"Optimization of Seed Priming Agents and Concentrations for Enhanced Germination and Early Seedling Establishment in Foxtail Millet Under Germinator Conditions"

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ABSTRACT

The purpose of this study is to analyse the effects of various seed priming agents across different concentrations on the emergence and early growth of foxtail millet. Research was carried out at the Agriculture and Forestry University, Chitwan, in a seed germinator under controlled environmental conditions. Various priming formulations, including hormonal priming (Gibberellic acid), halo priming ($ZnSO_4$, $CaCl_2$, KNO_3 and $MgSO_4$), Osmotic priming (PEG 6000), hydropriming, and control, were used. The parameters observed are root and shoot length, vigour indices, seedling dry weight, mean germination time (MGT), germination percentage, germination speed index (GSI) and allometric coefficient (AC). The results showed that priming with KNO_3 at 1% consistently and significantly outperformed other treatments, recording the highest germination percentage (74.54%), shortest MGT (2.33 days), greatest GSI (12.28), longest root and shoot length (7.28 cm, 4.36cm), and superior vigour indices (VI-I: 868.20; VI-II: 3.19). These findings establish 1% KNO_3 as an optimal priming protocol for foxtail millet under controlled conditions and provide a framework to guide field validation and commercial seed treatment protocols.

Keywords: Foxtail millet, Seed priming, Potassium nitrate, Germination parameters, Seedling vigour, Halopriming

INTRODUCTION

Foxtail millet (*Setaria italica* L.) a nutritious pseudo-cereal also called 'nutri-cereal' that has been cultivated for over 8,000 years, yet its cultivation and usage have been declining in recent decades(Shukla et al., 2026; Verma et al., 2026). The grains of foxtail are naturally rich in several micro and macronutrients, bioactive compounds, proteins and dietary fibre, which makes it nutritionally better than major cereal crops (Shukla et al., 2026). It can be cultivated extensively in challenging environments because of its resistance to drought, insects, disease, high salinity stress tolerance and adaptation to low soil fertility and minimal input needs (Verma et al., 2026). However, the major agronomic challenge limiting its adoption is that the successful establishment of foxtail millet remains critically constrained by poor and non-uniform seed germination, particularly under suboptimal soil moisture conditions (Kalsi & Bhasin, 2023; Shukla et al., 2026). The germination phase is the most vulnerable stage in foxtail millet's life cycle because the seedlings at this time possess limited root systems and are highly sensitive to environmental stresses, reducing the final grain yield with even the smallest delays in germination (Lu et al., 2025; Paul et al., 2022; Shukla et al., 2026).

Seed priming is a method where seeds are given water before sowing, which starts their internal chemical activities without letting the tiny root inside the seed come out (Jatana et al., 2024). It has emerged as a budget-friendly, environmentally sustainable strategy to improve germination, reduce mean germination time, activate defence mechanisms and enhance early seedling vigour across diverse crop species (Islam et al., 2026; Jatana et al., 2024; Paul et al., 2022). Out of different methods of seed priming, some of them include: hydropriming, osmo-priming with osmolytic solutions such as polyethylene glycol (PEG), chemical priming like halo priming

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with inorganic salts, and hormonal priming with phytohormones such as gibberellic acid (GA_3) (Amir et al., 2024).

Previous studies have revealed that zinc sulphate ($ZnSO_4$) priming increases seed germination percentage, seedling vigour, and photosynthetic efficiency by activating zinc-dependent antioxidant enzymes and mitigating oxidative damage (Bekele et al., 2024; Gamit et al., 2025). Calcium chloride ($CaCl_2$) priming has been proven to improve germination under salt stress by improving osmotic adjustment and ion homeostasis and lowering ROS accumulation and membrane damage (Chen et al., 2022). Magnesium sulphate ($MgSO_4$) priming has been shown to promote root development and photosynthetic pigment accumulation in different cereal crops (Sharavdorj et al., 2022). Potassium nitrate (KNO_3) is a widely used halo-priming agent that has been shown to enhance germination percentage, germination rate, and seedling vigour (Javed et al., 2020; Karaca, 2025; Moaaz Ali et al., 2020). It is due to multiple complementary mechanisms: K^+ functions as a primary osmoticum which promotes water uptake, reduces germination temperature requirements, and alleviates seed dormancy, whereas NO_3^- acts as both a nutrient source and a signalling molecule that modulates abscisic acid (ABA) metabolism (Karaca, 2025; Mebratu, 2022). Similarly, Gibberellic acid (GA_3) helps germination by forming hydrolytic enzymes such as α-amylase, which weaken endosperm cell walls, and antagonising ABA-mediated dormancy (Adhikari & Subedi, 2022; Jahan et al., 2025). In a similar way, Polyethylene glycol (PEG) priming is widely used to induce controlled hydration and initiate pre-germinative metabolism when water is limited, which makes them more able to handle drought conditions later on (Tounekti et al., 2020; F. Zhang et al., 2015).

