



RESEARCH ARTICLE

Seed priming alleviates the detrimental effects of moisture stress during seed germination of chilli (*Capsicum annum* L.)

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Abstract

The study was conducted during 2018–19 at SKUAST-K, Srinagar with an aim to improve moisture stress tolerance during germination and seedling establishment in chilli using different seed priming techniques. The data obtained indicate that the germination potential of chilli seeds significantly declined under moisture stress conditions as compared to control. However, different priming treatments improved seed germinability under both normal and moisture stress conditions. Under moisture stress, priming with melatonin (D2×P4) resulted in the highest values for FGP (90.66 %), SEP (87.33 %), RDW (0.15 g), SDW (0.055 g), TI (46.28), leaf chlorophyll (0.87 mg/g), CSI (97.92), RWC (79.50 %) and proline content (29.02 μmol/g), followed by osmopriming, whereas the lowest values for these parameters were observed in the control. The highest values of these attributes were coupled with the lowest T_{50G} and T_{50E} values (8.33 and 11.33 days, respectively). Under normal conditions, vermipriming gave the highest FGP (98.67) and SEP (93.33), followed by melatonin, whereas under moisture stress, melatonin priming achieved the highest FGP (90.66) and SEP (87.33), followed by vermipriming, indicating that vermipriming excelled in normal conditions while melatonin was more effective under stress.

Keywords: chilli; FGP; moisture stress; seed priming; seedling vigour; Timson's index

Introduction

Chilli (*Capsicum annum* L.) is a high-value vegetable and spice crop consumed in various forms, fresh green, red ripe, paste, powder or sauce and valued for its characteristic pungency from capsaicin (C₁₈H₂₇NO₃) and vibrant red colour due to keto-carotenoids, mainly capsanthin. India is the largest producer, contributing 43 % of global output, followed by China and accounting for 33 % of India's spice exports worth ₹10444.5 crore (1). The crop is cultivated on 8.52 lakh hectares, producing 19.58 lakh tonnes annually, with Andhra Pradesh and Telangana as leading producers (627.85 and 550.0 thousand metric tonnes, respectively). In Jammu & Kashmir, chilli occupies 2150 ha with 15.76 thousand metric tonnes of production (2, 3).

Seed germination and early seedling establishment are critical for crop yield. In chilli, moisture stress during these stages severely limits stand establishment and productivity. Inadequate soil moisture impairs seed imbibition, delays germination and leads to poor crop establishment through reduced root elongation, nutrient

uptake, chlorophyll synthesis and photosynthetic efficiency (4–6). It also induces osmotic stress, disrupts cellular metabolism and increases susceptibility to diseases, reducing biomass accumulation and survival rates (7, 8).

Seed priming offers a simple, low-cost and effective approach to mitigate such adverse effects, particularly for resource-limited farmers (9). It involves controlled hydration and re-drying of seeds to original moisture content, initiating metabolic processes essential for germination without radicle protrusion (10). Priming enhances drought tolerance through early mobilisation of food reserves, embryo cell elongation and endosperm weakening, leading to uniform and rapid germination (11). However, priming responses vary with crop, cultivar, priming agent, concentration and treatment duration. This study was therefore undertaken to evaluate the effectiveness of different seed priming methods in improving germination and biochemical attributes of locally grown chilli cv. Shalimar Long-I under normal and moisture-stress conditions.

Materials and Methods

The study was undertaken in the Plant Physiology laboratory at the Division of BSH, FoH, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir during the year 2018–19. Seeds of the locally grown chilli cv. Shalimar Long-1 were obtained from the Division of Vegetable Science, SKUAST-Kashmir. Seed priming (P) was done at $25 \pm 2^\circ\text{C}$ using pre-optimized priming techniques (6) viz., soaking of seeds in distilled water for 30 hr (hydropriming), -0.5 MPa PEG-6000 solution (osmopriming) for 18 h, $8\times$ vermiwash (vermipriming) (4) for 30 hr and in 5.0 ppm melatonin solution (hormonal priming) for 30 hr. After the specified period of seed soaking, they were shade dried to original seed moisture content (10.0%) and used for germination test with untreated seeds as control. Germination test was done both in stressed (-0.5 MPa) as well as control (0.00 MPa) at $25 \pm 2^\circ\text{C}$. A total of 500 seeds per priming treatment were placed in ten 14.0 cm Petri dishes, each lined with five layers of blotting paper. The blotting papers were saturated with either distilled water (control) or a polyethylene glycol (PEG) 6000 solution adjusted to a water potential of -0.5 MPa to induce moisture stress (12). The Petri dishes were then incubated in a seed germinator (ScienoCraft) set to a 16-hr light/8-hr dark photoperiod at a constant temperature of 25°C , following standard procedures used in germination and seedling growth studies (13). Daily count of seed germination up to 20 days was done up-to the final germination time.

The seeds were also sown in nursery trays with $2:1$ ratio of soil + vermicompost and placed in a plant growth chamber (Labotech-TM) at $25 \pm 2^\circ\text{C}$ and 75% R.H. with pre-set photoperiod of 16 hr. Trays for moisture stress treatment were supplied with -0.5 MPa PEG-6000 solution instead of distilled water that was supplied to control (non-stress) treatment trays. Aqueous solution of PEG-6000 was prepared using Equation 1 (14):

$$\text{Water potential (bar)} = \frac{-(1.18 \times 10^{-2}) C - (1.18 \times 10^{-4})}{CT + (8.39 \times 10^{-7}) C^2 T} \quad (\text{Eqn.1})$$

Where, C indicates polyethylene glycol (PEG) concentration, T indicates temperature (centigrade).

