



RESEARCH ARTICLE

Effect of seed priming with elicitor chemicals on germination and early seedling growth of different wheat genotypes

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Abstract

Elicitor priming of seed is an effective method for increasing early stress tolerance and seedling establishment of wheat. The present study was conducted at GLA University, Mathura, Uttar Pradesh, during the academic year 2024–25. The aim of study was undertaken to evaluate the effects of various elicitor chemicals specifically salicylic acid (SA), benzothiadiazole (BTH), jasmonic acid (JA) and hydrogen peroxide (H₂O₂) on seed germination parameters of different wheat cultivars. The effects of various elicitors (SA, H₂O₂, BTH and JA) at different concentrations on germination percentage, early seedling development and seed vigour index (SVI) in three wheat genotypes under non-stress and drought-stress conditions were studied. All priming treatments had a significant effect on enhancing germination and seedling performance as compared to unprimed seed. The H₂O₂ (2 %) and SA (0.5 mM), were among the elicitors with almost the highest germination (~100 and 98 % respectively) and gave the strongest seedlings. Salicylic acid (0.5 mM) resulted in the highest SVI (about 1538) and H₂O₂ (2 %) respectively. Under polyethylene glycol (PEG) -0.8 MPa simulated drought stress, SA- primed, H₂O₂ primed seeds held significantly increased germination compared to the unprimed seeds and this means increased stress resilience. The BTH treatments showed moderate effect on germination and growth, while no further increase with high concentrations. In contrast, JA exhibited a strong concentration-dependent response, low concentrations were tolerated, but as the doses of JA increased, with the most significant inhibition being with higher doses (4 mM JA) resulting in seedling mortality. Overall, the study established that optimum levels of SA and H₂O₂ effectively enhanced the wheat seeds performance and early vigour, whereas excessive JA application is detrimental. This study will help to identify suitable elicitors and treatment conditions to improve wheat seedling establishment and could potentially enhance the crop stress resilience and yield.

Keywords: benzothiadiazole; drought stress; hydrogen peroxide; jasmonic acid; salicylic acid; seed priming

Introduction

Wheat (*Triticum aestivum* L.) is the most significant cereal crop in the world and a major staple crop for global food security. For effective production, rapid and even germination is required. Seed priming is a pre-sowing technique in which seeds are partially hydrated to initiate metabolic processes and then re-dried before sowing (1–4), can lead to faster and more synchronised germination, improved seedling vigour and better yields (4–6). Numerous priming agents have been reported to stimulate seed germination and seedling growth under diverse environments for several crops. As an example, salicylic acid (SA), hydrogen peroxide (H₂O₂) and polyamines have been proven to enhance seedling growth and increase stress tolerance in different plant species

(7–9). Pre-treatment with SA, a plant signalling molecule, can enhance germination and seedling development, particularly during stress conditions by modulating antioxidant activity and other physiological processes (10, 11). Similarly, H₂O₂ is usually a reactive oxygen species (ROS) that, at low concentration acts as a signalling molecule that has the ability to condition seeds to withstand oxidative stress in the germination stage (9, 10). Polyamine priming with compounds such as spermidine or putrescine also has been observed to stimulate seeds, which results in earlier and more homogeneous emergence and greater seedling biomass in crops like rice and sunflower (12, 13).

Other than traditional conventional osmopriming agents, elicitors have gained attention for their capacity to induce defence-related responses in plants. Elicitors are compounds

(usually signalling molecules or pathogen-derived mimics) which result in accumulation of phytoalexins, reinforcement of cell walls and the activation of pathogenesis-related (PR) proteins as a part of the plant immune system (12–14). The term “elicitor” was originally used for molecules inducing phytoalexin (antimicrobial secondary metabolites) production in pathogen-infected plant cells (14), although it can be used in other contexts to describe material capable of causing plant defence. When used as seed treatment certain chemical elicitors can enhance seed germination and seedling vigour besides preconditioning the immune reactions of the plant (15–17). For instance, the use of chitosan, which is a natural biopolymer elicitor has been demonstrated to make a significant contribution towards germination percentage, rate of germination and seedling vigour index (SVI) of cereals compared to untreated seeds (15, 16). Other studies have recently found that there are several other chemical elicitors capable of enhancing seed performance in cereals (17). Salicylic acid is one of the most famous chemical elicitors and signalling molecules in plant defence mechanisms. Exogenous SA has been reported to induce tolerance to different abiotic and biotic stresses (18, 19) and it also functions as a growth regulator influencing seed germination and early seedling development (19, 20).