Past literature has identified the most significant effects of these priming agents in other crops. However, there is still a lack of systematic work optimising seed priming methods specifically for foxtail millet, and only a few studies have been conducted till now. While some studies have looked at specific priming agents in millet, no comprehensive screening encompassing GA_3, $ZnSO_4$, $CaCl_2$, KNO_3, $MgSO_4$, hydropriming, and PEG across graduated concentration series has been reported. This represents a major knowledge gap. So, the current study was carried out to examine the effect of 20 distinct priming treatments with different concentrations comprising GA_3, $ZnSO_4$, $CaCl_2$, KNO_3, $MgSO_4$, hydropriming, PEG, along with an unprimed control, on germination and seedling establishment parameters in foxtail millet. The study mainly aims to find the best priming agent and its right concentration to improve germination performance under standard germinator conditions and to provide a strong statistical basis for subsequent field validation studies.

MATERIALS AND METHODS

Experimental Site and Duration

The research was conducted using a standard seed germinator under controlled conditions at the Seed Testing Laboratory, Department of Agronomy, Agriculture and Forestry University, Rampur, Chitwan. The study was carried out during April 2026 with ambient laboratory conditions maintained at 25 ± 2°C throughout the experimental period.

Seed Material and Preparation

Foxtail millet (*Setaria italica* L., cv. *Beauv*) seeds were obtained from the National Agriculture Genetic Resources Centre (NAGRC), Khumaltar, Lalitpur, Nepal, with documented 80 % germination. The viability assessment was performed by soaking 5g of seeds in 10 ml of water, and the seeds that floated were regarded as non-viable and discarded (Ajinde et al., n.d.). The seeds were first surface sterilised by immersion in 1% sodium hypochlorite (NaOCl) solution for 3 min, followed by three successive rinses with sterile distilled water (Babu et al., 2022), and then the surface-sterilised seeds were blotted dry on sterile filter paper under laminar airflow at ambient temperature (25 ± 2°C) before proceeding to priming treatments.

Experimental Design and Priming Treatments

The experimental design was a completely randomized design (CRD) with 20 treatments, 3 replications, and each replication consisting of 30 seeds. The treatment details are shown in Table 1. All chemical reagents were

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obtained from Chitwan Science House (CMI), and the working priming solutions were freshly prepared before each treatment set using sterile distilled water.

The surface-sterilised seeds were immersed in priming solutions at a seed-to-solution ratio of 1:5 (w/v) in 100 mL glass beakers (Islam et al., 2026). The soaking duration was standardised and kept constant for all treatments at 16 hrs in darkness at 25 ± 1°C to prevent photo-induced germination. Following the 16-h soaking period, primed seeds were rinsed three times with sterile distilled water to remove surface-adherent solute residues. Rinsed seeds were surface-dried in sterile filter paper and were dried under the air at room temperature to return their original weight and moisture content. Meanwhile, the unprimed control seeds were stored under identical conditions without hydration.

Table 1: The treatment details used in the research are arranged in groups along with the differential concentrations.

Treatment	**Treatment details**	**Concentration**
T1	GA	25ppm
T2	GA	50 ppm
T3	GA	100 ppm
T4	$ZnSo_4$	0.25% (w/v)
T5	$ZnSo_4$	0.5% (w/v)
T6	$ZnSo_4$	0.75% (w/v)
T7	$CaCl_2$	1% (w/v)
T8	$Cacl_2$	2% (w/v)
T9	$CaCl_2$	3% (w/v)
T10	KNO_3	1% (w/v)
T11	KNO_3	2% (w/v)
T12	KNO_3	3% (w/v)
T13	$MgSO_4$	0.25% (w/v)
T14	$MgSO_4$	0.5% (w/v)
T15	$MgSO_4$	0.75% (w/v)
T16	hydropriming	
T17	Unprimed control	Dry seeds
T18	PEG	1% (w/v)
T19	PEG	2% (w/v)
T20	PEG	3% (w/v)

Germination Assay

Germination tests were conducted following ISTA (2025) protocols using the "between paper" (BP) method (TNAU Agritech, 2021). 30 seeds per replicate were placed on two layers of sterile Whatman grade 181 filter paper of 125mm, moistened with 4 mL of sterile distilled water, and cut into a circular shape to fit in a petri dish of 90mm. However, for hydropriming treatments, filter papers were soaked with 8 mL of sterile distilled water.

