



Seed Priming with Moringa Leaf Extract Improves Germination and Vigor in Soybean

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ABSTRACT

The germination stage represents a critical phase in plant growth and development, determining subsequent vigor and yield potential. In soybean (*Glycine max* L.) low seed quality and rapid deterioration during storage remain major constraints to achieving uniform and vigorous germination. Seed priming with natural bio stimulants such as moringa leaf extract (MLE) offers a promising strategy to enhance seed performance. This study evaluated the effects of 4% MLE as a bio stimulant for soybean seed priming under laboratory conditions. A factorial experimental design was conducted using three cultivars (Dering-1, Dega-1, and Devon-1) and three priming treatments (MLE 4%, hydro-priming, and unprimed control). Results showed that MLE 4% significantly increased the percentage of normal seedlings and vigor index, particularly in the Dega-1 and Devon-1. While hydro-priming accelerated germination time, MLE 4% enhanced germination quality, uniformity, and seedling biomass accumulation. The combination of MLE 4% and the Dega-1 cultivar produced the highest fresh and dry weights. Pearson correlation and principal component analyses confirmed the positive influence of MLE 4% on key germination traits. PCA clearly distinguished MLE 4% from the control, as evidenced by its superior germination performance. These findings demonstrate that MLE 4% is an effective and eco-friendly seed priming treatment for improving the physiological quality of soybean seeds, especially in cultivars responsive to bio-stimulant compounds.

Keywords: Germination, Moringa leaf extract, Seed priming, Soybean.

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INTRODUCTION

Soybean (*Glycine max* (L.) Merrill) is an important food crop favored by both Indonesian and global communities, ranking after rice and maize. It serves as a major source of protein and fat, and is widely used as a plant-based protein alternative for vegetarians (Qin et al., 2022). Additionally, soybeans are a commercially valuable legume crop utilized in the vegetable oil industry (Dwevedi & Kayastha, 2011). The demand for soybeans continues to rise, driven by population growth and increasing consumption of plant-based proteins, yet domestic production in countries such as Indonesia remains insufficient to meet demand, necessitating imports (Setyawan & Huda, 2022). In 2023, Indonesia imported approximately 2.27 million tons of soybeans (Central Bureau Statistics of Indonesia, 2024). This reliance on imports underscores the urgent need to

enhance domestic soybean production to reduce dependency and improve food security.

At the global scale, soybean is among the most traded oilseed commodities and underpins both human food e.g., tofu, tempeh, soy milk and livestock systems through soybean meal and oil (Toomer et al., 2023). Worldwide production has continued to expand, driven by both increased sown area and yield improvements, with a global harvest of 398.2 million tonnes in 2023, concentrated in Brazil, the United States, and Argentina (Volkova & Smolyaninova, 2024). Emerging tropical producers, including Brazil, Indonesia, Thailand, Colombia, and Malaysia, have contributed significantly to global output through intensification, cropland expansion, and export-oriented production (Winkler et al., 2025). These global dynamics underscore the strategic importance of strengthening domestic soybean production and improving

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seed systems in soybean-importing countries to reduce exposure to import price volatility and potential supply disruptions.

