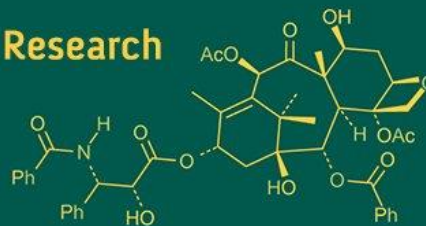


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(8): 523-528
www.biochemjournal.com
Received: 01-07-2026
Accepted: 27-07-2026

Shivam Kumar Patel
Jacob Institute of Biotechnology
& Bioengineering (JIBB), Sam
Higginbottom University of
Agriculture, Technology and
Sciences (SHUATS), Prayagraj,
Uttar Pradesh, India

Alok M Lal
Jacob Institute of Biotechnology
& Bioengineering (JIBB), Sam
Higginbottom University of
Agriculture, Technology and
Sciences (SHUATS), Prayagraj,
Uttar Pradesh, India

Prasada Rao Kongala
Jacob Institute of Biotechnology
& Bioengineering (JIBB), Sam
Higginbottom University of
Agriculture, Technology and
Sciences (SHUATS), Prayagraj,
Uttar Pradesh, India

Divyanshu Singh
Jacob Institute of Biotechnology
& Bioengineering (JIBB), Sam
Higginbottom University of
Agriculture, Technology and
Sciences (SHUATS), Prayagraj,
Uttar Pradesh, India

Shailendra Kumar Shrivastava
Jacob Institute of Biotechnology
& Bioengineering (JIBB), Sam
Higginbottom University of
Agriculture, Technology and
Sciences (SHUATS), Prayagraj,
Uttar Pradesh, India

Corresponding Author:
Alok M Lal
Jacob Institute of Biotechnology
& Bioengineering (JIBB), Sam
Higginbottom University of
Agriculture, Technology and
Sciences (SHUATS), Prayagraj,
Uttar Pradesh, India

Efficacy of seed priming with Gibberellic Acid (GA₃), Plant Growth Promoting Rhizobacteria (PGPR), and botanical extracts on germination and enzyme activity of sorghum (*Sorghum bicolor* L. Moench)

Shivam Kumar Patel, Alok M Lal, Prasada Rao Kongala, Divyanshu Singh and Shailendra Kumar Shrivastava

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i8Sg.9477>

Abstract

Seed priming is an effective pre-sowing technique for improving seed germination, metabolic activity and early seedling establishment in sorghum. The present investigation was conducted to evaluate the efficacy of gibberellic acid (GA₃), plant growth-promoting rhizobacteria (PGPR), and botanical extracts on germination and enzyme activity-related traits of *Sorghum bicolor* L. Moench. The experiment comprised nine seed priming treatments arranged in a randomized block design with three replications for field related parameters, while Complete Randomized Design was used for Laboratory work. Significant improvements were observed in germination percentage, speed of germination, germination index, vigour index-I and hydrolytic enzyme activities compared with the untreated control. PGPR @ 250 ppm was found to be the most effective treatment for improving germination and seed vigour, whereas GA₃ @ 200 µM significantly enhanced α-amylase, β-amylase, protease, lipase, phosphatase and dehydrogenase activities. The increased enzyme activities promoted efficient mobilization of stored food reserves, leading to faster and more uniform germination and vigorous seedling growth. Botanical priming treatments, particularly moringa leaf extract, also improved germination and enzymatic activities over the control, indicating their potential as eco-friendly alternatives for seed enhancement. Overall, the study demonstrated that PGPR @ 250 ppm and GA₃ @ 200 µM are effective seed priming agents for improving seed physiological quality and biochemical attributes, thereby ensuring better early crop establishment in sorghum.