The two layers of paper were placed inside covered Petri dishes to avoid evaporation. The petri dishes were randomised within the seed germinator and incubated at 30 ± 5°C, 75 ± 5% RH under a 16 h light/ 8 h dark photoperiod (Sadayandi et al., 2025; J. Zhang et al., 2024). Seeds were considered germinated when the radicle had protruded to a length of at least 2 mm (ISTA, 2025). Germination counts were recorded daily at 24-h intervals for 10 days post-sowing. Filter papers were re-moistened with sterile distilled water as required to maintain saturation throughout the incubation period.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

Data Collection

Germination

The germination percentage was calculated by using the formula given by Onofri et al. (2018).

$$\text{Germination } \% = \frac{Final\ number\ of\ seedlings\ emerged}{Total\ number\ of\ seeds\ sown} \times 100$$

Where the number of seedlings that emerged from each seed (radicle ≥2 mm) was counted every day up to 10 days.

MGT (Mean Germination Time)

Mean germination time shows how fast the seedlings emerged and was calculated using the formula given by Ranal & Santana (2006).

$$Mean\ Germination\ Time\ (days) = \frac{\sum n \times d}{\sum N}$$

Where n = number of seeds germinated on each day, d = number of days from the beginning of the test, and N = total number of seeds germinated at the end of the experiment.

GSI (Germination Speed Index)

According to Chan et al. (2018), the GSI was computed as follows:

GSI = (number of germinated seeds at first count/days of first count) + (number of germinated seeds at final count/days of final count).

The final count was taken at 10 days after sowing.

Allometric Coefficient (AC)

The growth ratio between the root and the shoot was expressed by the allometric coefficient, which was computed in accordance with (Lamichhane et al., 2021).

AC=Root length/Shoot length

Root length, shoot length, and dry weight

Five normal seedlings were selected randomly from each treatment. The root length was measured from the point of attachment of the seed to the tip of the longest root. Similarly, shoot length was measured from the point of attachment of the seed to the growing meristematic tip. Both lengths were expressed in centimetres.

To measure the seedling dry weight at 10 DAS, samples of five seedlings from each replication were oven-dried at 70°C for 24 hours, and the average seedling dry weight was calculated.

Seedling vigour indices

The seedling vigour index was measured for 10-day-old seedlings, taking the reference from (Choudhary et al., 2021) and was calculated using the formula given by (Goodi & Sharifzadeh, 2006):

$$Seedling\ vigor\ I\text{: } (Shoot\ length\ +\ Root\ length)\ \times\ Germination\%.$$

$$Seedling\ vigor\ II\text{: } Germination\%\ \times\ Seedling\ dry\ weight.$$

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

Statistical Analysis

The laboratory research under the germinator was performed in a Completely Randomized Design (CRD) consisting of 20 treatments with 3 replications. After collecting data from the sampled plants, the data were entered and arranged in MS Excel. The data were analysed through R-Studio, and Analysis of Variance (ANOVA) was done to test the effects of various priming agents on seedling parameters. Treatment averages were compared at the 5% level of significance using Duncan's Multiple Range Test (DMRT). Moreover, trend analysis and graphs were also prepared through R Studio software.

RESULTS

The treatments showed significant consequences on germination percentage, mean germination time (MGT), germination speed index (GSI), root length and shoot length, dry weight and vigour indices, whereas their influence on Allometric Coefficient (AC) was statistically non-significant.

Germination percentage, Mean Germination Time and Allometric Constant

Table 2: The effect of various priming treatments on germination %, Mean Germination time (MGT), Germination Speed Index (GSI) and Allometric Constant (AC)