Seeds treated with SA have been observed to improve the rate of germination, seedling length and SVI in various cereal crops (21, 22). As an example, priming wheat seeds with SA concentration of 0.5 mM greatly enhanced the final germination and seedling length under both normal and water-stress conditions (21) and SA-priming of rice seeds resulted in a higher germination rate, dry weight and vigour of the seedlings in drought stress (22). It has also been reported that SA priming mitigates the adverse effects of stresses like drought, salinity and heavy metals, hence enhancing germination and establishment of seedlings under stress conditions (18, 23, 24). Another elicitor that is used as a synthetic analog of SA, benzothiadiazole (BTH), which is used in agricultural practices. The BTH has been known to activate systemic acquired resistance in plants. Seed BTH priming has been observed to enhance germination, seedling emergence and general development of plants in various crops such as wheat, barley and maize (25, 26). Nevertheless, the processes through which BTH increases seedling vigour are not well understood and are the subject of active investigation. In the same manner, jasmonic acid (JA) is a plant hormone used in controlling plant stress responses and development. Seed JA or its methyl ester has shown positive results with respect to germination and in some cases e.g., JA priming may increase germination of seedlings in wheat and rice under certain stresses, but the effect is concentration-dependent (27, 28). Low concentrations of JA can induce germination, but high concentrations can suppress germination and seedling development because JA is involved in the activation of strong defence programs (usually to the sacrifice of development) (28, 29).

Although H_2O_2 is a ROS, it also acts as an signalling compound that is important in plants. It has been observed that priming seeds with low-dose H_2O_2 increases the germination rate and vigour index in crops such as wheat or maize (30, 31). The positive impact of H_2O_2 is believed to arise from an enhanced antioxidant defence and activation of germination-related enzymes, which together help seedlings cope with oxidative stress during imbibition (30–32). Notably, the efficacy of each elicitor may vary depending on the concentration applied and the crop

genotype. Although individual studies have shown the positive effects of each of the SA, BTH, JA and H_2O_2 on seed germination and seedling growth, comparative data on how these elicitors perform across multiple wheat genotypes are limited. It remains unclear which elicitor and at what concentration are most effective in seed germination and enhanced productivity in different wheat genotypes.

The present study was undertaken to evaluate the effects of various elicitor chemicals, specifically SA, BTH, JA and H_2O_2 on seed germination parameters of different wheat genotypes. Three wheat cultivars of agronomic importance were tested and for each elicitor, multiple concentrations were examined based on recommendations from previous literature (33). We hypothesised that elicitor priming would improve germination and early seedling growth compared to unprimed seeds, with optimal responses at specific concentrations for each chemical. The findings from this work will help to identify suitable elicitors and treatment conditions to enhance wheat seedling establishment and could potentially improve the crop stress resilience and yield.

Materials and Methods

Treatment of plant materials and seed priming

The seeds of three different varieties of wheat HD-2967, DBW-107 and Sonalika were selected based on their extensive cultivation and contrasting characteristics. Healthy, uniform seeds of all three cultivars were surface sterilised using 0.1 % mercuric chloride ($HgCl_2$) for 30 sec, followed by extensive washing in sterile distilled water. The priming treatments were SA 0.5 mM, 1 mM and 2 mM; BTH at 2 mM, 3 mM and 4 mM; JA at 1 mM, 2.5 mM and 4 mM; H_2O_2 at 2, 4 and 6 % (v/v); and water priming used as the control (hydropriming using sterile distilled water) (3). These concentrations were chosen according to preliminary trials and literature recommendations (33). For priming, wheat seeds of different varieties were soaked with 25 seeds per replication and a total of 75 seeds per treatment in the respective solutions for 2 hr and incubated at room temperature with slow agitation. After soaking, the seeds were washed using sterile distilled water and dried using paper towels at 22 °C until they reached their original seed moisture level (i.e. 60 % relative humidity), like unprimed dry seeds (1). This priming process involving controlled re-drying after hydration, enables the seeds to initiate early germination metabolism in the absence of radicle emergence, thus preconditioning them to emerge faster upon sowing.

Germination test under controlled conditions

Primed and control (unprimed) seeds were germinated in 90-mm Petri dishes lined with Whatman No.1 filter paper. Each dish contained 25 seeds of a given genotype and treatment. Filter papers were moistened with 5 mL of the same solution used for priming (to maintain consistent exposure). For example, SA-primed seeds were placed on filter paper wetted with the corresponding SA solution whereas control seeds were placed on paper moistened with sterile distilled water. This setup also allowed the imposition of osmotic stress in some treatments, for JA and H_2O_2 , the higher concentration solutions possessed higher osmotic potential, simulating a drier environment during germination.

In addition, another experiment to assess germination under drought stress involved wetting a subset of dishes from each treatment with filter paper moistened with an osmotic solution of

polyethylene glycol (PEG) to establish a water potential of 0.8 Mpa, under standard germination assay protocols for induction of water stress. The Petri dishes were stored in a germination chamber at 25 ± 1 °C, approximately, 60 % relative humidity and 12 hr of light/12 hr of dark photoperiod. Seeds were monitored daily for a period of 14 days and a seed was considered germinated, when the emerging radicle had reached at least 2 mm in length. The experimental design was factorial (3 genotypes $\times$ 5 priming treatments including control $\times$ different concentrations) in a completely randomised study where there were 3 replicates per treatment. Each replicate consisted of one Petri dish containing 25 seeds.