Final germination percentage (FGP) was calculated using Equation 2 (15):

$$\text{Final germination percent (FGP)} = \frac{\text{Total germinated seed after 12 days}}{\text{Total number of seeds}} \times 10 \quad (\text{Eqn.2})$$

Median germination time i.e., time to 50% germination (T_{50G}) was calculated using Equation 3 (16):

$$\text{Median germination time } (T_{50G}) = \frac{T_i + \{(N/2) - n_i\}(T_i - T_j)}{n_i - n_j} \quad (\text{Eqn.3})$$

Where, N represents final number of germination days; n_i and n_j cumulative number of seeds germinated by adjacent counts at times t_i and t_j when $n_i < N/2 < n_j$.

Final seedling emergence percent (SEP) and time to 50% seedling emergence (T_{50E}) were calculated using Equations 2 (15) and 3 (16) wherein number of emerged seedlings was taken instead of total germinated seeds. The root and shoot lengths of 20-day old seedlings were measured from collar region of seedling to the apex of root. Root and shoot dry weights (RDW and SDW) of 35 day's old nursery trays-grown seedlings were obtained by drying them in a hot air oven at $65 \pm 5^\circ\text{C}$. Seedling vigour index (SVI)-I and -II were calculated following the Equations 4 and 5 (17):

$$\text{SV - I} = \text{Seedling length (cm)} \times \text{germination } (\%) \quad (\text{Eqn.4})$$

$$\text{SV - II} = \text{Seedling dry weight (g)} \times \text{germination } (\%) \quad (\text{Eqn.5})$$

Timson's index (TI) provides an integrated value based on the percentage of germinated seeds over time and calculated by Equation 6 (18):

$$\text{Timson's index} = \frac{\sum G}{T} \quad (\text{Eqn.6})$$

Where G is the percentage of seed germinated per day and T is the germination period.

Extraction of chlorophyll was done using dimethyl sulfoxide (DMSO) as extractant and amount of chlorophyll was estimated (19) using Equation 7 (20):

$$\text{Total chlorophyll} = \frac{[20.2 (D_{645}) + 80.2 (D_{663})]}{1000 \times W} \times V \quad (\text{Eqn.7})$$

Where, D = Absorbance at specific wavelength, V = Final volume of DMSO (mL) and W = Weight of fresh leaf (g).

The chlorophyll stability index (CSI) was calculated (21) using the chlorophyll content of stressed and non-stressed seedlings (Equation 8):

$$\text{(CSI)} = \frac{\text{Total chlorophyll under stress}}{\text{Total chlorophyll under control}} \times 100 \quad (\text{Eqn.8})$$

Determination of relative water content (RWC) was done using Equation 9 (22).

$$\text{RWC } (\%) = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Turgid weight} - \text{Dry weight}} \times 100 \quad (\text{Eqn.9})$$

The seedling proline content was extracted in sulphosalicylic acid and estimated through the acid-ninhydrin assay (23), a widely adopted method in plant stress physiology (24).

All the data were analyzed using analysis of variance (ANOVA) and differences between treatment means were compared using the least significant difference (LSD) test at a 5% probability level. Pearson's correlation was also calculated to examine the relationships among germination, growth and physiological traits.

Results

Final germination (FGP) and final seedling emergence (SEP) percent

Data presented in Fig. 1 revealed that moisture stress (-0.5 MPa) significantly ($p \leq 0.05$) reduced the seed FGP as well as SEP in chilli cv. Kashmir Long-1 as there were only 87.0 % and 81.0 % of FGP and SEP under induced moisture stress (D_2) compared to higher FGP and SEP (96.0 and 91.0) in control (D_1). Different seed priming treatments markedly ($p \leq 0.05$) influenced the FGP as well as SEP wherein melatonin priming (P_5) recorded the highest FGP (94.0) and SEP (90.0) followed by vermipriming (P_4) and osmopriming (P_3) with their absolute FGP (92.0 and 91.0) and SEP (87.0 and 87.0) values, respectively. FGP and SEP values recorded with P_3 were also at par with hydropriming (P_2). Seeds without priming treatment (P_1) showed the poorest values of the FGP and SEP.

Data on interaction effects of moisture stress and seed priming ($D \times P$) showed that under normal moisture condition, vermipriming ($D_1 \times P_4$) resulted in highest FGP (99.0) as well as SEP (93.0) but found at par ($p \leq 0.05$) with melatonin priming ($D_1 \times P_5$). The $D_1 \times P_5$ was significantly followed by $D_1 \times P_2$ against the minimum

values of FGP and SEP (93.0 and 89.0) observed with non-primed seeds ($D_1 \times P_1$). However, interaction of different priming treatments with induced moisture stress treatment proved that melatonin priming ($D_2 \times P_5$) was the best treatment with recorded FGP and SEP values of 91.0 and 87.0 followed by osmopriming ($D_2 \times P_3$) and vermipriming ($D_2 \times P_4$).

Median of seed germination (T_{50G}) and seedling emergence (T_{50E})

As illustrated in Fig. 2, both moisture stress (D) and priming (P) exerted significant effects ($p \leq 0.05$) on seed germination and seedling emergence rates of chilli (*Capsicum annum* L.) cv. Kashmir Long-1, as reflected by the T_{50G} and T_{50E} parameters. Induced moisture stress at 0.5 MPa (D_2) delayed both seed germination and seedling emergence, as evidenced by increased T_{50G} (10.73 days) and T_{50E} (13.13 days) compared to the control values of 7.06 and 11.33 days, respectively. However, both T_{50G} and T_{50E} were found to shrink from 9.67 and 13.33 days (P_1) to 8.33 and 11.33 days (P_5) due to seed priming treatments. The lowest T_{50G} value recorded in P_5 was ascendingly followed by P_4 (8.50 days), P_3 (8.83 days) and P_2 (9.16 days) while as the lowest T_{50E} value was followed by P_4 (11.5 days), P_2 (12.33 day) and P_3 (12.66 day).