Treatment	Germination %	MGT	GSI	AC
GA@25ppm	72.53^{bcde}	2.69^{bc}	10.23^{abc}	1.45
GA@50ppm	73.34^{ab}	2.34^{c}	10.80^{ab}	1.45
GA@100ppm	73.15^{abcd}	2.60^{bc}	10.57^{ab}	1.39
$ZnSO_4$@0.25%	71.88^{bcde}	2.76^{bc}	9.71^{abc}	1.47
$ZnSO_4$@0.5%	73.01^{abcde}	2.67^{bc}	10.23^{abc}	1.44
$ZnSO_4$@0.75%	72.04^{bcde}	2.73^{bc}	9.95^{abc}	1.45
$CaCl_2$@1%	71.54^{bcde}	2.84^{bc}	8.90^{bcd}	1.53
$CaCl_2$@2%	71.96^{bcde}	2.74^{bc}	9.76^{abc}	1.53
$CaCl_2$@3%	71.12^{de}	3.11^{b}	9.76^{abc}	1.51
KNO_3@1%	74.54^{a}	2.33^{c}	12.28^{a}	1.52
KNO_3@2%	73.30^{abc}	2.53^{bc}	10.61^{ab}	1.45
KNO_3@3%	73.23^{abc}	2.55^{bc}	10.57^{ab}	1.45
$MgSO_4$@0.25%	71.60^{bcde}	2.80^{bc}	9.71^{abc}	1.46
$MgSO_4$@0.5%	71.76^{bcde}	2.79^{bc}	9.57^{abc}	1.48
$MgSO_4$@0.75%	71.36^{bcde}	2.84^{bc}	7.85^{bcde}	1.48
Hydropriming	72.30^{bcde}	2.72^{bc}	10.19^{abc}	1.47
Control	70.92^{e}	3.75^{a}	5.33^{e}	1.51
PEG@1%	71.04^{e}	3.13^{b}	6.23^{de}	1.55
PEG@2%	71.95^{bcde}	2.74^{bc}	9.76^{abc}	1.46
PEG@3%	71.23^{cde}	2.85^{bc}	7.28^{cde}	1.54
SEm	0.6108	0.199	0.9521	1.5039
LSD	1.75	0.56	2.72	0.29
F probability	**	*	**	NS
CV%	1.46	12.39	17.41	12.13
Grand Mean	72.19	2.78	9.46	1.48

Note: CV=Coefficient of variation, LSD= Least Significant Difference, (**=significant($p<0.01$), *=significant($p<0.5$), NS= Nonsignificant)

Among the treatments, KNO_3 at 1% recorded the highest germination percentage (74.54%), which was significantly superior to the control (70.92%) and comparable to GA_3 at 50 ppm (73.34%) and GA_3 at 100 ppm (73.15%), which is represented by Figure 1. Hydropriming (72.30%) and $ZnSO_4$ at 0.5% (73.01%) also improved germination percentage relative to the control, though differences were not always statistically

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

distinct. Mean Germination Time was lowest under KNO_3 at 1% (2.33 days) and GA_3 at 50 ppm (2.34 days), indicating faster germination compared to the control (3.75 days). Conversely, $CaCl_2$ at 3% (3.11 days) and PEG at 1% (3.13 days) prolonged germination time, reflecting inhibitory effects at higher concentrations. The highest GSI was observed with KNO_3 at 1% (12.28), accompanied by GA_3 at 50 ppm (10.80) and GA_3 at 100 ppm (10.57), which were significantly greater than the control (5.33). Treatments with PEG at 1% (6.23) and PEG at 3% (7.28) exhibited reduced GSI, which shows the negative impact of osmotic stress when the PEG levels are higher than optimal. Meanwhile, Allometric Coefficient (AC) showed no statistically significant differences among treatments, suggesting that priming agents influenced germination dynamics without markedly altering Allometric Coefficient at the seedling stage.