Growth measurements

On the 14th day after sowing, when germination had ceased increasing for all treatments, final germination counts were recorded and germination percentage (GP) was calculated. Ten normal seedlings from each dish (replicate) were randomly selected for growth measurements. Seedling shoot length (hypocotyl + epicotyl) and root length (primary radicle) were measured with a ruler in centimetres (cm). The mean shoot length and root length per treatment replicate were used for further analysis. These sampled seedlings were then blotted dry and weighed to obtain their fresh weight, after which they were oven-dried at 80 °C for 72 hr to determine dry weight.

Germination and vigour indices

Germination percentage (GP) was computed as the percentage of seeds that germinated out of the total seeds tested, using the formula:

$$GP (\%) = \frac{\text{Number of germinated seeds}}{\text{Total number of seeds}} \times 100 \quad (\text{Eq. 1})$$

Seed vigour index (SVI) was calculated to integrate both germination and seedling growth, using the formula:

$$SVI = (\text{Mean shoot length} + \text{Mean root length}) (\text{cm}) \times GP (\%) \quad (\text{Eq. 2})$$

Moreover, germination rate index (GRI), as well as mean germination time (MGT) were calculated to describe the speed of germination. The GRI was determined by summing germination over time (with an emphasis on earlier germinating seeds) by the conventional method (1, 34) and MGT was determined by the time-weighted average of germination events (1, 35) (a smaller MGT is indicative of quicker germination). Detailed GRI and MGT

results are not, however, given here as the attention is directed to final germination and vigour.

Statistical analysis

Data for germination percentage and seedling growth parameters were subjected to analysis of variance (ANOVA) appropriate for the factorial CRD design, as described by Panse and Sukhatme (36). The effects of the genotype, treatment and genotype $\times$ treatment interaction were tested. The least significant difference (LSD) test was used to determine the differences between the treatment means at the 5 % probability level. In each of the measured parameters, means followed by different letters were significantly different at $p < 0.05$. All statistical data were analysed in Statistix 8.1 (Analytical software, Florida, USA) and SPSS v25 (IBM Inc.). Basic calculations (e.g., percentage, indices) and graphs preparation had been done in Microsoft Excel 2024. Pearson's correlation coefficients among germination traits (e.g., between GP and SVI) were computed in OriginPro 9.1 (OriginLab Corp., Northampton, MA, USA) to examine relationships between variables.

Results

Germination percentage

Priming with elicitors had a marked influence on the germination success of wheat seeds (Fig. 1, Table 1). In the unprimed control (hydroprimed with water), final germination percentage was around 78 % (pooled across genotypes under non-stress conditions). All elicitor priming treatments improved germination to some extent compared to the control. The most significant enhancement was observed with H₂O₂ at a 2 % concentration, which achieved ~100 % germination in all three genotypes. Seeds primed with a low dose of SA (0.5 mM) also showed very high germination (98 %). Most other treatments resulted in final GP in the 90–97 % range. Even under the imposed drought stress (PEG -0.8 MPa), primed seeds showed higher germination than unprimed seeds (which had < 50 % germination at -0.8 MPa). For example, SA-primed seeds retained significantly better germination under water deficit: at -0.8 MPa, SA-primed seeds of cv. HD-2967 showed 62 % germination compared to only 19 % in non-primed seeds. In general, priming with SA or H₂O₂ was most effective in maintaining germination under stress. On the other hand, the JA treatments displayed a clear concentration-dependent effect. At the lowest JA dose (1 mM), final germination was high (91 %), comparable to other elicitors. However, germination declined as the JA concentration increased.

Table 1. Effect of seed priming with different elicitors on wheat germination and seedling growth

	Shoot length (cm)	Root length (cm)	Shoot + root length (cm)	Germination (%)	Seed vigour index
SA at 0.5 mM	6.14 ab	9.51 a	15.66 a	98.33 ab	1538.39 a
SA at 1 mM	5.89 ab	9.13 ab	15.03 ab	96.66 ab	1451.14 ab
SA at 2 mM	5.27 bc	7.91 bcd	13.18 bc	83.33 c	1093.75 cde
BTH at 2 mM	5.79 ab	7.74 bcd	13.54 abc	93.33 ab	1267.30 bc
BTH at 3 mM	4.45 cd	5.75 ef	10.20 d	96.66 ab	981.31 def
BTH at 4 mM	5.51 ab	7.12 cde	12.64 c	93.33 ab	1182.06 cd
H ₂ O ₂ at 2 %	6.39 a	8.40 abcd	14.80 abc	100.0 a	1479.78 a
H ₂ O ₂ at 4 %	5.70 ab	7.52 cd	13.22 bc	93.33 ab	1238.23 c
H ₂ O ₂ at 6 %	5.73 ab	6.91 de	12.65 c	76.67 c	961.41 ef
JA at 1 mM	4.59 cd	4.99 f	9.59 d	91.44 b	878.02 f
JA at 2.5 mM	3.93 d	4.69 f	8.62 d	76.67 c	658.95 g
JA at 4 mM	1.92 e	1.65 g	3.57 e	63.56 d	232.65 h
Control	6.21 ab	8.52 abc	14.74 abc	78.33 c	1154.94 cde

Cell values (letters) are mean $\pm$ SD; treatments with the same letter grouping are not significantly different; SA: salicylic acid; BTH: benzothiadiazole; H₂O₂: hydrogen peroxide; JA: jasmonic acid.

