulose as the binder. The encrusting process was carried out in a rotary drum (Model SKK12) spinning at 40 rpm and the seeds were evaluated for seed quality parameters.

Result: Encrusting seeds with all three types of plant nutrients had a positive impact on enhancing seed quality compared to non-encrusted seeds. In particular, encrusting seeds with 50 g/kg vermiculite and 1.87 g/kg KCl did not hinder the germination process. Moreover, it enhanced both the germination rate and speed of germination. Additionally, it promoted plant growth, including fresh and dry root weight, fresh shoot weight, fresh and dry plant weight, number of pods per plant, number of seeds per plant, seed weight per plant and pod weight per plant. Therefore, encrusting seeds with 50 g/kg vermiculite and 1.87 g/kg KCl is recommended to enhance the quality of Chiang Mai 60 soybean seeds.

Key words: Plant nutrient, Seed encrusting, Seed enhancement, Soybean.

INTRODUCTION

Soybeans are extensively cultivated in the northern region of Thailand and hold economic significance, especially in the production of various processed products such as soy milk, tofu and soy sauce *etc* (Pagano and Miransari, 2016). However, between 2010 and 2023, there was a significant downward trend in soybean production during the growing season (Agricultural Research Development Agency, 2016). Farmers usually grow soybeans between November and January of each year. They employ the method of seed dressing with rhizobium to enhance germination and seedling growth (Department of Agriculture, 2020). However, this method does not effectively stimulate rhizobium nodulation in the roots of soybean plants (Libault, 2014). The traditional approach faces challenges, particularly during the cultivation season, where soil moisture is limited, hindering adequate moisture for seed germination. Moreover, soil degradation issues in soybean cultivation areas result in a deficiency of essential nutrients for the survival of rhizobia (Razafintsalama *et al*., 2022). Consequently, the rhizobia fixation of nitrogen becomes insufficient to promote the growth of soybeans in the cultivation area. To address these challenges, farmers need to increase the quantity of seeds during cultivation to achieve the desired number of robust seedlings. However, this increased seed quantity leads to higher production costs for farmers.

Seed encrusting involves coating seeds with pelleting material, which has a higher thickness level than seed pelleting. Unlike seed pelleting, seed encrusting does not result in a perfectly round shape (Pedrini *et al*., 2021).

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Increasing seed size using a moisture-absorbent pelleting material can help enhance moisture absorption under low moisture conditions (Siri, 2015; Prakash *et al*., 2020). Furthermore, to tackle soil degradation issues, it is crucial to supplement the necessary nutrients to promote germination, strength and overall seedling growth, especially in areas with limited production resources. Essential plant nutrients play a significant role in promoting germination. For instance, nitrogen is vital for various enzymatic processes during seed germination (Osuna *et al*., 2015). Miyatake *et al.* (2019) discovered that coating soybean seeds with urea, tested at a depth of 20 cm, had a positive impact on root development, leading to improved seedling growth and increased soybean yield. Additionally, phosphorus is a key component of enzymes essential for nutrient absorption during seed germination (Yang, 2018). Potassium is crucial for enzymatic processes, facilitating carbohydrate movement and starch breakdown in seeds (Sivanesan *et al*., 2011). From these factors, seed encrusting with plant nutrients has evolved into essential modern seed technology, particularly suitable for use in areas with low moisture and degraded soil conditions.

Thus, the research objective was to examine changes in the germination, seedling vigour and yield components of soybeans. This study replaces traditional seed dressing with an efficient seed encrusting method, enhancing both the quality and quantity of yield. Importantly, this approach aids farmers in reducing costs in the soybean cultivation process.