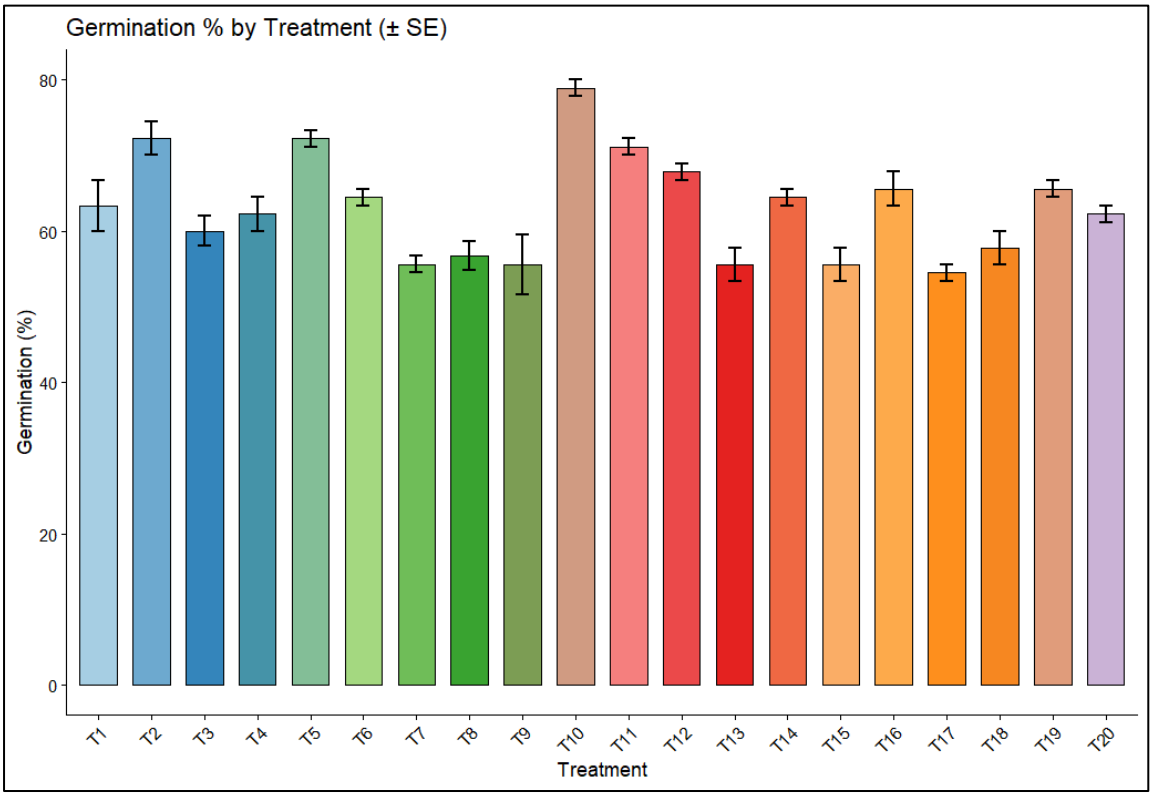

Figure 1:Germination percentage (%) of foxtail millet seeds under twenty priming treatments (T1–T20). Bars represent treatment means (n = 3), and error bars indicate ± standard error of the mean (SE)

Root length, Shoot length and dry weight

At 10 DAS, priming with KNO_3 at 1% produced the longest roots at all days: 5 DAS (3.73 cm), 7 DAS (5.33 cm) and 10 DAS (7.28 cm), which were significantly superior to the control and most other treatments. Meanwhile, at 5 DAS, GA_3 at 50 ppm (3.25 cm) also enhanced root elongation, while $CaCl_2$ at 3% (2.58 cm) and $MgSO_4$ at 0.75% (2.64 cm) resulted in shorter roots, comparable to the control. By 7 DAS, GA_3 at 50 ppm (4.50 cm) showed the second-highest root length, whereas the control (3.51 cm) and $CaCl_2$ at 3% (3.79 cm) exhibited reduced elongation, indicating inhibitory effects at higher $CaCl_2$ concentrations. Similar results were obtained at 10 DAS, where KNO_3 at 1% maintained its superiority (7.28 cm), GA_3 at 50 ppm (6.45 cm) and KNO_3 at 2% (6.10 cm) also promoted root elongation, whereas $ZnSO_4$ at 0.75% (5.20 cm), $MgSO_4$ at 0.25% (5.22 cm), and the control (5.01 cm) recorded the shortest roots.

Similarly, in case of shoot lengths, at 5 DAS, KNO_3 at 1% (2.60 cm) and KNO_3 at 2% (2.83 cm) produced the longest shoots whereas, GA_3 at 50 ppm (2.30 cm) also enhanced shoot elongation, while $CaCl_2$ at 3% (1.81 cm) and $MgSO_4$ at 0.75% (1.81 cm) recorded shorter shoots, comparable to the control. By 7 DAS, shoot length remained highest under KNO_3 at 1% (3.76 cm), followed by GA_3 at 50 ppm (3.44 cm). The control (2.52 cm) and $CaCl_2$ at 3% (2.68 cm) exhibited reduced elongation. At 10 DAS, KNO_3 at 1% maintained its superiority (4.36 cm), whereas $ZnSO_4$ at 0.25% (3.38 cm), $CaCl_2$ at 3% (3.31 cm), and the control (3.12 cm) recorded the shortest shoots.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