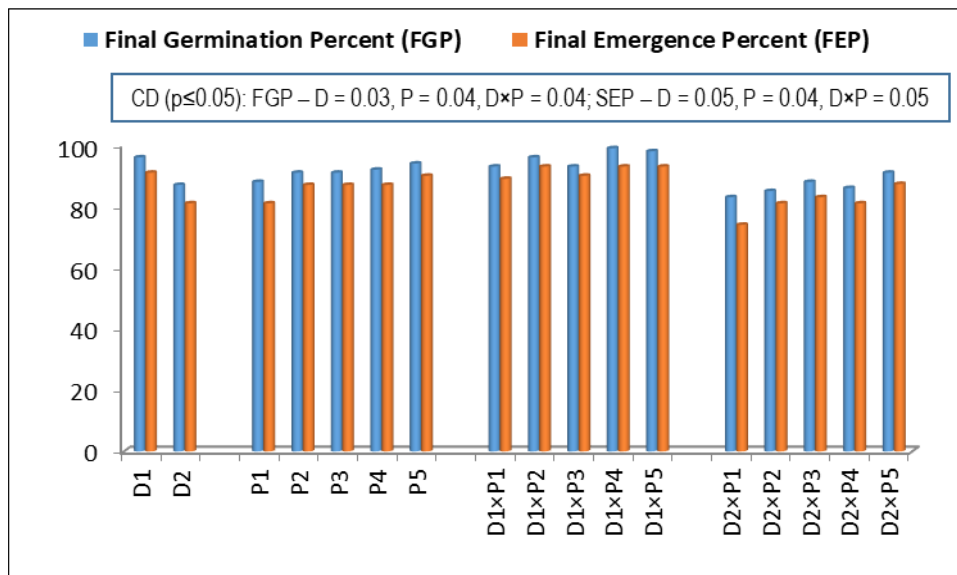


Fig. 1. Effect of moisture stress and seed priming treatments on final germination per cent (FGP) and final seedling emergence percent (SEP) in chilli (CDs of RWC are calculated on the basis of square root transformed values of the original data).

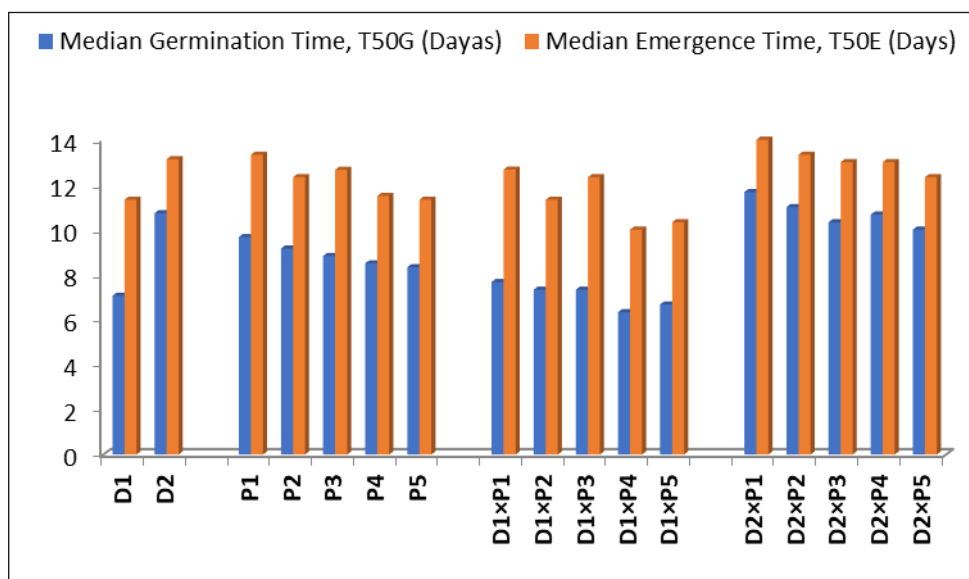


Fig. 2. Effect of moisture stress and seed priming treatments on median germination (T_{50G}) and emergence (T_{50E}) in chilli cv. Shalimar Long-1.

Interaction data for normal moisture condition clarified that vermipriming ($D_1 \times P_4$) resulted in shortened duration of seed germination and seedling emergence with T_{50G} and T_{50E} values of 6.33 and 10.00 days. However, if we investigate the interaction of priming treatments with moisture stress separately, melatonin priming ($D_2 \times P_5$) established as the best priming treatment with T_{50G} and T_{50E} values of 10.00 and 12.33 days, respectively.

Radicle and plumule length

Data on influence of moisture stress and priming on radicle and plumule length of Kashmir Long-1 chilli presented as Fig. 3 revealed that moisture stress significantly ($p \leq 0.05$) reduced both radical and plumule length from 4.59 and 4.42 cm in D_1 to 4.36 and 4.14 cm in D_2 , respectively. Seed priming treatments were found to increase the radical and plumule length from 3.90 and 3.95 cm, respectively in P_1 (no priming) to 4.74 and 4.55 cm in P_4 (vermipriming). The highest value of radicle length in P_4 was followed by P_3 (4.52 cm) and P_2 (4.40 cm) or P_5 (4.38 cm) whereas the highest plumule length (4.55 cm) was found statistically at par with P_5 (4.43 cm) that was followed by P_3 (4.25 cm) or P_2 (4.21 cm).

Interactions of moisture stress (D) and seed priming (P) treatments revealed that $D_1 \times P_4$ recorded the highest radicle (5.00

cm) and plumule (4.85 cm) length followed by $D_1 \times P_5$ and $D_2 \times P_5$ with radicle and plumule length of 4.92 and 4.39 cm and 4.74 and 4.39 cm, respectively against the minimum radicle and plumule length of 3.80 and 3.79 cm, respectively in $D_2 \times P_1$. However, considering the interaction of priming treatments with moisture stress separately clarified that melatonin priming ($D_2 \times P_5$) was the best treatment with radicle and plumule length of 4.74 and 4.39 cm, respectively followed by vermipriming ($D_2 \times P_4$), osmopriming ($D_2 \times P_3$) or hydropriming ($D_2 \times P_2$).