MATERIALS AND METHODS

Encrusting soybean seeds with plant nutrients that promote plant growth

The present experiment was conducted at the Division of Agronomy, Faculty of Agricultural Production, Maejo University, Chiang Mai, between August 2022 and April 2023. This research received seed samples of soybean variety 'Chiang Mai 60' from the Seed Research and Development Division, Chiang Mai, under the Department of Agriculture, Thailand. The initial quality of the seeds included a germination rate of 86%, purity of 98% and moisture content of 9%. The soybean seeds were surface sterilised with 1% sodium hypochlorite (NaOCl) for 30 seconds, washed with sterilised distilled water three times and dried with sterilised tissue paper. The mono matrix used to encrust soybean seeds contained vermiculite. A 0.4% (w/w) aqueous-carboxymethyl cellulose solution was prepared as a binder. With concentrations adapted from Kangsopa (2018), this experiment utilised three types of plant nutrients: 3.45 g/kg NH_4NO_3, 4.60 g/kg $NaH_2PO_4.H_2O$ and 1.87 g/kg KCl. Each method involved using 50 g of soybean seeds, which were then encrusted using a rotary drum (SKK12, CERES International Ltd., Bangkok, Thailand) spinning at 40 rpm, as described by Kangsopa *et al*. (2018) (Fig 1). The experimental methods involve the following treatments: T1- non-encrusted seeds; T2- encrusting with 50 g/kg vermiculite; T3- encrusting with 50 g/kg vermiculite + 3.45 g/kg NH_4NO_3; T4- encrusting with 50 g/kg vermiculite + 4.60 g/kg $NaH_2PO_4.H_2O$; T5- encrusting with 50 g/kg vermiculite + 1.87 g/kg KCl. The encrusted seeds were left at room temperature for 48 hours to reduce the seed moisture to 7%.

Seed measurement

Seed quality examination under laboratory conditions

All treatments were assessed using the Between-Paper method with four replicates and placed in a germinator under the following conditions: 25°C, 80% relative humidity, 180 μE light intensity and continuous 24-hour lighting. The data were recorded using various methods, as described below.

The germination percentage was determined by counting normal seedlings 4 and 8 days after planting, with each repetition involving 50 seeds (ISTA, 2013). To assess speed of germination, 50 encrusted seeds were randomly selected and the number developing into normal seedlings was determined in four repetitions from the first to the final count (AOSA, 1983). The mean germination time was computed daily for 8 days, following the standard germination assessment methods according to Ellis and Roberts (1980). Shoot and root length examinations occurred 10 days after planting, with four repetitions involving 10 seedlings each (Baki and Anderson, 1973). Subsequently, seedlings were used to assess fresh shoot and root weights. After placing them in a temperature-controlled chamber at 60°C for 72 hours, the dry shoot and root weights were measured.

Seed quality examination under greenhouse conditions

Fifty seeds were randomly selected for each round of four repetitive evaluations to test their germination in a peat moss nursery tray. The germination percentage, speed of germination and mean germination time mirrored those in the laboratory. Shoot length, measured in millimetres, underwent assessment with 4 repetitions of 10 plants each

A: non-encrusted seeds B: encrusted seeds

Fig 1: Characteristics of Chiang Mai 60 soybean seeds: Non-encrusted seeds (A) and encrusted seeds (B).

to evaluate each planting method. Testing occurred 8 days after planting and the shoot length was measured from the base near the seedling media to the leaf tip. Afterwards, the fresh and dry shoot weights were measured.

Plant height and growth of soybean

The height of the plants was measured 0, 7, 14, 21, 28, 35, 42, 49 and 56 days after sowing, with each treatment replicated four times. Four-inch pots were prepared and filled with 1 L of planting mix, made up of a blend of rice husk ash and chopped coconut in a 20:80 ratio. For each sowing method, 1 seed was sown per pot. Fertiliser was applied when the seedlings were 14 days old, using a balanced 15-15-15 formula at a consistent rate of 0.5 grams per pot between 7 and 21 days. Subsequently, 1.5 g was added per pot between 28 and 56 days of plant growth. At 85 days after sowing, the fresh weight of the plants was measured. Each set of plants for each treatment was carefully washed and the roots were separated from the plants by cutting at the base. Subsequently, each part of the plants for each treatment was oven-dried at 60°C for 72 hours and then used to evaluate dry plant weight and dry root weight, with each method repeated four times.

Yield components

The components of yield were determined simultaneously 56 days after planting. Subsequently, various characteristics were separated from the plants as follows: number of seeds/pod, number of pods/plant, number of seeds/plant, seed weight/pod, seed weight/plant and pod weight/plant. These characteristics were then assessed for each method with four repetitions.