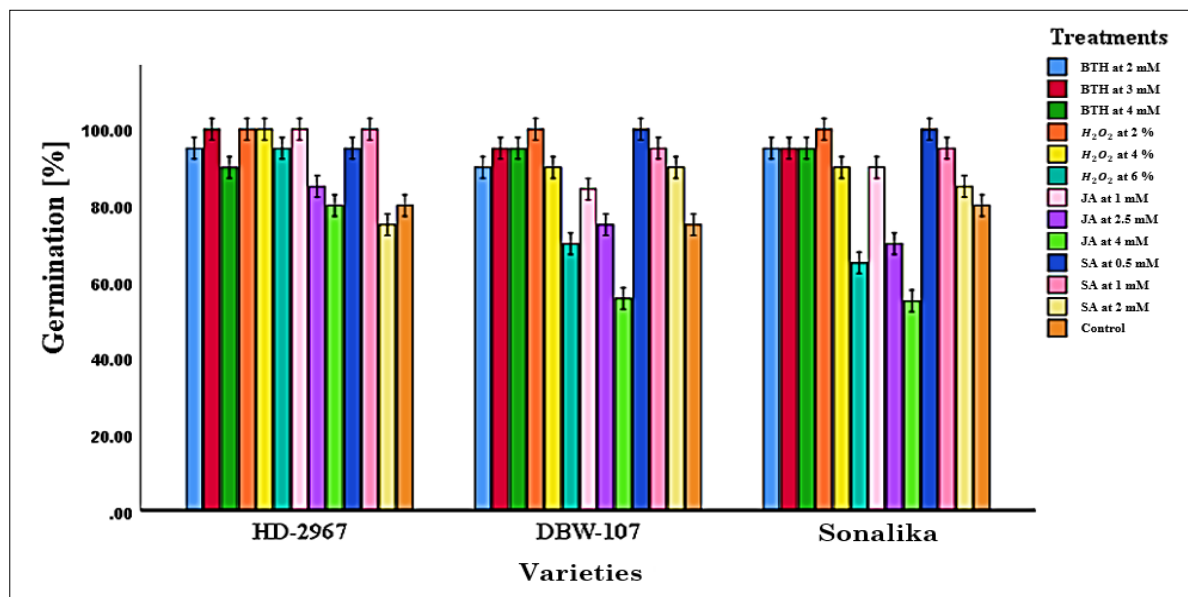


Fig. 1. Effect of inducer chemicals on germination (%) of wheat variety.

BTH: benzothiadiazole; H_2O_2 : hydrogen peroxide; JA: jasmonic acid; SA: salicylic acid.

A 4 mM JA concentration was highly inhibitory and germination of seeds was lowest at 4 mM JA (only 63.6 %) compared to all other treatments including the unprimed control. Therefore, a high level of JA was harmful to germination. There were no significant differences among cultivars in terms of a final GP under each treatment and the genotype $\times$ treatment interaction for germination was not significant ($p > 0.05$), indicating that the elicitor effects on germination were not significant stable throughout the three varieties of wheat.

Shoot and root growth

Priming treatments also affected early seedling growth (Fig. 2, 3 and 4; Table 1). The best seedlings in terms of length were recorded with SA priming at 0.5 mM. The average shoot length of the SA (0.5 mM) primed seeds was 6.14 cm and root length was 9.51 cm in 14 days, resulting in a seedling length (shoot + root) of 15.66 cm. They were much larger than those recorded for unprimed controls (shoot 5.2 cm, root 7.9 cm; total 13.1 cm). Treatment of H_2O_2 (2 %) came in the second place: shoots 6.4 cm, roots 8.4 cm, total length 14.8 cm, which was not statistically

different from the SA (0.5) shoot length. In contrast, the seedlings were seriously impaired by priming with the higher dose of JA (4 mM). Mean shoot length of JA (4 mM) primed seedlings was only 1.92 cm and root length was only 1.65 cm (total 3.57 cm), the lowest among all treatments. This is in line with the low germination at JA 4 mM. Other treatments showed intermediate effects. The BTH-primed seed produced moderate growth: e.g. at 2 mM BTH, mean shoot length was 5.8 cm and root length was 7.7 cm (total 13.5 cm), moderately higher than the control. Further addition of BTH (2–4 mM) did not increase growth; in contrast, 4 mM BTH recorded a slight decrease in mean shoot and root lengths compared to 2 mM. Jasmonic acid (1 mM) led to only a slight decrease in seedling size in terms of shoot (4.6 cm) and root (5.0 cm) when compared to the control, but JA 2.5 mM had a greater inhibitory effect. The SA (1 mM) priming kept seedling growth (shoot 5.9 cm, root 8.5 cm) high, whereas at 2 mM the seedling lengths were lower (shoot 5.0 cm, root 6.6 cm); therefore, 0.5–1 mM of SA could be considered the optimal concentration. Statistical analysis showed significant main effects of priming treatment on shoot length and root length ($p < 0.01$) (Table 1).