Root and shoot dry weight (RDW and SDW)

Data pertaining to root and shoot dry weight of Kashmir Long 1 chilli seedlings grown under the influence of moisture stress and seed priming (Fig. 4) indicated that root and shoot dry weight of seedlings (0.144 and 0.058 g/seedling) under normal moisture (D_1) significantly ($p \leq 0.05$) reduced to 0.116 and 0.04 g/seedling due to moisture stress (D_2). Seed priming increased the root and shoot dry weight, respectively from 0.11 and 0.035 g/seedling under control (P_1) to 0.15 and 0.055 g/seedling under melatonin priming (P_5).

Combined effects of moisture stress and priming treatments ($D \times P$) further revealed that vermipriming ($D_1 \times P_4$) produced highest root and shoot dry weight (0.16 and 0.07 g/seedling) against the

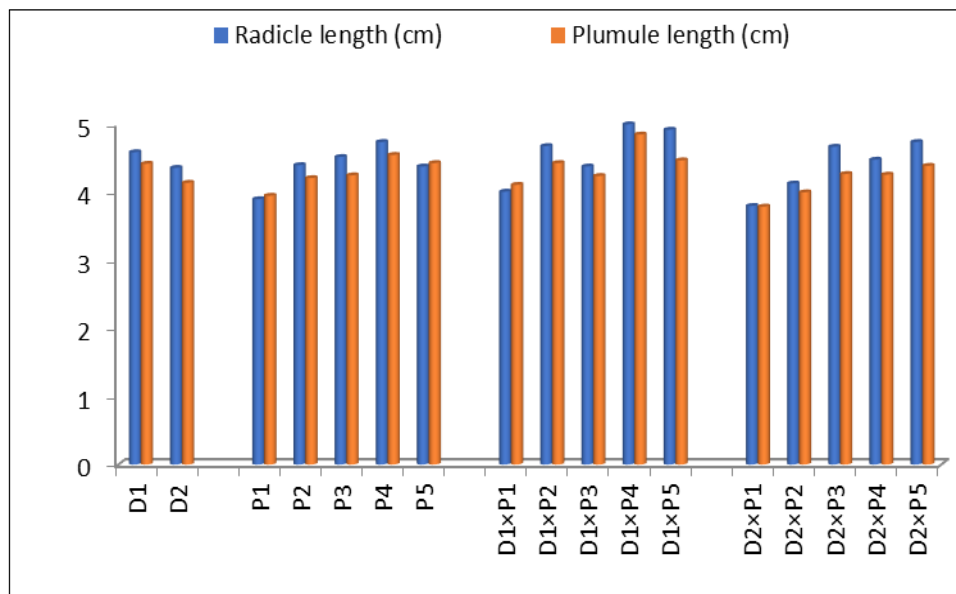


Fig. 3. Effect of moisture stress and seed priming treatments on radicle and plumule length in chilli cv. Shalimar Long-I.

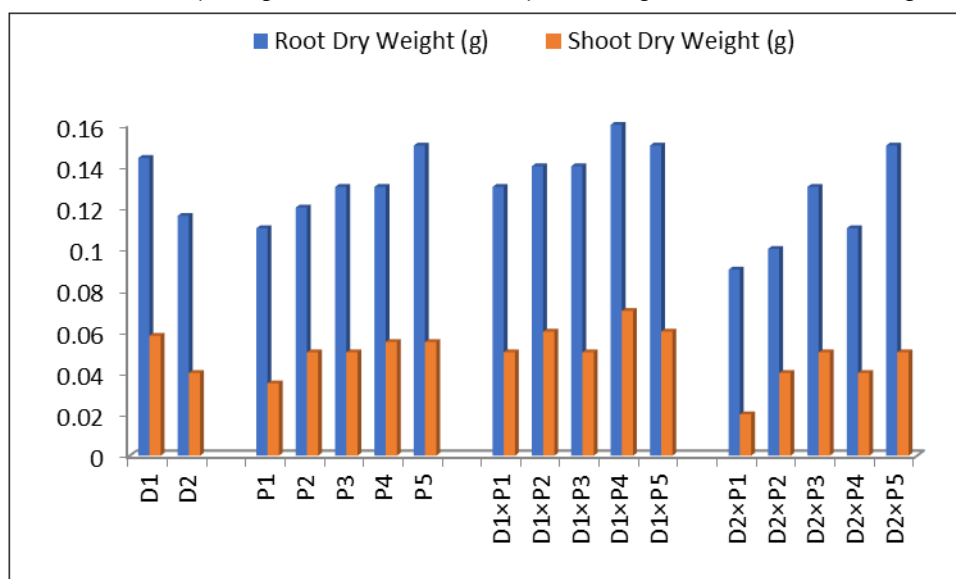


Fig. 4. Effect of moisture stress and seed priming treatments on root and shoot dry weight in chilli cv. Shalimar Long-I.

minimum root and shoot dry weight of 0.13 and 0.050 g/seedling in control ($D_1 \times P_1$) under normal moisture. However, under moisture stress ($D_2 \times P$), melatonin priming ($D_2 \times P_5$), recorded the maximum root and shoot dry weight of 0.15 and 0.05 g/seedling followed by $D_2 \times P_3$ (moisture stress \times osmopriming) against the minimum root and shoot dry weight of 0.09 and 0.02 g/seedling in $D_2 \times P_1$.

Timson's (TI) and seedling vigour indices (SVI-I and SVI-II)

Data presented in Fig. 5 show that values of TI (56.7), SVI-I (864.0) and SVI-II (20.0) were significantly ($p \leq 0.05$) higher under normal moisture condition (D_1) compared to lower TI (32.98), SVI-I (739.0) and SVI-II (14.0) values under moisture stress (D_2) condition. Among various priming treatments vermipriming (P_4) resulted in highest values of TI (47.5), SVI-I (848.0) and SVI-II (19.0) followed by melatonin priming (P_5), osmopriming (P_3) and hydropriming (P_2).