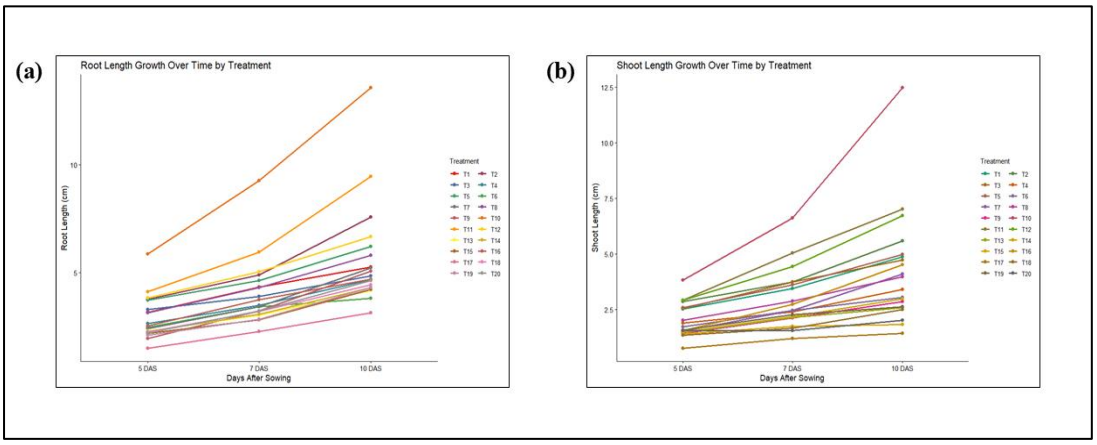

Figure 2: Temporal dynamics of mean root length (a) and shoot length (b) at 5, 7 and 10 days after sowing (DAS) across twenty seed priming treatments (T1–T20).

Additionally, the dry weight was highest under KNO_3 at 1% (0.0428 g), which was statistically superior to the control (0.0282 g). It was observed that GA_3 at 50 ppm (0.0417 g) and KNO_3 at 2% (0.0412 g) also enhanced DW, while $CaCl_2$ at 3% (0.0311 g), $MgSO_4$ at 0.75% (0.0317 g), and PEG at 1% (0.0282 g) recorded the lowest values, comparable to the control.

Table 3: The effect of different priming treatments on root length (cm), shoot length (cm) and dry weight (g). The root and shoot length were taken at 5,7 and 10 DAS, whereas DW was measured at 10 DAS.

	Root length (cm)			**Shoot length (cm)**			
Treatment	**RL 5 DAS**	**RL 7 DAS**	**RL 10 DAS**	**SL 5 DAS**	**SL 7 DAS**	**SL 10 DAS**	**DW**
GA@25ppm	2.97^{bc}	4.03^{bc}	5.62^{bc}	2.12^{abc}	3.00^{bcd}	3.63^{bcd}	0.0368^{a}
GA@50ppm	3.25^{ab}	4.50^{b}	6.45^{ab}	2.30^{ab}	3.44^{ab}	4.05^{ab}	0.0417^{ab}
GA@100ppm	3.03^{bc}	3.99^{bc}	5.42^{bc}	2.15^{ab}	3.12^{abcd}	3.72^{bcd}	0.0377^{abcd}
$ZnSO_4$@0.25%	2.80^{bc}	3.89^{bc}	5.28^{bc}	1.95^{bc}	2.78^{bcd}	3.38^{cd}	0.0336^{bcde}
$ZnSO_4$@0.5%	3.05^{bc}	4.13^{bc}	5.69^{bc}	2.15^{ab}	3.10^{abcd}	3.70^{bcd}	0.0375^{abcd}
$ZnSO_4$@0.75%	2.73^{bc}	3.86^{bc}	5.20^{c}	1.91^{bc}	2.85^{bcd}	3.45^{cd}	0.0359^{abcde}
$CaCl_2$@1%	2.72^{bc}	3.79bc	5.48^{bc}	1.85^{bc}	2.77^{bcd}	3.34^{cd}	0.0319^{de}
$CaCl_2$@2%	2.92^{bc}	4.10^{bc}	5.61^{bc}	2.04^{bc}	2.84^{bc}	3.45^{cd}	0.0359^{abcde}
$CaCl_2$@3%	2.58^{bc}	3.79^{bc}	5.42^{bc}	1.81^{bc}	2.68^{cd}	3.31^{cd}	0.0311d^{e}
KNO_3@1%	3.73^{a}	5.33^{a}	7.28^{a}	2.60^{a}	3.76^{a}	4.36^{a}	0.0428^{a}
KNO_3@2%	3.15^{abc}	4.24^{bc}	6.10^{bc}	2.83^{ab}	3.28^{abc}	3.88^{abc}	0.0412^{abc}
KNO_3@3%	3.12^{abc}	4.13^{bc}	5.85^{bc}	2.26^{ab}	3.12^{abcd}	3.72^{bcd}	0.0381^{abcd}
$MgSO_4$@0.25%	2.66^{bc}	3.75^{bc}	5.22^{c}	1.83^{bc}	2.76^{bcd}	3.36^{cd}	0.0321^{de}
$MgSO_4$@0.5%	2.71^{bc}	3.71^{bc}	5.39^{bc}	1.86^{bc}	2.77^{bcd}	3.37^{cd}	0.0326^{cde}
$MgSO_4$@0.75%	2.64^{bc}	3.66^{bc}	5.33^{bc}	1.81^{bc}	2.72^{cd}	3.32^{cd}	0.0317^{de}
Hydropriming	2.77^{bc}	3.98^{bc}	5.49^{bc}	1.87^{bc}	2.91^{bcd}	3.51^{bcd}	0.0363^{abcde}
Control	2.46^{c}	3.51^{c}	5.01^{c}	1.63^{c}	2.52^{d}	3.12^{d}	0.0282^{e}
PEG@1%	2.68^{bc}	3.84^{bc}	5.35^{bc}	1.80^{bc}	2.63^{cd}	3.23^{d}	0.0282^{e}
PEG@2%	2.67^{bc}	3.70^{bc}	5.35^{bc}	1.88^{bc}	2.78^{bcd}	3.38^{cd}	0.0338^{bcde}
PEG@3%	2.70^{bc}	3.81^{bc}	5.64^{bc}	1.87^{bc}	2.65^{cd}	3.32^{cd}	0.0313^{de}
SEm	0.2052	0.2745	0.3409	0.1512	0.2081	0.1763	0.0026
LSD	0.59	0.79	0.97	0.43	0.59	0.5	0.007
F probability	*	*	*	*	*	**	**
CV%	12.38	11.9	10.52	13.08	12.3	8.64	12.83
Grand Mean	2.87	3.99	5.61	2	2.92	3.53	0.034