At the same time, soybean productivity and seed supply chains are increasingly challenged by climate variability, which can constrain flowering, seed filling, and ultimately seed physiological quality (Goulart et al., 2023). Under such conditions, ensuring high quality seed lots and rapid, uniform crop establishment is a practical, low cost adaptation strategy to stabilize yield potential across seasons. Seed quality, encompassing viability and vigor, is a critical determinant of germination success and uniform crop establishment. High-quality seeds enable rapid, synchronous germination, which, in turn, supports optimal plant growth and yield potential (Reed et al., 2022). Germination starts with the absorption of water and concludes when the radicle emerges from the seed coat (Wolny et al., 2018). However, soybean seeds generally exhibit low storability, with rapid deterioration during storage in humid tropical climates, where high relative humidity accelerates moisture absorption, membrane damage, and loss of viability (Purwanti, 2004; Gebeyehu, 2020; Nasrullah et al., 2021). For example, Weerasekara et al. (2021) reported marked declines in soybean seed germination when seeds were stored at high relative humidity without hermetic protection, highlighting the importance of interventions to maintain or restore early seedling vigor before sowing. Although classified as orthodox, soybean seeds often have a relatively short shelf life, limiting their contribution to stable crop production (Sucahyono, 2013; Hasbianto & Yasin, 2014). To improve soybean yield, ensure good seed germination and vigor, and promote robust plant growth (Ku et al., 2013). Seed priming has become a commonly applied method to mitigate these challenges. Priming is a controlled hydration treatment in which water enters the seed (imbibition), triggering pre-germination metabolism and DNA repair without radicle elongation (El-Maarouf-Bouteau, 2022). Seed priming has also been shown to potentially shorten germination time, improve seed vigor, and promote uniform germination (Espanany et al., 2016; Tu et al., 2022). The priming process occurs in three phases: Phase I involves water uptake and enzyme activation, Phase II encompasses mobilization of food reserves, reorganization of membranes, and starch biosynthesis, concluding with seed re-drying, and Phase III begins with radicle emergence and subsequent seedling growth (Ruttanaruangboworn et al., 2017).

The integration of biostimulants in seed priming represents a sustainable approach to enhancing seed performance. Biostimulants are substances or microorganisms that improve nutrient efficiency, abiotic stress tolerance, and crop quality traits (Du Jardin, 2015). Among plant-derived biostimulants, *Moringa oleifera* leaf extract (MLE) has gained attention due to its wide availability in tropical and subtropical regions, low cultivation requirements, and multifaceted bioactive composition, including phytohormones (cytokinins, auxins, gibberellins), vitamins, minerals, amino acids, phenolics, and antioxidants (Rajbhar et al., 2018; Arif et al., 2023). MLE is

safe, cost effectively, environmentally friendly, and easy to prepare, making it suitable for smallholder farmers and large-scale agriculture alike (Yuniati et al., 2022). Experimental evidence supports MLE's efficacy as a plant biostimulant rather than merely a nutrient supplement. The phytohormone-rich extract enhances nutrient uptake, stress tolerance, and early seedling vigor across diverse crops (Mashamaite et al., 2022). For instance, MLE priming improved rice seedling establishment under drought stress (Khan et al., 2023) and enhanced germination and growth in salt-stressed lettuce (Shalaby, 2024). These studies suggest that MLE may mitigate seed deterioration and promote uniform germination in soybean, particularly in conditions where seed vigor is compromised by storage or environmental stress.

MLE priming enhances germination by introducing bioactive compounds into the embryo during hydration, stimulating enzymatic activity and physiological processes critical for seedling development (Tahir et al., 2022; Yuniati et al., 2023). Compounds such as cytokinins, ascorbic acid, and antioxidants accelerate germination, promote radicle growth, and support early plant development (Yasmeen, 2011; Wajid et al., 2018). While MLE priming has been extensively studied in cereals and vegetables (Phiri, 2010; Ahmed et al., 2021), research on soybean remains limited. Understanding cultivar-specific responses to MLE priming is essential for optimizing practical applications in soybean cultivation.

This study aims to evaluate the effect of seed priming using 4% MLE on the germination performance of three soybean cultivars under laboratory conditions. It addresses the research gap in soybean cultivar-dependent responses, integrating germination, vigor, and seedling growth metrics. The study further employs Pearson's correlation and principal component analysis (PCA) to identify trait syndromes and cultivar-specific performance patterns. The novelty lies in benchmarking hydropriming versus low concentration MLE priming, providing empirical evidence to inform practical priming recommendations for farmers and seed producers. By elucidating the potential of natural biostimulants for soybean seed priming, this work contributes to strategies to stabilize yield potential, enhance early crop establishment, and improve food security in regions reliant on soybean imports.

MATERIALS & METHODS

Bioethical Statement

This study did not involve any studies with human participants or animals. All experimental procedures involving plant materials were performed in compliance with institutional and international ethical standards.