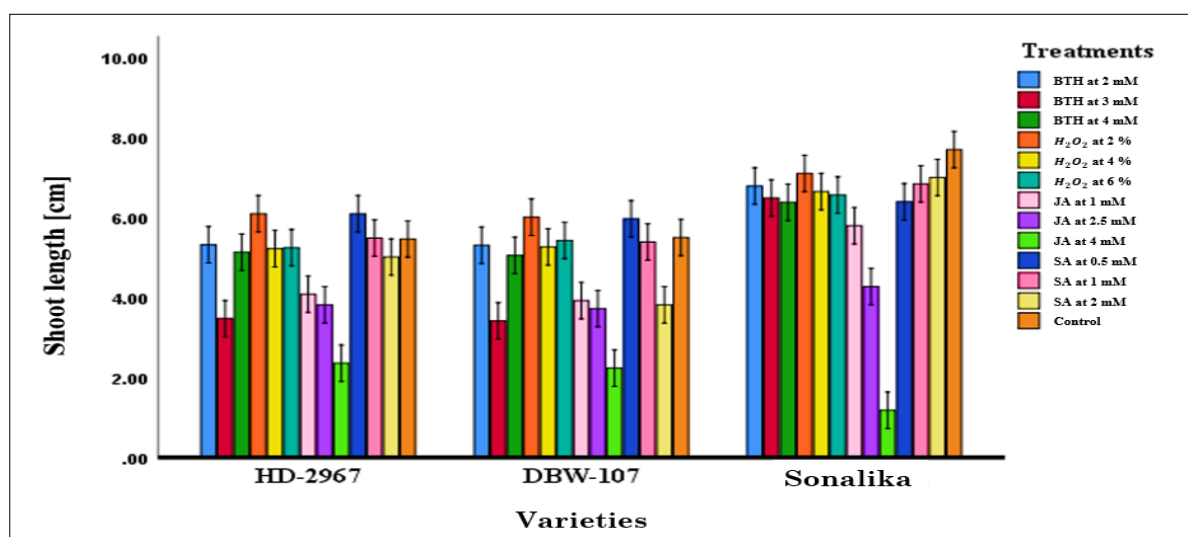


Fig. 2. Effect of inducer chemicals on shoot length of wheat variety.

BTH: benzothiadiazole; H_2O_2 : hydrogen peroxide; JA: jasmonic acid; SA: salicylic acid.

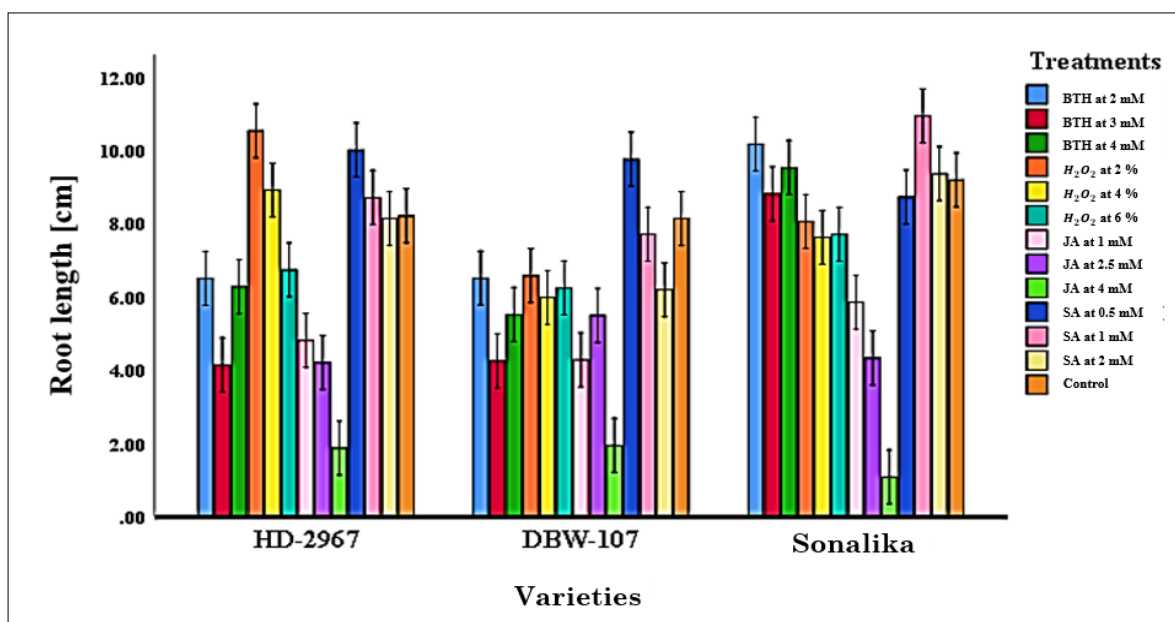


Fig. 3. Effect of inducer chemicals on root length of wheat variety.

BTH: benzothiadiazole; H_2O_2 : hydrogen peroxide; JA: jasmonic acid; SA: salicylic acid.