Interactions of two treatment factors *i.e.* moisture stress and seed priming ($D \times P$) again resulted in marked variations ($p \leq 0.05$) in TI, SVI-I and SVI-II values. The first set of interaction ($D_1 \times P$) clearly indicates that vermipriming ($D_1 \times P_4$) resulted in highest value of TI (61.8), SVI-I (971.0) and SVI-II (22.0) followed by melatonin priming ($D_1 \times P_5$), hydro priming ($D_1 \times P_2$) and osmopriming ($D_1 \times P_3$). However,

the second set of interaction ($D_2 \times P$) depict that melatonin priming ($D_2 \times P_5$) was the best treatment with highest value of TI (35.2), SVI-I (811.0) and SVI-II (18.0) followed by osmopriming ($D_2 \times P_3$), vermipriming ($D_2 \times P_4$) and hydropriming ($D_2 \times P_2$).

Chlorophyll content and its stability index (CSI)

Leaf chlorophyll of Kashmir Long-1 chilli seedlings was markedly controlled by moisture stress and seed priming treatments individually as well as in combination with each other (Fig. 6). Individual effects of moisture stress showed that leaf chlorophyll content was higher (0.80 mg/g) under control (D_1) and reduced significantly due to moisture stress (D_2) with absolute value of 0.69 mg/g. Different seed priming treatments improved leaf chlorophyll content differently in their individual capacity with highest (0.87 mg/g) in melatonin priming (P_5), followed by vermipriming (P_4) and osmopriming (P_3) with their absolute values of 0.80 and 0.75 mg/g FW, respectively against the minimum chlorophyll content recorded in unprimed control (P_1).

Interaction data of stress and priming treatments indicated that under normal moisture condition ($D_1 \times P$), vermipriming ($D_1 \times P_4$) was proved as best priming treatment with highest chlorophyll

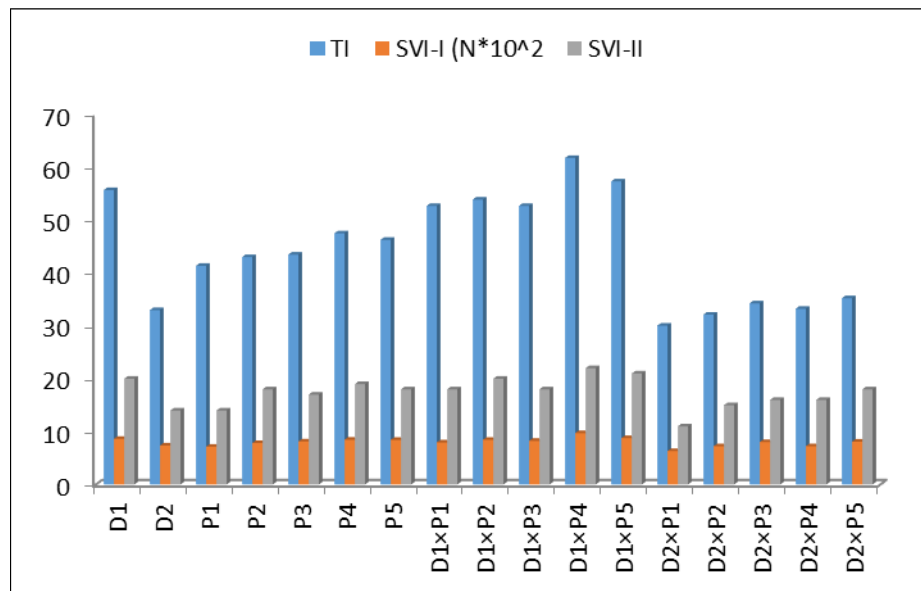


Fig. 5. Effect of moisture stress and seed priming treatments on Timson's germination index (TI) and seedling vigour indices in chilli cv. Shalimar Long-I.

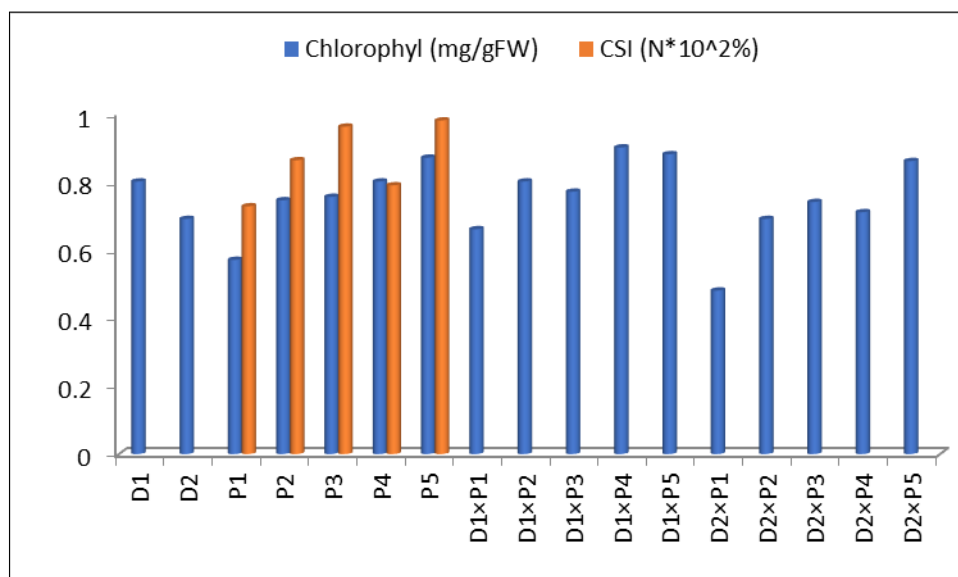


Fig. 6. Effect of moisture stress and seed priming treatments on chlorophyll content and its stability index in chilli cv. Shalimar Long-I.

content (0.90 mg/g FW) followed by melatonin- ($D_1 \times P_5$), hydro- ($D_1 \times P_2$) and osmo-priming ($D_1 \times P_2$) with their numerical values of 0.88 and 0.80 mg/g compared to control (0.66 mg/g). However, under moisture stress ($D_2 \times P$) melatonin priming ($D_2 \times P_5$) was proved as best with highest chlorophyll value of 0.86 mg/g FW followed by osmo-priming ($D_2 \times P_3$) and vermipriming ($D_2 \times P_4$) when compared with the least chlorophyll contents (0.48 mg/g) in control ($D_2 \times P_1$).