Experimental Design

This research was conducted from February to May 2025 at the Seed Technology Laboratory, Faculty of Agriculture, Universitas Padjadjaran, Indonesia (Fig. 1). This study aimed to evaluate the effect of seed priming using *Moringa oleifera* leaf extract (MLE) on the germination performance of three soybean cultivars. The experimental

design was a Completely Randomized Design (CRD) with two factors: priming treatments (control, hydro-priming, and MLE-priming 4%) and cultivars (Dering-1, Dega-1, Devon-1). Each treatment combination was replicated four times.



Fig. 1: Geographic location of the experimental site and Seed Technology Laboratory in Sumedang, West Java, Indonesia; (6°55'32\"S, 107°46'18\"E; 771 m a.s.l.); (Source: Google Earth).

MLE Preparation

The extraction process followed the method described by El Sheikha et al. (2022). Fresh Moringa leaves (30g) from a 2-year-old tree were washed, air-dried, and refrigerated for 12 hours. The leaves were blended with 300mL of distilled water for 15 minutes, filtered with a cloth and Whatman No. 1 paper, and centrifuged at 8000rpm for 15 minutes. The supernatant was diluted 1:25 with distilled water. MLE used in this study contained beneficial substances such as phenolic compounds (303.89mgL⁻¹) and flavonoids (83.14mgL⁻¹). It also tested positive for other bioactive compounds, including saponins, tannins, steroids, triterpenoids, and alkaloids.

Seed Priming and Germination Test

Soybean seeds of three cultivars (Dering-1, Dega-1, and Devon-1) were used. Seeds were surface-sterilized with 1% NaOCl for 2 minutes, then soaked in either distilled water (hydro-priming) or a 4% MLE solution for 30 minutes. Seeds were then rinsed with distilled water and air-dried. The paper roll method was used for the germination test. Twenty-five seeds were placed on moistened straw paper (with Aquadest or MLE according to treatment), rolled gently, wrapped in plastic to retain moisture, and incubated for 7 days in a germinator at 26/27° day/night temperatures and RH 74%. Seed germination was observed daily, with germination defined as the emergence of the radicle reaching 2mm in length.

Data Collection

The observed parameters consisted of germination percentage (GP), normal seedling percentage (NSP), and vigor index (VI) according to ISTA (2010). Germination time (GT) and coefficient of variation of germination time (CVt) as described by Sulaiman et al. (2023). In addition, germination index (GI) following Shah et al., (2021).

$$GP = \frac{\sum GS}{\sum TS} \times 100 \quad (1)$$

$$NSP = \frac{\sum NS}{\sum TS} \times 100 \quad (2)$$

$$GI = \frac{n_1}{t_1} + \frac{n_2}{t_2} + \dots + \frac{n_i}{t_i} \quad (3)$$

$$GT = \frac{\sum (n_1 t_1 + n_2 t_2 + \dots + n_i t_i)}{\sum (n_1 + n_2 + \dots + n_i)} \quad (4)$$

$$CVt = \frac{SDGT}{GT} \quad (5)$$

$$VI = \frac{\sum NS}{\sum TS} \times \text{seedling length} \quad (6)$$

where GS is the number of germinated seeds at the end of experiment (7d after incubation), TS is the number of tested seeds, NS is the normal seedling (defined as one that has well-developed organs including the plumule, hypocotyl, and root (ISTA, 2010)), n_i is the number of seeds germinated in the i th time, t_i is the time taken for seeds to germinate at i th, SDGT is standard deviation of the germination time, GT is mean germination time.

In addition, seedling characteristics were evaluated at 7 days after incubation. The parameters measured included root length, shoot length, the ratio of root length to hypocotyl length, and fresh and dry weight. For each replication, ten uniform and healthy seedlings were selected, and their values were averaged to obtain the final measurements.

Statistical Analysis

Data were collected and analyzed using Analysis of Variance (ANOVA) with SPSS v21 and Principal Component Analysis (PCA) with R 4.5.0. The differences in treatments were assessed by Tukey's Honest Significant Difference (HSD) test at 5% significance level. Data normality and homogeneity of variances were verified using the Shapiro-Wilk and Levene's tests, respectively, before performing ANOVA. PCA was performed after data standardization, and the suitability of the data was confirmed.