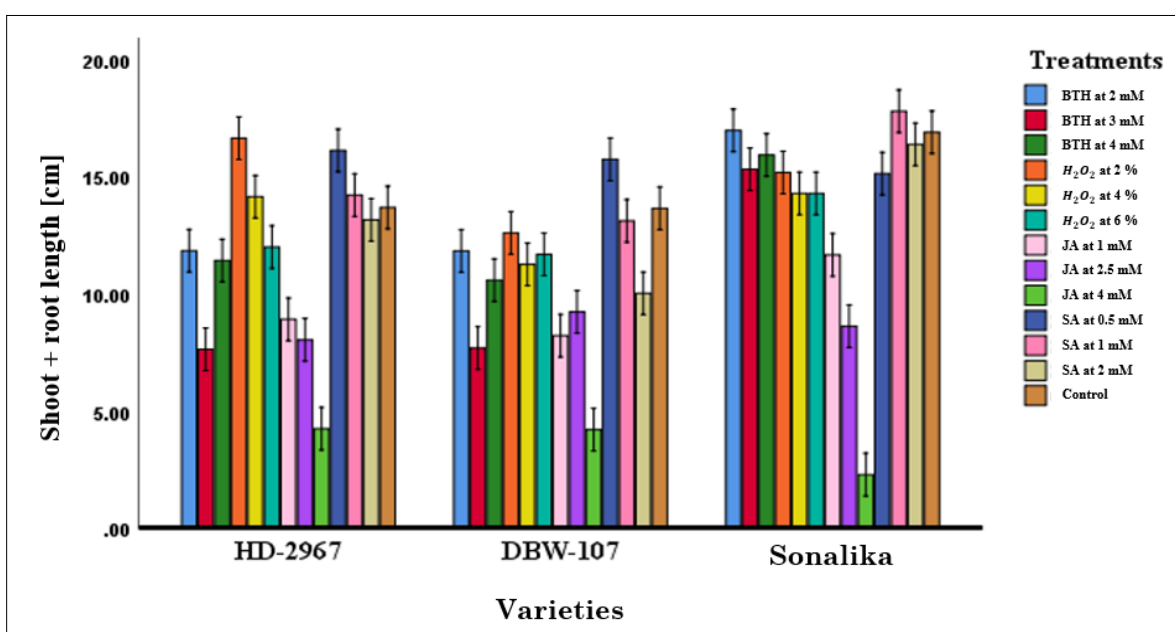


Fig. 4. Effect of inducer chemicals on shoot + root length of wheat variety.

BTH: benzothiadiazole; H_2O_2 : hydrogen peroxide; JA: jasmonic acid; SA: salicylic acid.

Genotypic differences in seedling lengths were observed (for example, cv. Sonalika had slightly longer roots on average than cv. HD-2967), but there was no significant treatment $\times$ genotype interactions. This indicates that while the varieties differ inherently in seedling size, they responded similarly to the priming treatments in qualitative terms.

Seed vigour index

The seed vigour index (SVI) trends reflected the combined effects of treatments on germination and seedling growth (Fig. 5 and Table 1). The highest SVI was obtained with 0.5 mM SA priming (SVI $\approx$ 1538), owing to near-maximal germination percentage and the longest seedlings in this treatment. Hydrogen peroxide 2 % was a close second (SVI $\approx$ 1480) and all other elicitor treatments also outperformed the control (SVI $\approx$ 1155) in vigour index, except the very high JA dose. For example, BTH at 2 mM yielded SVI 1267 and even at 4 mM BTH the SVI (1190) was slightly

higher than the control. The SA at 1 mM gave SVI 1451, indicating robust performance. In contrast, JA at 4 mM had by far the lowest vigour index (233) due to both poor germination and extremely short seedlings illustrating the severe inhibitory effect of an overdose of JA. Jasmonic acid (2.5 mM) was also detrimental (SVI 659). Interestingly, the highest H_2O_2 concentration (6 %) led to a decline in vigour (SVI 961) compared to 2 % and 4 % H_2O_2 , corresponding to a reduction in germination (down to 76 % at 6 % H_2O_2) and shorter roots. This suggests that too high a dose of H_2O_2 may begin to cause oxidative damage, overcoming its priming benefits (30, 31). The analyses indicated that lower levels of SA and H_2O_2 were the most advantageous elicitors in improving the performance of wheat seeds, whereas the influence of BTH was positive but less pronounced. The JA had a dual effect where the low dose was tolerable or slightly beneficial whereas high doses were detrimental to germination and growth. There was no evidence of a major genotype-treatment interaction for SVI, as