Note: CV=Coefficient of variation, LSD=Least Significant Difference, (**=significant($p<0.01$), *=significant($p<0.5$))

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

Vigour Indices

Vigour index I followed a trend similar to other parameters, with KNO_3 at 1% (868.20) producing the highest value, significantly exceeding all other treatments, whereas the control (576.75), $CaCl_2$ at 3% (622.18), and $MgSO_4$ at 0.25% (615.26) exhibited the lowest values. For vigour index II, KNO_3 at 1% (3.19) again outperformed all treatments, followed by GA_3 at 50 ppm (3.06) and KNO_3 at 2% (3.02). The control (2.00) and PEG at 1% (2.00) recorded the lowest values, indicating poor seedling establishment under these conditions.

Table 4: The effect of different priming treatments on Vigour Index I and Vigour Index II

Treatment	Vigour index I	Vigour index II
GA@25ppm	672.15^{cde}	2.67^{abcd}
GA@50ppm	770.98^{b}	3.06^{ab}
GA@100ppm	669.26^{cde}	2.76^{abcd}
$ZnSO_4$@0.25%	622.96^{de}	2.41^{cde}
$ZnSO_4$@0.5%	685.74^{bcd}	2.74^{abcd}
$ZnSO_4$@0.75%	623.89^{de}	2.59^{abcde}
$CaCl_2$@1%	631.84^{de}	2.28^{de}
$CaCl_2$@2%	652.26^{cde}	2.58^{abcde}
$CaCl_2$@3%	622.18^{de}	2.21^{de}
KNO_3@1%	868.20^{a}	3.19^{a}
KNO_3@2%	731.61^{bc}	3.02^{abc}
KNO_3@3%	701.28^{bcd}	2.79^{abcd}
$MgSO_4$@0.25%	615.26^{de}	2.29^{de}
$MgSO_4$@0.5%	628.96^{de}	2.33^{de}
$MgSO_4$@0.75%	617.69^{de}	2.26^{de}
Hydropriming	650.45^{cde}	2.63^{abcde}
Control	576.75^{e}	2.00^{e}
PEG@1%	610.25^{de}	2.00^{e}
PEG@2%	628.70^{de}	2.43^{bcde}
PEG@3%	638.45^{de}	2.23^{de}
Sem	28.1627	0.1913
LSD	80.49	0.546
F probability	***	**
CV%	7.38	13.10
Grand Mean	660.94	2.52

Note: CV=Coefficient of variation, LSD= Least Significant Difference, (***=significant ($p<0.001$), **=significant($p<0.01$))

DISCUSSION

The present study evaluated the efficacy of 20 priming treatments to identify the best agent to enhance the germination performance of foxtail millet under standard germinator conditions. The results obtained showed that seed priming with KNO_3 at 1% consistently emerged as the most efficacious treatment across germination percentage, mean germination time (MGT), germination speed index (GSI), root and shoot elongation, dry weight accumulation, and both vigour indices, while the effect of priming treatments on allometric coefficient (AC) was non-significant.