RESULTS & DISCUSSION

Germination Percentage and Normal Seedling Percentage

Germination percentage (GP) is the proportion of germinated seeds relative to the total number of seeds sown, expressed as a percentage. Statistical analysis showed that seed priming treatments (4% moringa leaf extract (MLE), hydropriming, and control) did not differ significantly in GP (Table 1). Seed priming has been reported to improve germination under specific conditions; however, its effectiveness depends on cultivar and environmental factors (Miladinov et al., 2018). In contrast, normal seedling percentage (NSP) was significantly higher under 4% MLE (84.67%) than in the control (76%) ($P = 0.021$) (Table 1), indicating improved seed physiological quality and seedling normality. Similar effects of MLE have been attributed to its bioactive compounds (e.g., cytokinins, ascorbic acid, and antioxidants), which stimulate metabolic activity and early seedling growth (Yasmeen, 2011; Wajid et al., 2018). In addition, calcium in MLE contributes to membrane stability,

thereby enhancing seed vigor and normal seedling development (Karim et al., 2020). For cultivar effects, Dering-1 exhibited significantly lower GP (80.67%) and NSP (72.33%) than Dega-1 and Devon-1 ($p < 0.001$), both of which showed GP > 90% and NSP > 80% (Table 1). These results highlight the importance of genetic factors in determining seed viability and early seedling performance. The superior performance of Dega-1 and Devon-1 likely reflects higher physiological seed quality, including greater reserve availability and faster metabolic activation (Nerling et al., 2018).

Table 1: Main effects of seed priming and cultivar on germination percentage, normal seedling percentage, germination index, germination time, coefficient of variation of germination time, and vigor index

Treatment	GP (%)	NSP (%)	GI	GT (days)	CVt	VI
Priming						
Control	86.00 a	76.00 a	14.65 a	1.53 ab	149.63 a	17.49 a
Hydro-priming	88.00 a	78.67 ab	16.02 a	1.39 a	148.95 a	19.08 a
MLE 4%	91.00 a	84.67 b	15.53 a	1.55 b	129.07 a	20.30 a
Cultivar						
Dering-1	80.67 a	72.33 a	14.65 a	1.44 a	146.09 a	15.74 a
Dega-1	92.00 b	82.00 b	15.98 a	1.46 a	140.43 a	20.70 b
Devon-1	92.33 b	85.00 b	15.55 a	1.57 a	141.12 a	20.44 b

Note: Numbers followed by the same letter within the same column are not significantly different according to Tukey's HSD test ($P < 0.05$).

The interaction between priming and cultivar (Table 2) revealed that the highest GP occurred in 4% MLE x Dega-1 and hydropriming x Devon-1 (both 97%), whereas hydropriming x Dering-1 showed the lowest GP (77%). Across treatments, Dering-1 consistently exhibited lower GP than the other cultivars. A similar pattern was observed for NSP. The highest NSP was recorded in 4% MLE x Dega-1 (91%) and hydropriming x Devon-1 (89%), while control and hydropriming treatments of Dering-1 resulted in the lowest NSP (70%) (Table 2).

Table 2: Interaction effects of seed priming and cultivar on germination percentage, normal seedling percentage, germination index, germination time, coefficient of variation of germination time, and vigor index

Treatment	GP (%)	NSP (%)	GI	GT (days)	CVt	VI
Control						
Dering-1	82.00 ab	70.00 a	12.67 a	1.67 bc	143.78 ab	15.33 a
Dega-1	89.00 abc	78.00 ab	15.62 ab	1.42 ab	147.51 ab	18.25 ab
Devon-1	87.00 abc	80.00 ab	15.65 ab	1.49 abc	157.58 ab	18.88 ab
Hydro-Priming						
Dering-1	77.00 a	70.00 a	14.92 ab	1.32 a	144.22 ab	15.37 a
Dega-1	90.00 abc	77.00 ab	15.63 ab	1.40 ab	134.23 ab	20.59 ab
Devon-1	97.00 c	89.00 b	17.52 b	1.47 abc	168.40 b	21.29 ab
MLE 4%						
Dering-1	83.00 ab	77.00 ab	16.37 ab	1.33 a	150.27 ab	16.51 ab
Dega-1	97.00 c	91.00 b	16.71 ab	1.56 abc	139.54 ab	23.26 b
Devon-1	93.00 bc	86.00 ab	13.50 ab	1.77 c	97.39 a	21.14 ab

Note: Numbers followed by the same letter within the same column are not significantly different according to Tukey's HSD test ($P < 0.05$).