Statistical analysis

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

RESULTS AND DISCUSSION

Soybean germination and seedling growth

Under both laboratory and greenhouse conditions, soybean seeds subjected to encrusting exhibited significantly higher germination rates than non-encrusted seeds. Specifically, encrusting seeds with 4.60 g/kg $NaH_2PO_4.H_2O$ resulted in faster germination than non-encrusted seeds. The mean germination time of encrusted seeds was also higher than that of non-encrusted seeds (Table 1). Notably, all encrusting methods, particularly vermiculite encrusting, showed faster germination and reduced mean germination time compared to non-encrusted seeds. Vermiculite's water-absorbing properties, with the ability to retain 3-4 times its weight in water (Bar-Tal *et al*., 2019), contribute to improved water management in soybean seeds. The addition of NH_4NO_3 to encrusted seeds provides NO_3^-, enhancing protein synthesis and promoting faster germination and growth (Lyu *et al*., 2022). $NaH_2PO_4.H_2O$ serves as a phosphorus substitute, stimulating enzymes crucial for seed germination (Lambers, 2022). Soares *et al*. (2016) found that coating soybean seeds with phosphorus significantly increased dry shoot weight, dry root weight, yield components and plant height. It also increased the number of root nodules, promoting nitrogen fixation. Furthermore, KCl contributes to enzyme activity, carbohydrate metabolism and starch breakdown within the seeds, maintaining pH balance and improving water and nutrient absorption in seedlings (Oosterhuis *et al*., 2014).

Encrusting soybean seeds with 3.45 g/kg NH_4NO_3 significantly boosts shoot length and fresh shoot weight compared to non-encrusted seeds. This effect is attributed to the NO_3^- uptake during seed encrusting, enhancing protein synthesis and activating vital enzymes for seedling cell division. Seed encrusting with 1.87 g/kg KCl had the highest root length. KCl application increases cytoplasmic and vacuolar K^+ levels, promoting starch synthesis, enzyme activity related to root elongation and aiding in gas exchange and water balance regulation (Tzohar *et al*., 2021). This

Table 1: Germination percentage (GE), speed of germination (SPG) and mean germination time (MGT) of soybean seeds after encrusting with different types of plant nutrients and testing under laboratory and greenhouse conditions.

Treatment	Laboratory conditions			Greenhouse conditions		
	GE (%)[1]	SPG (seedling/day)	MGT (day)	GE (%)	SPG (seedling/day)	MGT (day)
Non-encrusted seeds	86b[2]	8.82c	3.03a	84b	8.55b	3.33a
Encrusted seeds (P)	95a	9.50ab	2.68b	94a	9.50a	2.76b
P+ NH_4NO_3 3.45 g/kg	98a	9.05bc	2.54b	98a	9.75a	2.76b
P+ $NaH_2PO_4.H_2O$ 4.60 g/kg	96a	9.75a	2.69b	98a	9.80a	2.62b
P+ KCl 1.87 g/kg	96a	9.60ab	2.61b	97a	9.20a	2.51b
F-test	*	*	*	*	*	**
CV.%	5.11	2.92	5.22	10.49	5.47	6.89

*, **: Significantly different at P≤0.05 and P≤0.01, respectively.

[1]Data are arcsine transformed before statistical analysis.

[2]Means within a column followed by the same letter are not significantly at P≤0.05 by DMRT.

positive impact is seen without hindering root system development. Under lab conditions, all encrusting methods showed significantly higher shoot and root dry weights than non-encrusted seeds (Table 2). The findings suggest that incorporating all three plant nutrients enhances the growth of soybean seedlings, which aligns with their favourable characteristics.

Under greenhouse conditions, encrusting seeds with all three types of plant nutrients resulted in a higher shoot length compared to non-encrusted seeds and only encrusted seeds. Encrusting seeds with 3.45 g/kg NH_4NO_3 led to a higher fresh shoot weight compared to non-encrusted seeds, but this treatment did not differ significantly from other encrusting methods. Additionally, all encrusting methods clearly demonstrated that shoot dry weight was significantly higher and statistically different from that of non-encrusted seeds (Table 3). These findings, obtained using peat moss as a representative substrate, reflect field-like conditions. The seed encrusting method with all three plant nutrients yielded positive results similar to those observed in laboratory conditions. Notably, vermiculite's moisture-absorbing ability and efficient post-germination nutrient utilisation align with previously described characteristics. Importantly, seed encrusting with all three plant nutrients facilitates rapid cell expansion and activates key enzymes in cell division (Wan *et al*., 2023), evident in the robust growth and biomass of soybean seedlings.