Chlorophyll stability index which was calculated using chlorophyll content under moisture stress and normal conditions, showed highest CSI value (97.92 %) for melatonin priming (P_5) which was closely followed (96.10 %) by osmo-priming (P_3). The least value of CSI (72.72 %) was seen in no priming (P_1) followed increasingly by vermipriming (P_4) and hydropriming (P_2) treatments having values of 78.88 % and 86.25 %, respectively.

Leaf relative water (RWC) and proline contents

Results pertaining to leaf RWC proline contents and of Kashmir Long 1 chilli seedling under the control of moisture stress and priming are presented in Fig. 7. Relative water content (RWC) was significantly varied due to moisture stress treatments and showed higher value (79.80 %) under control (D_1) compared to a reduced RWC (72.93 %) under moisture stress (D_2) condition. Seed priming increased the RWC from 70.50 % under control (P_1) to 79.50 % under melatonin priming (P_5) and vermipriming (P_4). Values of RWC under other priming treatments were 78.33 % and 74.00 % under osmo-priming (P_3) and hydropriming (P_2), respectively. Combination of different moisture stress and priming treatments revealed that different priming treatments varied markedly among different treatment. Under normal condition vermipriming ($D_1 \times P_4$) was able to maintain highest RWC (86.33 %) followed by melatonin priming ($D_1 \times P_5$) and osmo-priming ($D_1 \times P_3$) with RWC value of 83.67 % and 81.33 %, respectively. However, under moisture stress the highest RWC (75.33 %) was recorded with melatonin priming ($D_1 \times P_5$) followed by vermipriming ($D_1 \times P_4$) or osmo-priming ($D_1 \times P_3$) and hydropriming ($D_1 \times P_2$) with their absolute values of 72.67 %, 75.33 % and 72.00 %, respectively.

Data also indicated that leaf proline content of 10.86 $\mu\text{mol/g}$ under normal condition (D_1) was significantly increased to 31.9 $\mu\text{mol/g}$ due to moisture stress (D_2). Seed priming further increased

the leaf proline content from 11.35 $\mu\text{mol/g}$ under control (P_1) to 16.87, 27.14, 22.53 and 29.02 $\mu\text{mol/g}$ under hydropriming (P_2), osmo-priming (P_3), vermipriming (P_4) and melatonin priming (P_5), respectively. Interaction of different moisture stress and priming ($D \times P$) treatments with respect to leaf proline content revealed that different priming treatments under no moisture stress ($D_1 \times P$) varied markedly and osmo-priming ($D_1 \times P_3$) resulted in highest leaf proline content of 14.58 $\mu\text{mol/g}$ followed by 14.27 and 12.28 $\mu\text{mol/g}$ in melatonin priming ($D_1 \times P_5$) and osmo-priming ($D_1 \times P_3$) against the minimum leaf proline content of 5.14 $\mu\text{mol/g}$ in control ($D_1 \times P_1$). So far as interactions of priming treatments with moisture stress ($D_2 \times P$) is concerned, melatonin priming ($D_2 \times P_5$) again recorded the maximum leaf proline content of 43.77 $\mu\text{mol/g}$ followed by osmo-priming ($D_2 \times P_3$), vermipriming ($D_2 \times P_4$) and hydropriming ($D_2 \times P_2$) with proline content of 39.7, 32.78 and 25.7 $\mu\text{mol/g}$, respectively compared to minimum leaf proline content of 17.55 $\mu\text{mol/g}$ in $D_2 \times P_1$.

Discussion

Seed germination and early seedling growth

Seed germination represents the first and most sensitive phase of a plant's life cycle and is particularly vulnerable to moisture deficit conditions. In the present study, moisture stress at -0.5 MPa markedly reduced final germination percentage (FGP) and seedling emergence percentage (SEP), while extending the duration of seed germination and seedling emergence, as indicated by the median germination time (T_{50G}) and median emergence time (T_{50E}) in Shalimar Long-1 chilli. Moisture stress significantly reduced radicle and plumule growth, as well as seedling vigour indices (SV-I and SV-II), indicating a pronounced suppression of early seedling development. Such reductions in seed germination and growth attributes align with previous findings in okra and other crops, where germination delays and growth suppression under drought were attributed to reduced water uptake during imbibition, leading to delayed metabolic activation, including protein and mitochondria synthesis and mobilization of soluble sugars during the lag phase of germination (25–28).