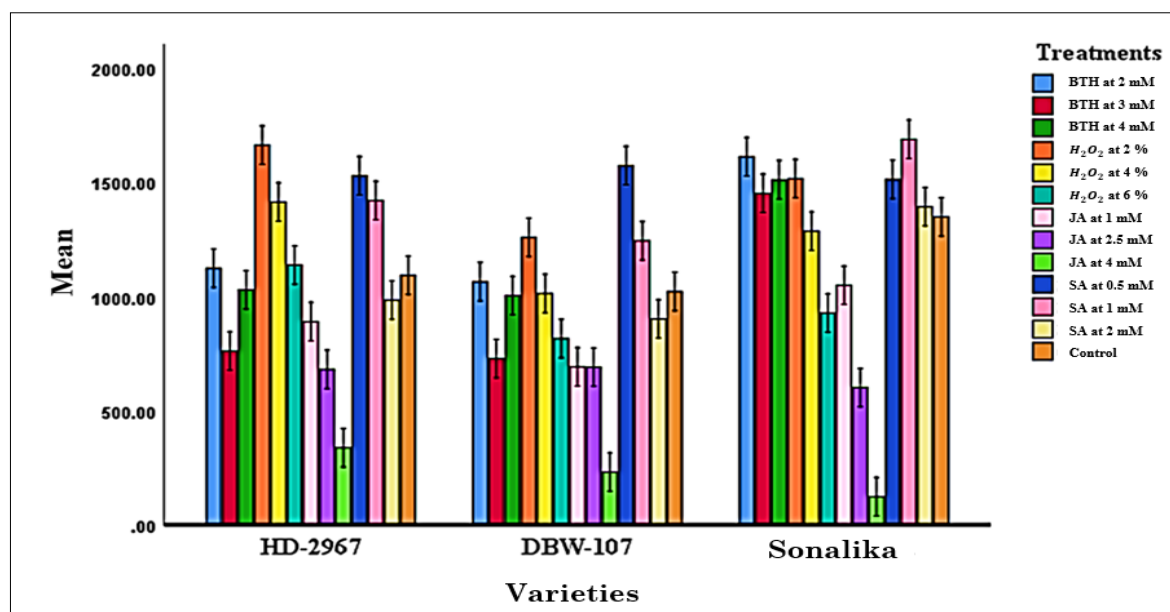


Fig. 5. Effect of inducer chemicals on seed vigour index of wheat variety.

BTH: benzothiadiazole; H₂O₂: hydrogen peroxide; JA: jasmonic acid; SA: salicylic acid.

observed in GP, indicating that each genotype was equally placed in the overall ranking of treatment. Minor differences among genotypes were noted (e.g., HD-2967 had slightly higher absolute SVI values than Sonalika under some treatments), but all genotypes benefited from SA (0.5 mM) and H₂O₂ (2 %) and suffered under JA in the same qualitative manner.

Discussion

It is evident that the present study shows that seed priming with the chosen elicitor chemicals can significantly improve germination and early seedling development in wheat, especially when abiotic stress is involved. The enhancement in the germination percentage, seedling length and the germination vigour index after priming is highly significant and in line with the previous findings that indicated the positive influence of priming in stimulating metabolic and physiological activities before radicle emergence (5, 10). Seed priming is generally considered a technique that facilitates synchronised germination, enzyme acceleration, membrane healing and reserve mobilisation, allowing seeds to adapt better to sub-optimal environments. In the current study, unprimed seeds underwent a strong reduction in germination in the presence of simulated drought stress (-0.8 MPa PEG) but primed seeds particularly SA-primed seeds, retained remarkably better germination and vigour. These results are consistent with the early reports who indicated that primed wheat seedlings were less responsive to low substrate water potentials and also showed better germination under osmotic stress compared to control seedlings (37). The SVI of rice decreased with increasing moisture stress, which was relieved by SA priming significantly (38). The SA-primed seeds were found in the research to have an estimated 29 % higher vigour index under extreme drought conditions than unprimed control, in addition to supporting the role of SA in mitigating drought stress during germination.

The advantageous impacts of SA priming might be related to the fact that the signalling molecule is one of the essential triggers of antioxidant defences and stress-related pathways, prior to germination (18, 23). It has also been observed that SA priming can increase the activity of antioxidant enzymes like superoxide

dismutase, catalase and peroxidase thereby reducing oxidative injury during seed imbibition and initial seedling development (22, 39). In line with these reports, SA priming especially at 0.5 mM significantly improved germination and seedling development under both non-stress and stress conditions in the current study. Also, SA has been shown to activate dehydration-responsive genes, such as late embryogenesis abundant (LEA) proteins and dehydrins, as well as osmoprotectant accumulation, both contributing to seed resistance to drought and salinity (22, 39, 40). It is worth noting that the beneficial effects of SA were concentration-dependent, with an increased dosage (2 mM) being less effective, which can probably be explained by hormonal imbalance or oxidative stress caused by SA in supra-optimal concentrations (20, 23). This shows that dose optimisation is important and the most effective dose to be 0.5–1.0 mM SA used in improving the performance of cereal seeds (21).

Priming with BTH resulted in moderate improvements in germination and seedling growth compared to SA and H₂O₂. The BTH is primarily recognised as an inducer of systemic acquired resistance and relatively fewer studies have examined its role during seed germination. Nevertheless, previous researchers reported enhanced germination and vigour in wheat and barley following BTH treatment, along with increased defence enzyme activity (26, 27). In the present study, BTH at 2–3 mM modestly increased germination percentage and seedling length, suggesting that its primary role may be linked more to defence priming than to growth promotion. As SA analog, BTH may partially activate SA-dependent signalling pathways, leading to the accumulation of protective proteins or reinforcement of cell walls, which could aid early seedling establishment (13, 25). The lack of pronounced growth stimulation by BTH under controlled laboratory conditions may indicate that its benefits become more apparent under biotic stress, where induced resistance provides a clear advantage. The absence of additional benefits at higher concentrations further suggests that excessive activation of defence responses may impose metabolic costs, limiting growth enhancement.