Plant height

In all experimental methods, soybeans showed a significant increase in plant height. Even at the 14-day evaluation, it was observed that the seedling height was not significantly different. However, when evaluated between 28 and 56 days, seeds encrusted with 3.45 g/kg NH_4NO_3, 4.60 g/kg $NaH_2PO_4.H_2O$ and 1.87 g/kg KCl clearly exhibited higher plant heights compared to non-encrusted seeds and only encrusted seeds (Fig 2). Significant changes were observed when the soybean seedlings were 10-14 days old. The true leaves of soybean plants exhibited distinct characteristics of being wider and larger than those that were not encrusted. In seed encrusting methods, soybean seedlings that received nitrate (NO_3^-) and ammonium (NH_4^+) (Coskun *et al*., 2016) showed rapid cell expansion compared to non-encrusted seeds. Additionally, the results of encrusting seeds with $NaH_2PO_4.H_2O$ showed that it dissociates into $H_2PO_4^-$ and HPO_4^{2-}, playing a crucial role in enzyme synthesis related to plant growth (Marschner, 2012; Oosterhuis *et al*., 2014). Adequate phosphorus enables plants to convert starch and sugar into energy in cells, thereby improving the plant's ability to produce active compounds and grow healthier. This may result in increased plant height

Table 2: Shoot length (SHL), root length (RHL), shoot fresh weight (SFW), root fresh weight (RFW), shoot dry weight (SDW) and root dry weight (RDW) of soybean seeds after encrusting with different types of plant nutrients and testing under laboratory conditions.

Treatment	Laboratory conditions					
	SHL (cm.)	RHL (cm.)	SFW (g)	RFW (g)	SDW (g)	RDW (g)
Non-encrusted seeds	10.64c[1]	12.91ab	5.73c	2.30b	0.56b	0.11b
Encrusted seeds (P)	12.75b	12.99ab	6.01bc	2.86ab	0.77a	0.17a
P+ NH_4NO_3 3.45 g/kg	14.31a	13.36b	6.70a	3.08a	0.86a	0.19a
P+ $NaH_2PO_4.H_2O$ 4.60 g/kg	13.60ab	13.44b	6.10bc	2.99ab	0.80a	0.16a
P+ KCl 1.87 g/kg	13.23b	14.85a	6.26ab	3.11a	0.82a	0.21a
F-test	**	*	**	*	**	*
CV.%	4.22	5.22	4.84	9.91	7.71	112.85

*, **: Significantly different at P≤0.05 and P≤0.01, respectively.

[1] Means within a column followed by the same letter are not significantly at P≤0.05 by DMRT.

Table 3: Shoot length, shoot fresh weight and shoot dry weight of soybean seeds after encrusting with different types of plant nutrients and testing under greenhouse conditions.

Treatment	Greenhouse condition		
	Shoot length (cm.)	Shoot fresh weight (g)	Shoot dry weight (g)
Non-encrusted seeds	7.74b[1]	8.02b	0.91b
Encrusted seeds (P)	8.77ab	8.63ab	1.02a
P+ NH_4NO_3 3.45 g/kg	9.15a	9.19a	1.05a
P+ $NaH_2PO_4.H_2O$ 4.60 g/kg	9.56a	8.38ab	1.04a
P+ KCl 1.87 g/kg	9.78a	8.70ab	1.06a
F-test	**	**	**
CV.%	5.92	7.47	10.89