Germination Index and Germination Time

Seed priming treatments had no significant effect on the germination index (GI) but significantly affected germination time (GT). Hydropriming produced the shortest GT (1.39 days), significantly faster than 4% MLE (1.55 days; $P = 0.023$) (Table 1). Germination time reflects the onset of active germination and is closely related to water uptake and enzyme activation (Talská et al., 2020; Corbinau et al., 2023). Priming can enhance RNA activity

and ATP production, thereby accelerating germination processes (Ahmed et al., 2021). No significant cultivar effect was observed for GI or GT (Table 1). Interaction analysis (Table 2) showed that the highest GI occurred in hydropriming x Devon-1 (17.52), whereas the lowest GI was recorded in control x Dering-1 (12.67) ($P = 0.016$). A higher GI indicates faster and more synchronous germination (Siregar et al., 2023). For GT, hydropriming x Dering-1 resulted in the shortest GT (1.32 days), comparable to 4% MLE x Dering-1 (1.33 days), while the longest GT was observed in 4% MLE x Devon-1 (1.77 days) (Table 2). These results indicate that hydropriming generally accelerates germination, with the magnitude of the response depending on cultivar, confirming cultivar-specific sensitivity to priming (Damalas et al., 2019).

Coefficient of Variation of Germination Time and Vigor Index

Based on Table 1, seed priming treatments did not significantly affect the coefficient of variation of germination time (CVt) or vigor index (VI). CVt represents germination uniformity, whereas VI reflects the capacity to produce fast-growing and uniform seedlings (Damalas et al., 2019). In contrast, VI was significantly higher in Dega-1 (20.70) and Devon-1 (20.44) than in Dering-1 (15.74), indicating greater inherent vigor potential in these cultivars. At the interaction level (Table 2), the lowest CVt was observed in 4% MLE x Devon-1, indicating more uniform germination, while the highest VI was recorded in 4% MLE x Dega-1 (23.26). These effects are consistent with reports that MLE enhances metabolic activity and seed vigor (Basra et al., 2011; Yasmeen et al., 2013). Bioactive compounds in MLE, including cytokinins, vitamin C, and phenolics, support enzymatic activity, reserve mobilization, and antioxidant protection, thereby promoting uniform and vigorous seedling growth (Rady et al., 2017; Dawood, 2018).

Radicle Length, Hypocotyl Length and Radicle/Hypocotyl Length Ratio

Seed priming treatments did not significantly affect radicle length (RL) (Table 3). Hypocotyl length (HL) was greatest under hydropriming (11.27 cm), while the highest radicle/hypocotyl length ratio (RHLR) was observed under 4% MLE (1.40), significantly higher than the control (1.07) ($P = 0.024$). A higher RHLR indicates greater allocation to root development (Kaspar, 2022). Among cultivars, Dega-1 showed the longest RL and together with Devon-1, exhibited significantly higher RHLR than Dering-1, reflecting genotypic differences in root growth potential (Table 3) (Jin et al., 2010). Interaction effects were not significant for RL but were significant for HL and RHLR (Table 4). The highest RHLR (1.82) was recorded in 4% MLE x Devon-1, which also produced the shortest HL (8.90 cm), indicating a shift toward root-dominated growth.