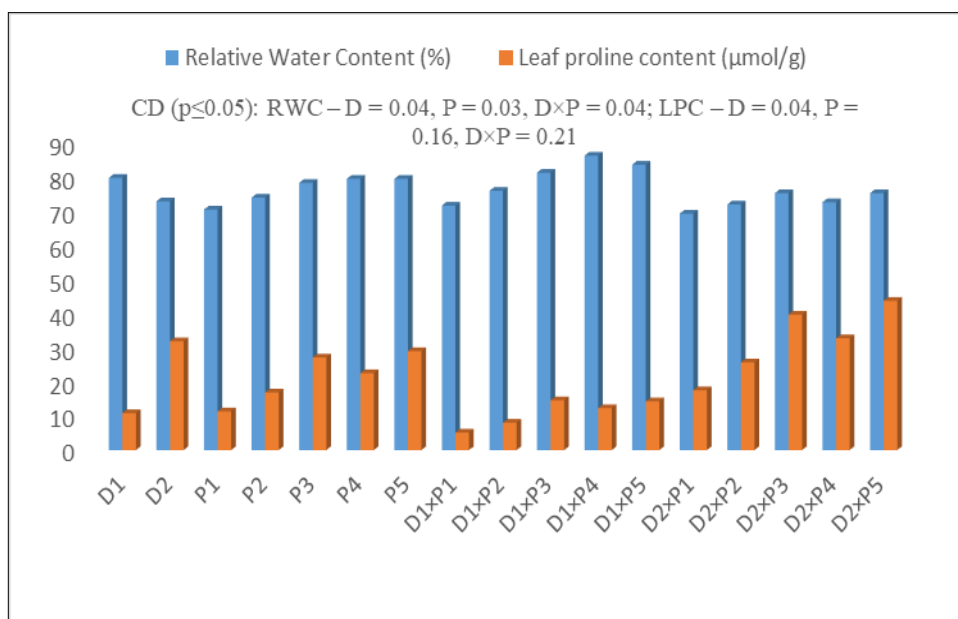


Fig. 7. Effect of moisture and seed priming treatments on leaf relative water content and leaf proline content in chilli cv. Shalimar Long-1 (CDs of RWC are calculated on the basis of square root transformed values of the original data).

Different seed priming treatments improved all germination and early seedling attributes under both normal and stress conditions, with effects being more pronounced under moisture stress. The interaction between the two factors confirmed the detrimental effects of moisture stress and the beneficial effects of priming, with priming not only mitigating the negative impact of drought but also enhancing seed germination and growth attributes of chilli under non-stress conditions. Similar beneficial effects of seed priming on germination, mean emergence time and seedling vigour under osmotic stress have also been reported in paddy, where priming with plant growth-promoting rhizobacteria (PGPR) significantly enhanced emergence and vigour under water-limited conditions (29). Pearson's correlation analysis (Table 1) revealed that FGP was positively associated with radicle length ($r = 0.661^{**}$), plumule length ($r = 0.794^{**}$), Timson's index ($r = 0.916^{**}$), SVI-I ($r = 0.904^{**}$) and SVI-II ($r = 0.926^{**}$), but negatively associated with T_{50G} ($r = -0.938^{*}$) and T_{50E} ($r = -0.920^{*}$). These relationships between FGP and other germination attributes are consistent with previous findings in okra (*Abelmoschus esculentus* (L.) Moench) and other species (5).

Seed priming is known to regulate respiration, starch metabolism and antioxidant systems, thereby reducing sensitivity to adverse external conditions (30, 31). In the present study, vermipriming emerged as the most effective treatment under normal conditions, while melatonin priming performed best under moisture stress. This differential performance likely reflects the distinct physiological contributions of each priming agent. Vermipriming supplies a complex matrix of humic substances, micronutrients and plant growth-promoting microorganisms. Similar priming-induced improvements in antioxidant activity and metabolic readiness during germination have been reported in leafy greens and drumstick under semi-arid conditions (13, 32) that enhance enzymatic activity, nutrient uptake and hormonal balance in unstressed environments (33, 34). These inputs accelerate metabolic readiness during germination, leading to stronger early

growth when external stress is minimal. Melatonin priming, on the other hand, is well-documented for its potent antioxidant activity, regulation of reactive oxygen species (ROS) and modulation of stress-responsive genes (35–37). Under moisture stress, ROS accumulation disrupts membrane integrity and enzyme function (38, 39). Melatonin's ability to stabilize cellular membranes, protect photosynthetic pigments, enhance osmolyte accumulation (such as proline) and regulate aquaporin expression likely contributed to its superior performance in stressed seedlings. Similar protective roles of melatonin have been observed in drought-stressed maize, wheat and pepper, where it enhanced germination and seedling vigour through both osmotic adjustment and oxidative stress mitigation.

Physiological attributes

Moisture stress led to a reduction in chlorophyll content, reflecting impairment of the photosynthetic machinery (40–43). Seed priming, however, significantly enhanced both chlorophyll content and the Chlorophyll Stability Index (CSI), indicating improved photosynthetic capacity and greater stress tolerance (42). Higher CSI values suggest reduced chlorophyll degradation under stress conditions (43). In the present study, priming treatments, particularly P4 and P5, appeared to protect chloroplast structure and stabilize pigment content under both normal and moisture-deficit conditions. The elevated CSI in primed seedlings under stress demonstrates that seed priming can mitigate the adverse effects of moisture deficit by maintaining pigment integrity. These findings agree with reports in other crops, where seed priming improved chlorophyll retention and photosynthetic performance under drought stress (42, 44). Different germination attributes in Shalimar Long-I chilli viz., FGP, T_{50} , radicle length, plumule length, TI, root dry weight, shoot dry weight, SVI-I and SVI-II were found to have strong association with chlorophyll contents (Table 1). Overall, the results underscore the potential of seed priming as a practical strategy to enhance early photosynthetic efficiency and stress resilience in chilli.

Table 1. Pearson's correlation coefficients among different characters of germinating chilli seeds cv. Shalimar Long-I