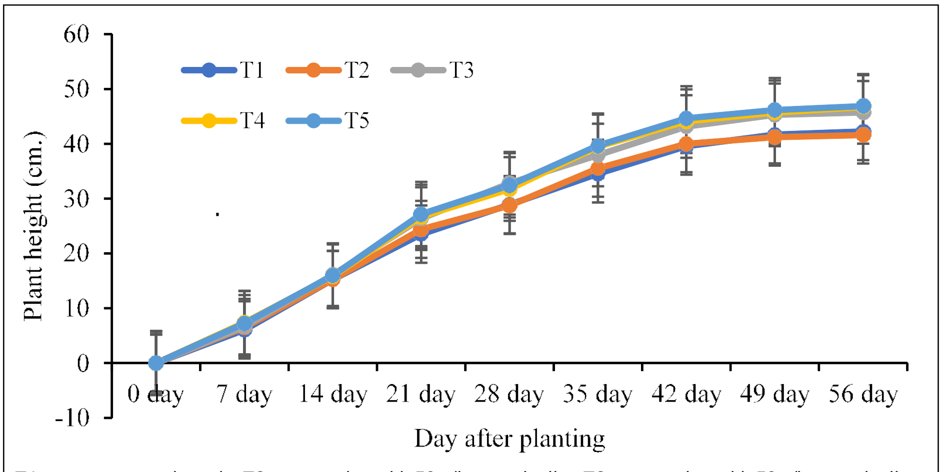
**: Significantly different at P≤0.01.

[1]Means within a column followed by the same letter are not significantly at P≤0.05 by DMRT.

(Oosterhuis *et al*., 2014). Encrusting seeds with KCl in the form of K^+ has been found to promote photosynthesis and enhance water and nutrient uptake by roots (Marschner, 2012). This indicates that faster germination helps seedlings acquire nutrients more rapidly. Seedlings with well-established root systems can absorb essential nutrients more efficiently, contributing to faster growth (Tanaka and Makino, 2009). After 14 days, distinct developmental differences were observed in soybean seedlings using all seed encrusting methods with nutrient additives compared to non-encrusted seeds and vermiculite-encrusted seeds. Upon considering the final height at 56 days, the results clearly showed that seed encrusting with 3.45 g/kg NH_4NO_3, 4.60 g/kg $NaH_2PO_4.H_2O$ and 1.87 g/kg KCl resulted in height increases of 8, 10 and 11%, respectively, compared to non-encrusted seeds.

Plant growth and yield components after soybean seed encrusting

The assessment of plant growth after 85 days of growth revealed that encrusting seeds with 1.87 g/kg KCl resulted in a significant increase in plant fresh weight, up to 34%, compared to non-encrusted seeds. Encrusting seeds with 3.45 g/kg NH_4NO_3 and 1.87 g/kg KCl also showed a substantial increase in plant dry weight, by 22 and 32%, respectively, compared to non-encrusted seeds. Moreover, seeds encrusted with 4.60 g/kg $NaH_2PO_4.H_2O$ and 1.87 g/kg KCl exhibited significantly higher root dry weights and were statistically different from non-encrusted seeds. Encrusting seeds with the 3 plant nutrients clearly demonstrated a significant improvement in the growth of soybean plants compared to non-encrusted seeds (Table 4). Seeds encrusted with the 3 nutrients had a significantly higher average number of seeds per pod and differed from non-encrusted seeds. Encrusting seeds with 1.87 g/kg KCl resulted in statistically higher values for the number of pods per plant, the number of seeds per plant, the seed weight per plant and the pod weight per plant compared to non-encrusted seeds. Furthermore, the



T1 - non-encrusted seeds, T2 - encrusting with 50 g/kg vermiculite, T3 - encrusting with 50 g/kg vermiculite + 3.45 g/kg NH_4NO_3, T4 - encrusting with 50 g/kg vermiculite + 4.60 g/kg $NaH_2PO_4.H_2O$ and T5 - encrusting with 50 g/kg vermiculite + 1.87 g/kg KCl.

Fig 2: Plant height of soybean seeds after encrusting with different types of plant nutrients 56 days after sowing.

Table 4: Plant fresh weight, plant dry weight and root dry weight of soybean seeds after encrusting with different types of plant nutrients 56 days after sowing.

Treatment	Plant fresh weight (g)	(%)[2]	Plant dry weight (g)	(%)	Root dry weight (g)	(%)
Non-encrusted seeds	37.75b[1]		8.85b		2.81b	
Encrusted seeds (P)	35.19b	(-6)	8.20b	(-7)	3.09b	(+10)
P+ NH_4NO_3 3.45 g/kg	45.07ab	(+19)	10.79a	(+22)	3.57ab	(+27)
P+ $NaH_2PO_4.H_2O$ 4.60 g/kg	42.46ab	(+13)	9.52ab	(+8)	4.05a	(+44)
P+ KCl 1.87 g/kg	50.72a	(+34)	11.68a	(+32)	4.47a	(+59)
F-test	**		**		**	
CV.%	18.07		19.38		12.88	

**: Significantly different at P≤0.01.

[1] Means within a column followed by the same letter are not significantly at P≤0.05 by DMRT.