Total Fresh Weight and Dry Weight of Seedlings

Seed priming treatments alone did not significantly affect fresh weight (FW) or dry weight (DW) (Table 3). However, cultivars differed significantly, with Dega-1 showing the highest FW and DW, followed by Devon-1,

while Dering-1 exhibited the lowest biomass. This suggests that Dega-1 has genetic traits favoring efficient early biomass accumulation (Nur'aini & Rachmawati, 2022). Significant interaction effects were observed, with 4% MLE x Dega-1 producing the highest FW (7.63g) and DW (0.57g) (Table 4). These results agree with previous studies showing that MLE priming enhances biomass accumulation by stimulating metabolic activity and nutrient mobilization (Yasmeen et al., 2013; Khan et al., 2022). Cytokinins in MLE promote cell division, contributing proportionally to both fresh and dry biomass formation (Azzam et al., 2022; Mantja et al., 2023). Overall, 4% MLE priming effectively enhanced early seedling growth, with response magnitude strongly influenced by cultivar characteristics.

Table 3: Main effects of seed priming and cultivar on radicle length, hypocotyl length, radicle/hypocotyl length ratio, fresh weight, and dry weight

Treatment	RL (cm)	HL (cm)	RHLR	FW (g)	DW (g)
Priming					
Control	11.77 a	11.14 ab	1.07 a	5.93 a	0.43 a
Hydro-priming	12.97 a	11.27 b	1.16 ab	5.98 a	0.43 a
MLE 4%	13.73 a	10.07 a	1.40 b	6.20 a	0.45 a
Cultivar					
Dering-1	10.83 a	10.93 a	0.99 a	5.00 a	0.34 a
Dega-1	14.29 b	10.85 a	1.33 b	6.92 c	0.52 c
Devon-1	13.34 ab	10.69 a	1.32 b	6.18 b	0.46 b

Note: Numbers followed by the same letter within the same column are not significantly different according to Tukey's HSD test ($P < 0.05$).

Table 4: Interaction effects of seed priming and cultivar on radicle length, hypocotyl length, radicle/hypocotyl length ratio, fresh weight, and dry weight

Treatment	RL (cm)	HL (cm)	RHLR	FW (g)	DW (g)
Control					
Dering-1	10.75 a	11.18 ab	0.96 a	4.98 a	0.37 ab
Dega-1	12.95 a	10.30 ab	1.27 ab	6.65 bc	0.47 bc
Devon-1	11.60 a	11.95 b	0.66 a	6.16 ab	0.46 bc
Hydro-Priming					
Dering-1	10.73 a	11.30 ab	0.96 a	5.00 a	0.33 a
Dega-1	15.48 a	11.28 ab	1.38 ab	6.48 bc	0.52 bc
Devon-1	12.70 a	11.23 ab	1.15 ab	6.44 bc	0.45 abc
MLE 4%					
Dering-1	11.03 a	10.33 ab	1.06 a	5.02 a	0.33 a
Dega-1	14.45 a	10.98 ab	1.33 ab	7.63 c	0.57 c
Devon-1	15.73 a	8.90 a	1.82 b	5.94 ab	0.46 abc

Note: Numbers followed by the same letter within the same column are not significantly different according to Tukey's HSD test ($P < 0.05$).

Correlation Analysis among Parameters

Based on Pearson's correlation analysis (Table 5), most parameters showed significant associations. Germination percentage (GP) was strongly and positively correlated with normal seedling percentage (NSP) ($r = 0.757$), vigor index (VI) ($r = 0.692^{**}$), fresh weight (FW) ($r = 0.670^{**}$), and dry weight (DW) ($r = 0.584^{**}$), indicating that higher germination is closely linked to improved early growth performance. NSP also showed a highly significant positive correlation with VI ($r = 0.807^{**}$) and a significant correlation with radicle length (RL) ($r = 0.336^*$), suggesting that normal seedlings are generally more vigorous and exhibit better root development. Germination index (GI) was significantly and negatively correlated with germination time (GT) ($r = -0.580$), confirming that faster-germinating seeds complete germination more quickly. GI was also positively correlated with the coefficient of variation of germination time (CVt) ($r = 0.575^{**}$) and VI ($r = 0.480^{**}$), reflecting the relationship between germination speed, uniformity, and vigor. In contrast, GT showed a negative correlation with CVt ($r = -$