KNO_3 at 1% consistently outperformed all treatments, recording the highest germination percentage (74.54%), shortest MGT (2.33 days), greatest GSI (12.28), and superior vigour indices (VI-I and VI-II), all significantly exceeding the unprimed control. This may be due to the well-documented role of potassium and nitrate ions in

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modulating seed dormancy and stimulating enzymatic pathways prerequisite to radicle emergence (Poornima et al., 2026). These results correspond with (Poornima et al., 2026), who demonstrated KNO_3 priming achieved the earliest germination, highest germination percentage, and greatest vigour index in Gaillardia. The priming-induced biochemical changes caused by the combined effect of potassium and nitrate, which include enzyme activation, dormancy breaking, and catabolism of germination inhibitors, are well-established mechanisms underlying such improvements (Dawood, 2018; Poornima et al., 2026; Siddique et al., 2024).

GA_3 at 50 ppm produced the second-most favourable germination response (73.34%; MGT 2.34 days; GSI 10.80), consistent with gibberellin-mediated endosperm weakening and upregulation of pre-germinative metabolism as mentioned by Gnawali & Subedi (2021) and Jahan et al. (2025). The response to GA_3 was non-linear: 50 ppm outperformed both 25 and 100 ppm concentrations, indicating a classical hormetic dose–response relationship. $ZnSO_4$ treatments led to small improvements in germination, with 0.5% showing slight effectiveness. Zinc's role as a metalloenzyme cofactor in oxidative stress mitigation and signal transduction during imbibition is well established (Bekele et al., 2024). The comparatively modest responses in the present study suggest species-specific sensitivity to GA and zinc concentration thresholds.

$CaCl_2$ priming, especially at 3%, gave the lowest germination rates because it caused osmotic stress, which affected how well seeds absorb water and activated enzymes. This shows the narrow range of concentration where using $CaCl_2$ priming is helpful rather than harmful. Similarly, $MgSO_4$ treatments failed to generate consistent germination improvements, with 0.75% leading to the worst germination. PEG-based osmotic priming at 1% and 3% performed the worst among all treatments due to a lot of osmotic stress, which hinders seed performance. Earlier studies by Han et al. (2022) also suggested that adding oligosaccharides can help reduce the stress caused by PEG in foxtail millet.

Thus, from a practical farming viewpoint, KNO_3 at 1% is recommended as the best choice for a priming agent for improving seed performance and early seedling establishment in this crop. This is because it is affordable, readily available, provides dual macronutrient provision, and works best across all evaluated parameters. GA_3 at 50 ppm represents a viable alternative, especially where using potassium nitrate is restricted or where hormonal priming is strategically preferred.

One of the major limitations of this study is that it was done under controlled conditions. Because of this, future research should test the agronomic performance of KNO_3- and GA_3-primed seeds in real field conditions where factors like fluctuating temperature, changing nutrient levels, and soil moisture stress are present. This will help to find out if the early growth benefits seen in controlled conditions actually lead to better harvest results. In addition, the mechanisms behind priming-induced performance, like stress memory, changes in gene activities that control dormancy and antioxidant system activation need more study using advanced tools such as gene expression analysis and metabolite profiling. This will help build a clearer picture of how seed priming works at a molecular level in this and related species.

CONCLUSION

The present study shows comprehensive evidence that seed priming efficacy in the foxtail millet cropping system depends on the agent and concentration. The best treatment was KNO_3 at 1%, which consistently emerged as the optimal treatment across all evaluated germination and early seedling growth parameters. This treatment led to the highest germination percentage, the shortest mean germination time, the greatest germination speed index, the longest root and shoot length at all developmental stages, the greatest seedling dry weight, and the highest vigour indices, all significantly better than the unprimed control. A second good option was GA_3 at 50 ppm, which also worked well. Similarly, $ZnSO_4$ and $MgSO_4$ treatments helped little when used at low concentrations, but didn't improve germination or growth much compared to untreated seeds when used at higher levels. $CaCl_2$ priming was largely ineffective across the range tested, and at 3% concentration, it actually slowed down germination and growth, reduced dry weight and both vigour indices. Using PEG-based osmotic priming at concentrations of 1% or higher was also not helpful and even slowed things down. The allometric coefficient was unaffected by any priming treatment.

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