Keywords: *Sorghum bicolor*, Seed priming, Gibberellic acid (GA₃), Plant Growth-Promoting Rhizobacteria (PGPR), Botanical extracts; germination, enzyme activity, seed vigour

Introduction

Sorghum (*Sorghum bicolor* L. Moench) is one of the major cereal crops cultivated worldwide for food, fodder and industrial purposes. Due to its remarkable adaptability to drought, high temperature and poor soil conditions, it plays an important role in sustainable agriculture, particularly in semi-arid and marginal production environments. Sorghum grains are nutritionally important because they contain carbohydrates, proteins, dietary fibre, minerals and bioactive compounds beneficial for human and animal nutrition. However, productivity of sorghum is often limited by poor seed germination, weak crop establishment and environmental stresses during different growth stages (Singh *et al.*, 2022; Kumar and Verma, 2023) [22, 29].

Seed quality is a key determinant of crop performance as it influences germination, seedling vigour and subsequent plant growth. Poor seed vigour results in delayed emergence, uneven plant stand and reduced biomass accumulation, ultimately affecting yield potential. Seed priming has emerged as an effective seed enhancement technique that improves physiological readiness of seeds by controlled hydration before sowing. This process activates metabolic activities, enhances enzymatic reactions, improves membrane stability and promotes rapid and uniform germination under field conditions (Rao *et al.*, 2021) [28].

Different approaches of seed priming, including hormonal priming, biopriming and botanical priming, have gained importance due to their ability to enhance crop performance in an eco-friendly manner.

Priming improves germination through activation of hydrolytic enzymes, mobilization of stored reserves, repair of cellular damage and regulation of endogenous hormones (Patel and Singh, 2023)^[20]. Among plant growth regulators, gibberellic acid (GA₃) is widely recognized for its role in breaking seed dormancy, stimulating enzyme activity, promoting cell elongation and enhancing vegetative growth. GA₃ priming improves α -amylase activity, carbohydrate mobilization and early seedling establishment, resulting in improved growth and yield attributes (Mehta *et al.*, 2024)^[12].

Previous studies have reported that GA₃ application enhances germination percentage, seedling vigour, shoot and root growth, chlorophyll content and biomass production in different crops. In sorghum, GA₃ priming has been associated with improved metabolic activation, enhanced antioxidant capacity and better crop establishment under stress conditions (Rao *et al.*, 2022)^[25]. However, limited information is available regarding the influence of GA₃ priming on combined physiological, yield and nutritional quality traits of sorghum grains.

Plant growth-promoting rhizobacteria (PGPR) have gained considerable attention as biological seed enhancement agents due to their beneficial effects on plant growth and stress tolerance. PGPR promotes plant development through nitrogen fixation, phosphorus solubilization, phytohormone production, siderophore synthesis and improved nutrient acquisition. These microorganisms also enhance root development, chlorophyll content and antioxidant defence mechanisms, thereby improving plant growth and productivity (Rao and Singh, 2023; Patel *et al.*, 2024)^[27, 21]. In cereals, PGPR inoculation has been reported to improve germination, biomass accumulation and yield by enhancing physiological efficiency and stress adaptation.

Botanical seed priming is another sustainable approach that utilizes plant extracts rich in natural growth-promoting substances, antioxidants, vitamins, minerals and bioactive compounds. Plant extracts such as moringa leaf extract contain naturally occurring cytokinins, amino acids and nutrients that stimulate enzymatic activity, improve seedling vigour and enhance plant growth (Mehta *et al.*, 2023)^[13]. Botanical priming has also been associated with improved antioxidant defence, delayed senescence and enhanced tolerance against environmental stresses.

Although several studies have demonstrated the individual benefits of GA₃, PGPR and botanical priming on seed germination and crop growth, comparative evaluation of these priming agents under uniform field conditions is still limited. Moreover, their influence on physiological traits, yield components and nutritional quality parameters of sorghum grains requires further investigation. Therefore, the present study was undertaken to evaluate the effect of GA₃, PGPR and botanical seed priming treatments on germination behaviour, biochemical responses, growth, yield performance and grain quality of sorghum.