	T_{50G}	RL	PL	TI	RSR	SEP	T_{50E}	RDW	SDW	SVI	SVII	CHL	RWC	LPC
FGP	-0.938 [*]	0.661 ^{**}	0.794 ^{**}	0.916 ^{**}	0.174	0.944 ^{**}	-0.920 [*]	0.882 ^{**}	0.891 ^{**}	0.904 ^{**}	0.926 ^{**}	0.769 ^{**}	0.820 ^{**}	-0.441
T_{50G}		-0.539 [*]	-0.708 [*]	-0.992 [*]	0.097	-0.938 [*]	0.864 ^{**}	-0.810 [*]	0.849 [*]	-0.868 [*]	-0.910 [*]	-0.659 [*]	-0.796 [*]	0.612 ^{**}
RL			0.908 ^{**}	0.482	0.581 ^{**}	0.685 ^{**}	-0.788 [*]	0.768 ^{**}	0.825 ^{**}	0.821 ^{**}	0.784 ^{**}	0.885 ^{**}	0.794 ^{**}	0.189
PL				0.673 ^{**}	0.455	0.802 ^{**}	-0.908 [*]	0.859 ^{**}	0.916 ^{**}	0.933 ^{**}	0.886 ^{**}	0.908 ^{**}	0.863 ^{**}	-0.018
TI					-0.185	0.895 ^{**}	-0.847 [*]	0.748 ^{**}	0.808 ^{**}	0.833 ^{**}	0.880 ^{**}	0.585 ^{**}	0.761 ^{**}	-0.692 [*]
RSR						0.160	-0.252	0.451	0.269	0.288	0.171	0.581 ^{**}	0.328	0.753 ^{**}
SEP							-0.891 [*]	0.918 ^{**}	0.944 ^{**}	0.927 ^{**}	0.966 ^{**}	0.840 ^{**}	0.802 ^{**}	-0.367
T_{50E}								-0.860 [*]	-0.911 [*]	-0.928 [*]	-0.955 [*]	-0.857 [*]	-0.887 [*]	0.316
RDW									0.902 ^{**}	0.928 ^{**}	0.888 ^{**}	0.897 ^{**}	0.836 ^{**}	-0.076
SDW										0.979 ^{**}	0.973 ^{**}	0.903 ^{**}	0.836 ^{**}	-0.203
SVI											0.958 ^{**}	0.889 ^{**}	0.908 ^{**}	-0.212
SVII												0.877 ^{**}	0.850 ^{**}	-0.370
CHL													0.837 ^{**}	0.132
RWC														-0.155

^{*}, ^{**} Significant at 0.05 and 0.01 probability levels, respectively. FGP: final germination percent; T_{50G} : median germination time; RL: radicle length; PL: plumule; TI: Timson's index; RSR: root/shoot ratio; SEP: seedling emergence percent; T_{50E} : median emergence time; RDW: root dry weight; SDW: shoot dry weight; SV-I: seedling vigour index I; SV-II: seedling vigour index II; CHL: chlorophyll content; RWC: relative water content; LPC: leaf proline content.

Reduction in relative water content (RWC) represents one of the earliest and most fundamental physiological responses to moisture stress. Declines in RWC are closely linked with decreased leaf water potential (Ψ_w), stomatal closure and reduced gas exchange, which collectively contribute to elevated leaf temperature and impaired photosynthetic efficiency (11, 45). Maintaining adequate RWC is critical for sustaining turgor-driven cellular processes, enzymatic activities and overall plant growth under water-limited conditions. In the present study, seed priming treatments demonstrated a notable recuperative effect on RWC, corroborating earlier reports that priming enhances seedling water status under stress (46). Seed priming preconditions seeds to modulate osmotic adjustment, antioxidant defense and membrane stability, thereby improving water uptake and retention during early growth stages. In our findings, vermipriming was most effective in improving RWC under normal conditions, likely due to enhanced nutrient mobilization and early vigor, whereas melatonin priming showed superior performance under moisture stress, reflecting its role in mitigating oxidative damage and regulating stress-responsive water balance mechanisms.

Proline accumulation is widely recognized as a key adaptive mechanism in plants under abiotic stress, primarily functioning as an osmolyte to maintain cellular water balance and turgor under water deficit conditions (35). Beyond its osmotic role, proline also contributes to maintaining intracellular redox homeostasis by scavenging reactive oxygen species (ROS) and stabilizing proteins and membranes under stress conditions (37). In the present study, moisture stress led to a significant increase in seedling proline content, reflecting the innate physiological strategy of chilli plants to mitigate the deleterious effects of water deficit.

Seed priming further enhanced proline accumulation, suggesting that pre-treatment prepares seedlings for imminent environmental challenges by inducing a “primed” metabolic state. This elevated proline pool likely supports osmotic adjustment, ROS detoxification and cellular protection, thereby facilitating better stress tolerance and ensuring successful completion of the plant life cycle under adverse conditions. These observations agree with previous reports that highlight the dual role of proline as an osmoprotectant and redox balancer in plants subjected to drought and other abiotic stresses (35–37).

These results provide a practical basis for recommending targeted seed priming strategies to improve chilli productivity under varying field conditions.

Conclusion

The present study demonstrates that moisture stress significantly impairs seed germination, early seedling growth and physiological functioning in Shalimar Long-I chilli. Stress-induced reductions in final germination percentage, seedling emergence, radicle and plumule growth, seedling vigour indices, chlorophyll content, relative water content and osmolyte balance highlight the sensitivity of chilli seedlings to water deficit conditions. Seed priming emerged as an effective strategy to mitigate these adverse effects, with vermipriming showing superior performance under normal conditions and melatonin priming proving most beneficial under moisture stress. Primed seedlings exhibited enhanced germination and growth attributes, higher chlorophyll content and stability, improved water retention and greater accumulation of proline,

indicating improved photosynthetic capacity, osmotic adjustment and redox homeostasis. Strong correlations among germination, growth and physiological traits further emphasize the integrated role of these mechanisms in stress adaptation. Overall, the findings underscore that seed priming can serve as a practical and reliable approach to enhance early seedling establishment, physiological resilience and stress tolerance in chilli, thereby supporting sustainable cultivation under both optimal and moisture-limited environments.

The results of this study provide a basis for evaluating seed priming under field conditions across different agro-climatic zones to validate stress tolerance and seedling establishment. Further research can focus on the molecular and biochemical mechanisms underlying priming-induced resilience, as well as its integration with nutrient management and other agronomic practices. Extending similar studies to other vegetable crops could help develop standardized priming protocols for broader agricultural applications.

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Authors' contributions

FAK conceived the idea, SK conducted the experiment, SAB and SH helped in laboratory analysis and interpretation of the data, KH helped in conducting the experiment, SAM helped in statistical analysis of the data, SN provided the plant material and helped in developing programme of experiment and MA helped in developing technical programme and analysis of the raw data.

Compliance with ethical standards

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

Ethical issues: None

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