0.398), indicating that prolonged germination was associated with reduced temporal variability. The vigor index exhibited significant positive correlations with several growth-related traits, including RL ($r = 0.766^{**}$), radicle-to-hypocotyl length ratio (RHLR) ($r = 0.562^{**}$), FW ($r = 0.658^{**}$), and DW ($r = 0.654^{**}$), confirming that higher seed vigor translates into stronger early growth and biomass accumulation. The very strong correlation between RL and RHLR ($r = 0.877$) highlights the dominant role of root development in balancing seedling growth. FW and DW were also strongly correlated ($r = 0.799^{**}$), indicating close alignment between fresh biomass and dry matter accumulation. The correlation heatmap is presented in Fig. 2.

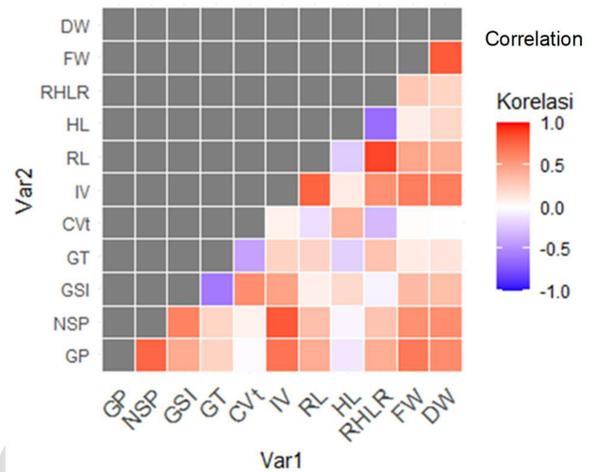


Fig. 2: Correlation heatmap showing the relationships among measured variables related to seed vigor and seedling growth.

Principal Component Analysis (PCA) Biplot among Treatments

Based on PCA results (Fig. 3), the first two principal components (PC1 and PC2) accounted for 100% of the total variation, with 79.8% and 20.2%, respectively, indicating that the biplot adequately represents the relationships among treatments and traits. The 4% moringa leaf extract (MLE) treatment clustered closely with vectors representing DW, FW, RHLR, NSP, GP, VI, and HL, indicating its consistent positive association with seed quality and early seedling growth traits. In contrast, the control treatment was positioned near the GT vector, indicating longer germination duration and slower early growth. This pattern supports previous findings that unprimed seeds often experience delayed metabolic activation during water uptake (Upreti et al., 2024). Hydropriming was relatively distant from most growth-related variables, suggesting a more limited overall effect than 4% MLE.

Mechanistic Interpretation, Cultivar Response and Practical Implications

The present results support the established concept that seed priming advances early metabolic phases of germination (phases I-II), allowing faster and more uniform seedling establishment once favorable conditions occur (Corbineau et al., 2023). In this study, hydropriming primarily improved germination time and related traits,

Table 5: Pearson's correlation coefficients among germination and early seedling growth parameters

	GP	NSP	GI	GT	CVt	VI	RL	HL	RHLR	FW	DW
GP											
NSP	0.757**										
GI	0.437**	0.623**									
GT	0.230	0.220	-0.580**								
CVt	-0.020	0.070	0.575**	-0.398*							
VI	0.692**	0.807**	0.480**	0.230	0.070						
RL	0.430**	0.336*	0.080	0.220	-0.130	0.766**					
HL	-0.100	-0.050	0.200	-0.200	0.386*	0.100	-0.220				
RHLR	0.422*	0.310	-0.050	0.310	-0.300	0.562**	0.877**	-0.626**			
FW	0.670**	0.570**	0.354*	0.110	0.020	0.658**	0.464**	0.090	0.290		
DW	0.584**	0.577**	0.339*	0.130	-0.010	0.654**	0.409*	0.210	0.220	0.799**	

** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed).

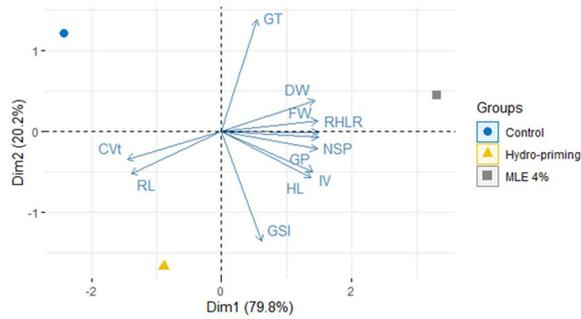


Fig. 3: Principal Component Analysis (PCA) biplot showing the relationships among treatments based on seed vigor and seedling growth parameters.

consistent with its role in facilitating membrane reorganization, macromolecular repair, and activation of reserve-mobilizing enzymes. From a practical perspective, hydropriming remains a simple, low-cost strategy to enhance germination speed and uniformity, although its effects may be limited when seed lots already possess high baseline viability or when additional biochemical stimulation is required to improve early growth. The enhanced performance observed under 4% moringa leaf extract (MLE) priming indicates that MLE provides benefits beyond hydration alone. MLE contains phytohormones, antioxidants, minerals, and organic compounds that can synergistically stimulate cell division, protect against oxidative stress during metabolic reactivation, and promote early root and shoot growth (Mashamaite et al., 2022). Similar improvements in seedling establishment and stress-related physiology following MLE priming have been reported in rice and wheat under drought and salinity conditions (Khan et al., 2023; Muneeba et al., 2024), supporting its role as a genuine biostimulant. Evidence from soybean under abiotic stress likewise indicates that biopriming responses are strongly genotype dependent (Almakas et al., 2024), consistent with the patterns observed in this study.

A key outcome is the clear cultivar-specific response to priming. Dega-1 and Devon-1 generally exhibited superior germination and normal seedling percentages, whereas Dering-1 showed lower baseline performance but responded more strongly to MLE in terms of biomass accumulation and root-shoot allocation. Such genotype-by-priming interactions are biologically plausible, reflecting differences in seed coat properties, reserve composition, and inherent seed vigor. These findings emphasize that priming strategies should be cultivar specific rather than

universally applied, in agreement with previous reports in soybean (Ntshalintshali et al., 2025). The observed improvements in radicle length, hypocotyl length, and radicle-hypocotyl length ratio further highlight the functional significance of priming. Enhanced root development during early growth can improve water and nutrient acquisition, particularly under variable or stress environments (Lynch, 2022). Increased fresh and dry biomass suggests that priming not only accelerates germination but also improves early growth efficiency, a response reported for other biostimulant priming agents in soybean (Oliveira et al., 2024).

Multivariate analyses supported these interpretations. Positive correlations among vigor index, normal seedling percentage, and seedling growth traits, together with PCA separation of treatments, indicate that improvements in seed physiological quality are closely linked to enhanced early morphology. Importantly, seedling biomass and root-related traits contributed strongly to treatment discrimination, underscoring the value of incorporating growth-based parameters alongside standard germination metrics. From an application standpoint, two complementary recommendations emerge. Hydropriming can be promoted as a broadly applicable, inexpensive method to improve germination speed, while 4% MLE priming is a promising option for enhancing early growth and biomass, particularly in responsive cultivars. To ensure consistent outcomes, standardization of MLE preparation is essential (Lang et al., 2024). Finally, this study was conducted under laboratory conditions, and field validation across environments is required. Future work should disentangle soaking versus germination-phase effects of MLE, explore wider concentration ranges, and integrate biochemical indicators to further clarify cultivar-specific mechanisms. Despite these limitations, the findings demonstrate that MLE priming is a biologically sound and practically feasible strategy to improve early soybean performance, with effectiveness shaped by both priming type and cultivar.

Conclusion

Seed priming with 4% moringa leaf extract (MLE) markedly enhanced soybean germination performance, especially in Dega-1 and Devon-1 cultivars, by increasing germination percentage, seedling vigor index, radicle-to-hypocotyl length ratio, and seedling biomass relative to control and hydro-priming. These results establish 4% MLE priming as a reliable method to improve seed physiological quality through enhanced root system development and

uniform emergence. Further evaluation under field conditions is recommended to validate its effectiveness in improving crop establishment and maximizing yield potential.

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