Materials and Methods

The present investigation entitled “Efficacy of Seed Priming with Gibberellic Acid (GA₃), Plant Growth-Promoting Rhizobacteria (PGPR), and Botanical Extracts on Germination and Enzyme Activity of Sorghum (*Sorghum bicolor* L. Moench)” was conducted during two consecutive Kharif cropping seasons, 2021-22 and 2022-23. at Central crop research field and Laboratory investigations were carried out at Jacob Institute of Biotechnology &

Bioengineering (JIBB), Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh, India.

The experiment was designed to evaluate the influence of different seed priming treatments on germination behaviour, biochemical responses, growth attributes, yield performance and nutritional quality parameters of sorghum. Healthy and uniform seeds of sorghum were subjected to different priming treatments including gibberellic acid (GA₃), plant growth-promoting rhizobacteria (PGPR), and botanical extracts. The treated seeds were evaluated under experimental conditions for various physio-chemical, biochemical and quality parameters.

The experiment consisted of nine treatments including untreated control (T₀), GA₃ @ 100 μ M (T₁), GA₃ @ 200 μ M (T₂), PGPR @ 250 ppm (T₃), PGPR @ 500 ppm (T₄), moringa leaf extract @ 2% (T₅), moringa leaf extract @ 5% (T₆), custard apple leaf extract @ 2% (T₇), and custard apple leaf extract @ 5% (T₈). The experiment was conducted in a randomized block design (RBD) with appropriate replications for field related parameters while Complete Randomized Design was used for laboratory trails.

Preparation and Application of Seed Priming Treatments

Seed priming treatments were prepared using hormonal, biological and botanical agents under laboratory conditions to ensure uniformity and reproducibility. Gibberellic acid (GA₃) solutions were prepared at 100 and 200 μ M concentrations using freshly prepared solutions for hormonal priming. Biological priming was performed using PGPR cultures containing *Bacillus* spp. and *Pseudomonas* spp., multiplied in LB medium and applied at 250 and 500 ppm concentrations. For botanical priming, aqueous leaf extracts of moringa (*Moringa oleifera*) and custard apple (*Annona squamosa*) were prepared at 2% and 5% concentrations from shade-dried leaf powder. Healthy sorghum seeds were obtained and surface sterilized before treatment application. The seeds were separately soaked in respective priming solutions for 12 hours at 25 °C, whereas distilled water-soaked seeds were maintained as control. After completion of priming, excess solution was removed, and seeds were air-dried under room temperature until the original moisture level was restored. The treated seeds were subsequently used for germination studies, biochemical analysis, growth evaluation and yield assessment under experimental conditions.

Observation Recorded

Germination Percentage: Germination percentage was calculated by counting the number of normal seedlings at the final count and expressing it as a percentage of the total number of seeds sown. This parameter reflects the overall viability and effectiveness of seed priming treatments. Speed of germination was determined using daily germination counts to evaluate the rate at which seeds germinated. It indicates the rapidity and uniformity of seed emergence under different priming treatments.

Germination Index: Germination index was calculated by assigning greater weight to seeds that germinated earlier, thereby integrating both germination speed and total germination. Higher GI values indicate faster and more synchronized germination.

Vigour Index I: Vigour index I was computed by multiplying germination percentage with mean seedling length (shoot + root). This index provides a combined measure of germination performance and early seedling growth.

Observations related to Enzymes activity during germination

α -Amylase activity in primed sorghum seeds was estimated following the method described by AOAC (2002), which measures the hydrolysis of starch into reducing sugars during germination. Crude enzyme extract obtained from germinating seeds was incubated with starch substrate under controlled conditions, and the released sugars were quantified spectrophotometrically. Increased α -amylase activity reflects enhanced starch degradation and improved reserve mobilization due to seed priming.

β -Amylase activity was determined according to the procedure outlined by Nandi *et al.*, (1994) by estimating the amount of maltose released from starch in germinating sorghum seeds. Enzyme extract was incubated with substrate and maltose content was measured colorimetrically. Higher β -amylase activity indicates efficient carbohydrate metabolism and greater energy availability during early seedling growth.