[2] The number in parentheses refers to the percentage of increase (+) and decrease (-) compared to the non-encrusted seeds.

Table 5: Yield components of soybean seeds after encrusting with different types of plant nutrients 56 days after sowing.

Treatment	No. of seed/pod (seed)	No. of pod/plant (pod)	No. of seed/plant (seed)	Seed weight/pod (g)	Seed weight/plant (g)	Pod weight/plant (g)
Non-encrusted seeds	2.92b[1]	44.60b	64.36b	1.98b	20.46b	57.52b
Encrusted seeds (P)	3.36ab	45.40ab	66.16b	2.16b	21.67ab	60.08ab
P+ NH_4NO_3 3.45 g/kg	4.00a	48.60ab	67.40b	2.42ab	23.14ab	66.32ab
P+ $NaH_2PO_4.H_2O$ 4.60 g/kg	3.88a	48.20ab	68.08b	2.60a	25.70ab	67.44ab
P+ KCl 1.87 g/kg	4.04a	56.80a	93.04a	2.52a	28.84a	75.48a
F-test	**	**	**	**	**	**
CV.%	6.93	13.73	15.52	10.52	18.27	17.22

**: Significantly different at P≤0.01.

[1]Means within a column followed by the same letter are not significantly at P≤0.05 by DMRT.

experimental results indicate a clear trend towards significantly increased yield components when encrusting seeds with the 3 nutrients (Table 5).

Early rapid growth is key to enhancing the plant's nutrient acquisition for faster development. Vermiculite-encrusted seeds efficiently transported nutrients, significantly boosting shoot and root weights in the 56-day evaluation. Notably, KCl outperforms other methods of promoting soybean growth, which are crucial for stomatal regulation, cell expansion and environmental resilience. Potassium also plays a pivotal role in photosynthesis and nutrient synthesis (Hu *et al*., 2016). Nitrogen during the seedling stage is crucial for protein synthesis, supporting cell formation, cell wall synthesis and energy metabolism (Chen *et al*., 2018). Seed encrusting with $NaH_2PO_4.H_2O$ and KCl significantly increased the root dry weight, benefiting root development and nutrient uptake. Phosphorus from $NaH_2PO_4.H_2O$ enhances root growth and nutrient uptake efficiency (Chen *et al*., 2023). Both phosphorus and potassium enhance plant resilience to environmental fluctuations. Adequate phosphorus and potassium support strong root development and overall plant growth (Tränkner *et al*., 2018). Despite the experiment not studying nutrient elements' influence during soybean growth, the results indicate a significant improvement in production components. Healthy seedlings considerably impact the final yield. Seed encrusting with plant nutrients, especially 1.87 g/kg KCl, enhanced the production components compared to non-encrusted seeds.

CONCLUSION

The encrusting method with 50 g/kg vermiculite and 1.87 g/kg KCl resulted in higher seed quality, plant height and growth and yield parameters, including germination rate, fresh root weight, fresh and dry plant weight, number of pods per plant, number of seeds per plant, seed weight per plant and pod weight per plant. KCl enhances enzyme activity, speeds up carbohydrate metabolism and aids in starch breakdown within seeds. Potassium is crucial for soybean growth, playing a significant role in photosynthesis, nutrient synthesis and regulating stomata for transpiration and nutrient uptake. Therefore, it is recommended as the best method to enhance the quality of soybean seeds, specifically the Chiang Mai 60 variety. Additionally, encrusting with 50 g/kg vermiculite and 3.45 g/kg NH_4NO_3 or 4.60 g/kg $NaH_2PO_4.H_2O$ also promoted seed quality, growth and yield compared to the non-encrusted seeds. These methods can be considered alternative approaches for enhancing the quality of soybean seeds.

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Conflict of interest

All authors declared that there is no conflict of interest.

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