The priming of wheat seeds with JA reveals the dualistic and dose-dependent effect of this hormone. Low JA concentration (1 mM) had no negative effect on germination and even in the

presence of mild osmotic stress, had slight positive effects on seed performance. The observation agrees with the previous research that low doses of JA increase antioxidant activity and tolerance to stress during germination (27, 28). Nevertheless, increasing levels of JA (2.5 mM and above) significantly slowed down germination and seedling growth with intense inhibition of both occurring at 4 mM. Such biphasic effects of JA have been well documented and are often attributed to JA-induced reinforcement of dormancy signals, increased ABA accumulation, or excessive ROS generation at high doses (27, 41). High JA concentrations can also induce an energetically expensive defence response and this shift in resources may compromise cell expansion and radicle protrusion (29). These results indicate a need to carefully regulate doses in case JA is applied as a seed priming agent and that combinatorial priming approaches with low JA concentrations and growth-active compounds may provide advantages that can be used to exploit its protective ability without reducing germination.

The present study revealed H_2O_2 as one of the most effective priming agents. Although traditionally regarded as a harmful ROS, H_2O_2 at low, controlled concentrations functions as a signalling molecule that induces stress acclimation (9). Our results, showing nearly 100 % germination and high vigour following 2 % H_2O_2 priming, agree with early researchers (30, 31), who reported improved germination and antioxidant capacity in wheat and maize under abiotic stress following H_2O_2 priming. The enhanced performance of H_2O_2 primed seeds may be attributed to the up regulation of antioxidant enzymes, improved membrane stability and faster detoxification of ROS during imbibition. Nevertheless, the inhibitory action at the highest concentration (6 %) supports the idea that an extreme oxidative exposure may harm the embryo tissues and slow down germination, which supports the idea of oxidative priming as a balance between signalling and toxicity.

All three genotypes of wheat responded to the elicitor priming program, but there were small genotype-specific variations in the absolute germination and growth parameters. Significantly, there was no major genotype $\times$ treatment interaction, which implies that the relative efficacy of the priming agents SA (0.5 mM) and H_2O_2 (2 %) being superior and high-dose JA being harmful was uniform across genotypes. This implies that such priming responses are broadly applicable in wheat. However, the genotypic differences in the seed coat traits, hormonal sensitivity and antioxidant potential could influence the degree of response which could be further assessed in a broader region of cultivars (21).

Overall, the enhanced germination and early seedling development observed in this work could be explained by a combination of overlapping mechanisms caused by elicitor priming such as the increased antioxidant activity, elevated reserve mobilisation, hormonal adjustment and potential epigenetic imprinting (12). Although the current research was based on physiological outcomes, the similar patterns obtained provide a good basis for further molecular studies to clarify changes in gene expression related to elicitor-mediated seed priming. These findings would be useful in strengthening the use of elicitor priming as an affordable and environment friendly approach to establish wheat cultivation under abiotic stress environments.

Conclusion

The current research shows that seed priming through elicitors is a viable and applicable method for stimulating wheat seed germination and seedling robustness. Salicylic acid (SA) (0.5 mM) and hydrogen peroxide (H_2O_2) (2 %) among the elicitors tested, had the highest effectiveness and thus enhanced germination percentage, seedling growth and seed vigour index (SVI) in all the tested wheat genotypes even under simulated water stress. These treatments encouraged quicker and more homogenous establishment of seedlings and with a total vigour enhancement of approximately 30–35 % higher than that of unprimed seeds. Benzothiadiazole (BTH) priming produced moderate improvements in germination and vigour, suggesting its potential utility when induction of defence responses is also desired. Conversely, jasmonic acid (JA) displayed a definite dose-dependent effect, where low concentrations had a neutral or slightly positive effect, whereas higher concentration significantly inhibited germination and early development and the significance of dose optimisation in priming regimens should not be overlooked. Overall, the obtained results reveal SA and H_2O_2 as potential priming agents because they are effective and less expensive and have a simplified process of application, thus being applicable in the context of integrating them into seed-enhancement activities. The elicitor-based priming provides a sustainable approach for enhancing wheat establishment and stress resistance in stress-prone environments. Additional field validation and mechanistic research are needed to translate these laboratory results into practical strategies for improving wheat production under changing weather conditions.

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Authors' contributions

NK¹ conducted the experiment, recorded observations and analysed the data. DKC guided the research by formulating the research concept and PK approved the final manuscript. SS participated in the study design, performed the statistical analysis and reviewed the manuscript. MM contributed to conducting the experiment. MM, NK², CSC and BSM assisted in summarising and revising the manuscript. All authors have read and approved the final manuscript (NK¹- Neelam Kumari, NK²- Nancy Khwairakpam)

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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