Protease activity in primed sorghum seeds was analyzed using the method described by Dahot (1992), which quantifies amino acids released from storage proteins during germination. The enzyme extract was incubated with protein substrate and absorbance was recorded at a specific wavelength. Enhanced protease activity signifies improved protein mobilization and nitrogen availability as a result of seed priming treatments.

Lipase activity was assessed following the protocol of Gadge *et al.*, (2011) by estimating the free fatty acids liberated from lipid substrates in germinating sorghum seeds. The enzyme extract was incubated with lipid substrate and the activity was measured spectrophotometrically. Increased lipase activity indicates effective lipid breakdown, contributing to improved seedling establishment after priming.

Phosphatase activity was estimated using the method suggested by Prazers *et al.*, (2004), which measures the release of inorganic phosphate from organic phosphorus compounds in germinating seeds. Crude enzyme extract was incubated with suitable substrate and phosphate content was quantified. Higher phosphatase activity reflects enhanced phosphorus mobilization and metabolic efficiency in primed seeds.

Dehydrogenase activity was determined according to Mrid *et al.*, (2018) using a tetrazolium reduction assay to assess respiratory activity in germinating sorghum seeds. The intensity of color development indicated the level of enzymatic reduction and metabolic activity. Increased dehydrogenase activity denotes improved seed viability and vigor as influenced by seed priming treatments.

Results and Discussion

Germination Percentage (%)

The data presented in the table 1, showed that the germination percentage was significantly influenced by different seed priming treatments during both years of experimentation. During the first year, germination ranged from 80.33% (T_0 -Control) to 95.86% (T_3 -PGPR 250 ppm),

whereas in the second year it varied from 81.55% to 97.27%, respectively. The pooled analysis revealed maximum germination under T_3 (PGPR 250 ppm) (96.57%), followed by T_2 (GA_3 200 μ M) (92.33%) and T_7 (Custard apple leaf extract 2%) (91.34%), while the minimum was recorded in control (80.94%). The improvement in germination under PGPR and GA_3 priming may be due to enhanced metabolic activation, increased enzyme synthesis and improved mobilization of stored food reserves. Similar improvement in germination due to seed priming has been reported by Jisha *et al.*, (2013) ^[10], who observed enhanced germination performance in primed cereal seeds. The present findings suggest that priming treatments improved physiological readiness of seeds, resulting in faster and more uniform crop establishment.

Speed of Germination

Seed priming significantly improved the speed of germination during both years. The first-year values ranged from 10.04 (T_0) to 11.98 (T_3), while second-year values ranged from 11.04 to 13.58. The pooled analysis recorded maximum speed of germination under T_3 (PGPR 250 ppm) (12.78) followed by T_2 (GA_3 200 μ M) (12.21), whereas the lowest value was observed in control (10.54). Increased germination speed under priming treatments may be attributed to hydration-induced activation of enzymes and repair mechanisms within the seed. Similar observations were reported by Ashraf and Foolad (2005), who stated that priming enhances early metabolic activity and reduces germination time. The present results indicate that PGPR and GA_3 treatments accelerated the germination process by improving seed physiological efficiency.

Germination Index (GI)

The germination index showed significant variation among treatments. During the first year, GI ranged from 21.59 (control) to 34.35 (T_3), while during the second year it varied from 25.89 to 41.23. The pooled analysis recorded the highest GI under T_3 -PGPR 250 ppm (37.79) followed by T_2 - GA_3 200 μ M (36.09) and T_6 -Moringa leaf extract 5% (35.22). Higher GI reflects rapid and uniform seedling emergence due to improved metabolic activity and faster reserve mobilization. Similar findings were reported by Kumar *et al.*, (2021), who observed increased germination indices under microbial and hormonal priming treatments. The enhanced GI in treated seeds indicates improved seed vigour and better establishment potential under field conditions.

Vigour Index-I

Vigour index-I differed significantly among treatments during both years. The values ranged from 540.87-999.40 during the first year and 655.67-1216.73 during the second year. The pooled data showed maximum vigour index under T_3 (PGPR 250 ppm) (1108.06) followed by T_2 (GA_3 200 μ M) (1073.98), while the lowest was recorded in control (598.27). The increased vigour index was mainly due to improvement in both germination percentage and seedling growth parameters. According to Moeinzadeh *et al.*, (2010), seed priming improves seedling vigour by enhancing enzymatic activity and physiological processes during early growth. The present findings confirm that priming treatments improved seedling establishment and early growth performance in sorghum.

Enzyme Activities

The data shown in table 2, states that the activities of hydrolytic and metabolic enzymes were significantly influenced by different seed priming treatments, indicating enhanced biochemical activation during early seed germination. The pooled data revealed that the maximum enzyme activities were recorded under T₂ (GA₃ 200 µM), which showed α-amylase activity of 13.80 U mg⁻¹, β-amylase activity of 8.70 U mg⁻¹, protease activity of 40.03 U/mL, lipase activity of 6.70 U/mL, phosphatase activity of 1.29 µmol pNP min⁻¹ g⁻¹ FW and dehydrogenase activity of 0.63 OD value. In comparison, the untreated control (T₀) recorded the lowest activities with α-amylase (8.40 U mg⁻¹), β-amylase (2.60 U mg⁻¹), protease (33.93 U/mL), lipase (3.86 U/mL), phosphatase (0.92 µmol pNP min⁻¹ g⁻¹ FW) and dehydrogenase (0.48 OD value).

The enhancement of α-amylase and β-amylase activity under GA₃ priming may be attributed to the stimulatory effect of gibberellic acid on the synthesis and activation of hydrolytic enzymes during seed germination. Increased

amylase activity facilitates rapid degradation of stored starch into soluble sugars, providing energy and carbon skeletons required for embryo growth and seedling establishment. Similar findings were reported by Bewley *et al.*, (2013) [5], who stated that hormonal priming accelerates reserve mobilization by activating hydrolytic enzymes during early germination stages.

Table 2, revealed that the activity of protease was also increased significantly under priming treatments, with the highest value recorded in T₂ (40.03 U/mL) followed by T₅ (Moringa leaf extract 2%) (37.03 U/mL) and T₁ (GA₃ 100 µM) (36.74 U/mL). Enhanced protease activity indicates improved degradation of storage proteins into amino acids, which supports rapid cell division and seedling growth. The increased protein mobilization under primed seeds may have contributed to higher germination percentage and vigour index observed in the present study. Similar enhancement of proteolytic activity due to seed priming has been reported by Farooq *et al.*, (2008) [6].

Table 1: Effect of GA₃, PGPR and Botanicals Seed priming on Germination attributes of Sorghum (*Sorghum bicolor* L. Moench)

Treatment	Germination%			Speed of germination			Germination index (GI)		Vigour index I			
	1st yr.	2nd yr.	Pooled	1st yr.	2nd yr.	Pooled	1st yr.	2nd yr.	Pooled	1st yr.	2nd yr.	Pooled
T ₀ -Control	80.33	81.55	80.94	10.04	11.04	10.54	21.59	25.89	23.74	540.87	655.67	598.27
T ₁ -GA ₃ @ 100µM	91.65	93.01	92.33	11.46	12.96	12.21	32.84	39.33	36.09	974.12	1173.83	1073.9
T ₂ -GA ₃ @ 200 µM	95.86	97.27	96.57	11.98	13.58	12.78	34.35	41.23	37.79	999.4	1216.7	1108.06
T ₃ -PGPR @ 250 ppm	85.33	86.61	85.97	10.67	12.07	11.37	30.58	36.63	33.6	791.83	964.44	878.14
T ₄ -PGPR @ 500 ppm	87.67	88.98	88.33	10.96	12.45	11.7	31.42	37.81	34.62	835.87	1018.06	926.97
T ₅ -Moringa leaf extract @ 2%	89.3	90.63	89.97	11.16	12.66	11.91	32	38.43	35.22	861.43	1050.13	955.78
T ₆ -Moringa leaf extract @ 5%	90.67	92.02	91.34	11.33	12.84	12.09	32.49	38.96	35.72	887.29	1081.82	984.56
T ₇ -Custard apple leaf extract @ 2%	86.99	88.29	87.64	10.87	12.06	11.47	24.94	30.04	27.49	653.23	796.32	724.77
T ₈ -Custard apple leaf extract @ 5%	85.67	86.96	86.31	10.71	11.82	11.27	24.56	29.35	26.96	633.45	772.4	702.92
Results	S	S	S	S	S	S	S	S	S	S	S	S
S. Ed. (±)	0.642	0.937	0.406	0.08	0.172	0.124	0.568	0.587	0.577	4.777	9.396	4.269
S.E.M.	0.454	0.662	0.287	0.057	0.122	0.088	0.402	0.415	0.408	3.378	6.644	3.019
C.D. 5%	1.282	1.871	0.811	0.16	0.343	0.247	0.247	1.134	1.172	1.152	9.54	18.766
C.V.	0.701	1.471	0.279	0.088	0.358	0.197	0.197	1.645	1.463	1.542	4.292	13.654

A similar trend was observed for lipase activity, where the maximum activity was recorded under T₂ (6.70 U/mL) followed by T₅ (6.03 U/mL) and T₁ (5.73 U/mL), while the lowest activity was observed in control (3.86 U/mL). Increased lipase activity promotes hydrolysis of stored lipids into fatty acids and glycerol, which subsequently enter respiratory pathways to provide energy during germination. This enhanced metabolic conversion helps in faster seedling growth and establishment.

The activity of phosphatase increased under all priming treatments compared with control. The highest phosphatase activity was observed under T₂ (1.29 µmol pNP min⁻¹ g⁻¹ FW), followed by T₃ (PGPR 250 ppm) (1.25 µmol pNP min⁻¹ g⁻¹ FW) and T₄ (PGPR 500 ppm) (1.22 µmol pNP

min⁻¹ g⁻¹ FW). Increased phosphatase activity may enhance the availability of inorganic phosphate by hydrolysing stored phosphate compounds, thereby supporting energy metabolism and early seedling development. The improvement under PGPR treatment may also be associated with microbial-mediated nutrient mobilization.

The highest dehydrogenase activity was recorded under T₂ (0.63 OD value) followed by T₃ (0.62 OD value) and T₄ (0.59 OD value), whereas the lowest activity was found in control (0.48 OD value). Dehydrogenase activity reflects the respiratory efficiency and metabolic status of germinating seeds. The higher activity observed under primed seeds indicates enhanced respiration, increased mitochondrial activity and better physiological performance.

Table 2: Effect of GA₃, PGPR and Botanicals Seed Priming on Enzymes activity during germination of Sorghum (*Sorghum bicolor* L. Moench)

Treatment	α -Amylase (U mg ⁻¹ d)	β -Amylase (U mg ⁻¹ d)	Protease (U/mL)	Lipase (U/mL)	Phosphatase (μ mol pNp min ⁻¹ gm ⁻¹ FW)	Dehydrogenase (OD value)
T ₀ -Control	8.4	2.6	33.93	3.86	0.92	0.48
T ₁ -GA ₃ @ 100 μ M	12.8	5.4	36.74	5.73	1.14	0.54
T ₂ -GA ₃ @ 200 μ M	13.8	8.7	40.03	6.7	1.29	0.63
T ₃ -PGPR @ 250 ppm	8.7	5.4	36.73	3.07	1.25	0.62
T ₄ -PGPR @ 500 ppm	11.5	4.7	36.03	5.03	1.22	0.59
T ₅ -Moringa leaf extract @ 2%	12.2	5.7	37.03	6.03	1.21	0.56
T ₆ -Moringa leaf extract @ 5%	13.5	3.4	34.73	4.93	1.2	0.55
T ₇ -Custard apple leaf extract @ 2%	11	4.3	35.63	4.63	1.11	0.54
T ₈ -Custard apple leaf extract @ 5%	10.3	3.7	35.03	4.92	1.16	0.53
Results	S	S	S	S	S	S
S. Ed. ($\pm$)	0.348	0.331	0.369	0.373	0.083	0.029
S.E.M.	0.246	0.234	0.261	0.264	0.059	0.02
C.D. 5%	0.783	0.695	0.661	0.737	0.745	0.166
C.V.	7.279	1.6	3.369	0.564	4.184	0.893

Conclusion

The findings of the present study demonstrated that seed priming with gibberellic acid (GA₃), plant growth-promoting rhizobacteria (PGPR), and botanical extracts significantly enhanced germination and enzyme activity-related traits of sorghum compared with the untreated control. Among the different treatments, PGPR @ 250 ppm proved most effective in improving germination, germination speed, germination index, and seedling vigour, while GA₃ @ 200 μ M was superior in promoting hypocotyl and radicle growth as well as enhancing the activities of hydrolytic and metabolic enzymes. The improved enzymatic activities facilitated efficient mobilization of stored food reserves and accelerated early seedling development. Overall, the study suggests that seed priming, particularly with PGPR @ 250 ppm and GA₃ @ 200 μ M, is a promising and sustainable strategy for improving seed performance and ensuring vigorous crop establishment in sorghum.

References

- Al-Baldawi MHK, Hamza JH. Seed priming effect on field emergence and grain yield in sorghum. *Journal of Central European Agriculture*. 2017;18(2):404-423. doi:10.5513/JCEA01/18.2.1915.
- Ashraf M, Foolad MR. Pre-sowing seed treatment—A shotgun approach to improve germination, plant growth, and crop yield under saline and non-saline conditions. *Advances in Agronomy*. 2005;88:223-271. doi:10.1016/S0065-2113(05)88006-X.
- Basra SMA, Farooq M, Tabassum R, Ahmad N. Physiological and biochemical aspects of seed vigour enhancement treatments in fine rice (*Oryza sativa* L.). *Seed Science and Technology*. 2005;33(3):623-628.
- Bewley JD. Seed germination and dormancy. *The Plant Cell*. 1997;9(7):1055-1066.
- Bewley JD, Bradford KJ, Hilhorst HWM, Nonogaki H. *Seeds: Physiology of Development, Germination and Dormancy*. 3rd ed. Dordrecht: Springer; 2013.
- Farooq M, Basra SMA, Rehman H, Saleem BA. Seed priming enhances the performance of late-sown wheat by improving chilling tolerance. *Journal of Agronomy and Crop Science*. 2008;194(1):55-60.
- Farooq M, Basra SMA, Wahid A, Ahmad N, Saleem BA. Improving the drought tolerance in rice by exogenous application of glycinebetaine. *Journal of Agronomy and Crop Science*. 2009;194(5):325-333.
- Farooq M, Basra SMA, Wahid A, Khaliq A, Kobayashi N. Rice seed invigoration by osmohardening. *Seed Science and Technology*. 2009;37(2):356-365.
- Finch-Savage WE, Leubner-Metzger G. Seed dormancy and the control of germination. *New Phytologist*. 2006;171(3):501-523.
- Jisha KC, Vijayakumari K, Puthur JT. Seed priming for abiotic stress tolerance: An overview. *Acta Physiologiae Plantarum*. 2013;35(5):1381-1396.
- McDonald MB. Seed priming. In: Black M, Bewley JD, editors. *Seed Technology and Its Biological Basis*. Sheffield: Sheffield Academic Press; 2000. p. 287-325.
- Mehta N, Gupta R. Physiological responses of GA₃ primed sorghum under salinity stress. *Plant Stress Biology*. 2024;8(4):275-289.
- Mehta N, Sharma D, Singh R. Botanical seed priming in cereal crops: A review. *Journal of Agroecology*. 2023;15(3):198-220.
- Nagakethan Kumar P, Dayal A, Rai PK. Effect of seed priming with micro nutrients, botanicals on seedling characteristics of sorghum (*Sorghum bicolor* L. Moench). *International Journal of Plant & Soil Science*. 2021;33(22):218-225.
- Nimir NEA, Zhou G, Zhu G, Ibrahim ME. Response of some sorghum varieties to GA₃ concentrations under different salt compositions. *Chilean Journal of Agricultural Research*. 2020;80(4):478-486.
- Nisha, Jakhar SS, Bhuker A, Satpal. Effect of priming treatment to enhance seed quality of sorghum. *Seed Research*. 2025.
- Nouman W, Siddiqui MT, Basra SMA, Farooq H, Zubair M, Gull T. Biomass and enzymatic responses to *Moringa* leaf extract in cereals. *Turkish Journal of Agriculture and Forestry*. 2014;38:1-14. doi:10.3906/tar-1308-12.
- Oberoi HK, Manchanda P, et al. *Moringa* leaf extract (MLE) seed priming provides early seedling protection to biofuel crop: Sweet sorghum against salinity. 2024/2025. *Journal details pending*.
- Paparella S, Araújo SS, Rossi G, Wijayasinghe M, Carbonera D, Balestrazzi A. Seed priming: State of the art and new perspectives. *Plant Cell Reports*. 2015;34:1281-1293. doi:10.1007/s00299-015-1784-6.
- Patel H, Singh A. Metabolic insights into seed priming mechanisms. *Plant Metabolism Journal*. 2023;9(2):145-167.

21. Patel V, Rao M. PGPR inoculation enhances grain quality in sorghum. *International Journal of Crop Quality*. 2024;11(1):75-90.
22. Patil SV, Mathad RC, Hiremath SM. Influence of seed biopriming duration with *Azospirillum lipoferum* on seed quality parameters of sorghum. *International Journal of Chemical Studies*. 2020;8(5):2315-2319.
23. Rajjou L, Duval M, Gallardo K, Catusse J, Bally J, Job C, *et al.* Seed germination and vigor. *Annual Review of Plant Biology*. 2012;63:507-533.
24. Ramesh A, Sharma SK, Sharma MP, Yadav N, Joshi OP. Inoculation of zinc solubilizing bacteria and *Azospirillum* on growth, yield and nutrient uptake of sorghum. *Archives of Agronomy and Soil Science*. 2021;67(2):1-12.
25. Rao KK, Reddy MS, Naik SK. Salinity stress mitigation in sorghum through seed biopriming with plant growth-promoting rhizobacteria. *Journal of Soil Salinity and Water Quality*. 2022;14(1):45-53.
26. Rao M, Patel V. Combined seed priming: Hormones, microbes, and botanicals. *Journal of Crop Enhancement*. 2024;10(3):301-324.
27. Rao M, Singh A, Sharma D. Botanical priming effects on sorghum growth and stress physiology. *Journal of Crop Science and Biotechnology*. 2023;17(5):456-472.
28. Rao M, Verma S, Singh R. Seed priming for improved sorghum establishment: Status and prospects. *Advances in Agronomy*. 2021;29(1):89-112.
29. Rao M, Verma S, Singh R. Photosynthetic and growth responses in GA₃ primed sorghum. *Journal of Plant Physiology*. 2022;12(4):312-326.
30. Rathinavel S, Bhuvaneswari R, Murugan K. Effect of GA₃ seed priming on germination and enzyme activity in sorghum (*Sorghum bicolor*). *Journal of Agricultural Science and Technology*. 2017;19:25-34.
31. Zhu G, An L, Jiao X, Chen X, Zhou G, *et al.* Effects of gibberellic acid on water uptake and germination of sweet sorghum seeds under salinity stress. *Chilean Journal of Agricultural Research*. 2019;79(3):415-424.