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Seed Priming with Potassium Nitrate and Gibberellic Acid Enhances the Performance of Dry Direct Seeded Rice (*Oryza sativa* L.) in North-Western India

Buta Singh Dhillon [1,*], Virender Kumar [2,*], Pardeep Sagwal [3], Navjyot Kaur [1], Gurjit Singh Mangat [1] and Sudhanshu Singh [3]

[1] Department of Plant Breeding & Genetics, Punjab Agricultural University, Ludhiana 141004, India; navjyot_grewal@yahoo.com (N.K.); gsmangat-pbg@pau.edu (G.S.M.)
[2] International Rice Research Institute, Los Baños 4031, Philippines
[3] International Rice Research Institute, South Asia Regional Centre, Varanasi 221106, India; p.sagwal@irri.org (P.S.); sud.singh@irri.org (S.S.)
* Correspondence: bsdhillon@pau.edu (B.S.D.); virender.kumar@irri.org (V.K.); Tel.: +91-8146100360 (B.S.D.); +63-9175189431 (V.K.)

Abstract: Poor early growth and uneven crop establishment are reported as the major bottlenecks in wide-scale adoption and optimal yield realization of dry direct-seeded rice (DSR). Seed priming can potentially help overcome these problems in DSR. Therefore, laboratory and field studies were conducted at Punjab Agricultural University, Ludhiana, India, during *kharif*/wet-season 2018 and 2019 to evaluate the effect of different priming techniques on germination, establishment, growth, and grain yield of rice under DSR conditions. The following priming treatments were evaluated: dry non-primed seed (control), hydropriming with distilled water, halopriming with 2.0% potassium nitrate, hormopriming with 50 ppm gibberellic acid (GA_3), and osmopriming with polyethylene glycol (PEG) (−0.6 MPa), each with 12 and 24 h priming duration. In 2019, priming treatments were tested under two DSR establishment methods—conventional DSR (sowing in dry soil followed by irrigation) and soil mulch DSR (locally known as *vattar* DSR) (sowing in moist soil after pre-sowing irrigation), whereas in 2018, priming treatments were evaluated under conventional DSR only. In both years, halopriming and hormopriming resulted in a 7–11% increase in rice yields compared to non-primed dry seed (control). Osmopriming resulted in a 4% yield increase compared to control in 2018 but not in 2019. The higher yields in halopriming and hormopriming were attributed to higher and rapid germination/crop emergence, better root growth, and improvement in yield attributes. Priming effect on crop emergence, growth, and yield did not differ by DSR establishment methods and duration of priming. Conventional DSR and soil mulch DSR did not differ in grain yield, whereas they differed in crop emergence, growth, and yield attributes. These results suggest that halopriming with 2.0% potassium nitrate and hormopriming with 50 ppm GA_3 has good potential to improve crop establishment and yield of rice in both conventional and soil mulch DSR systems.

Keywords: direct-seeded rice; gibberellic acid; PEG; potassium nitrate; productivity; root mass density; seed priming; vigor index

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1. Introduction

Rice is a staple food for about 50% of the world population [1]. In India, rice is grown on 44.5 million hectares, accounting for 25% of global rice area and 21% of global rice production [2]. During 2019–2020, India exported 9.5 million MT of rice to countries such as Iran, Saudi Arab, Vietnam, USA, Nepal, Benin, Somalia, and Guinea etc. [3]. Therefore, the sustainability of Indian rice production is crucial for global food security. Additionally, in the future, to ensure both food security and environmental sustainability, it will be required to produce rice with a lower environmental footprint using less labor, water, and agrochemicals, while buffering the effect of climate change [4,5]. This requires paradigm shifts from the current resource-intensive rice cultivation method to resource-efficient and cost-effective cultivation methods [4,5].

In northwest India, where high yields of rice are quite common, rice is widely grown by the puddled transplanting (PTR) method during the *kharif*/wet-season (June to October/November) [4,6]. In this method, rice seedlings are first raised in a nursery. At about 25–30 days, seedlings are uprooted and manually transplanted to the puddled (wet-tilled) soil in the main field, and the field is then kept flooded for the majority of the season [4]. This method is preferred because of its several advantages, including assured good crop establishment, weed suppression [7], and higher nutrient availability under flooded/anaerobic conditions [8].

Recently, the sustainability of the flooded PTR method in northwest India has been threatened because it consumes a large amount of labor, water, and energy—all of which are becoming increasingly scarce and expensive in the region [9,10]. All of these factors present foundational challenges to sustaining high levels of rice production. The puddling operation in PTR also adversely affects the yield of the succeeding wheat crop in rotation by 8% due to its negative impact on soil physical properties [9]. Negative impact of puddling has also been reported on succeeding soybean crop [11]. Moreover, PTR is also associated with emissions of large amounts of greenhouse gas (GHG) in the form of methane, [12] and higher energy consumption [13]. All of these factors demand alternate methods that are labor-, water-, and energy-efficient, cost-effective, and mitigate climate change effects.

Dry direct-seeded rice (DSR) has emerged as a socio-economically viable and environmentally promising alternative to PTR to achieve productivity gains with lower water and labor utilization, production costs, and GHG emissions [4,10,14,15]. In DSR, seeds are directly sown (drill-sown with a machine or manually broadcast) in the main field, instead of nursery raising and transplanting rice seedlings as is the case in PTR. DSR can be established either by (1) sowing in dry soil followed by irrigation (conventional DSR) or by (2) sowing in moist soil after pre-sowing irrigation (locally known as *vattar* DSR, also known as soil mulch DSR [12,16,17]. Based on field studies conducted in the region, DSR in comparison to PTR provides multiple benefits, including savings in labor (by eliminating the processes of nursery raising, uprooting, and transplanting seedlings), water (18–50%), cost of cultivation (INR 6436–7950 ha^{-1}), and positively impacting succeeding wheat yield (8–10%) in rotation, higher net income, and reduction in global warming potential (32–44%) [9,10,13,18,19].

Risks of poor and non-uniform crop establishment and higher weed infestations are some of the constraints in the wide-scale adoption of DSR [9,20,21]. The rapid and uniform emergence with early vigor can lead to uniform and good crop establishment, which is crucial for attaining full yield potential and suppressing weeds in DSR [22,23]. In DSR, desired crop establishment is constrained by multiple factors, such as soil moisture drying associated with high temperatures, and inundation/flooding caused by monsoon rains during crop emergence/early establishment [9,12,24]. Soil mulch/*vattar* DSR, an innovative approach, was developed to address the issue of inundation risk because this method reduces the early irrigation requirement for the first 15 to 21 days by conserving soil moisture through the soil mulch effect [25,26], and hence facilitates early planting of DSR (i.e., 2 to 3 weeks before the onset of the monsoon) which, in turn, reduces the risk of stand mortality caused by inundating rains during the early phases of crop growth. However, in this method, the top soil layer (~2 cm) dries up very quickly; hence emergence can be affected by soil moisture depletion if seeds are not placed in the moist zone. In the conventional DSR method, there is a risk of temporary excess moisture stress, especially at places in the field where water stagnates at low-lying places in a non-leveled field or if rainfall occurs during the germination period leading to field inundation [4,9].

Sustainable and effective technologies are inevitable to improve the rapid and uniform crop emergence and early growth under DSR. Pre-sowing seed priming is one such technology [27] that suggests that the yield gap in DSR compared to PTR caused by poor crop establishment can be closed with seed priming technology. Improved seed invigoration techniques, such as seed priming for its positive impacts including rapid and uniform crop establishment, early vigor, and yield gains, have been studied in various crops including mungbean [28], soybean [29], sorghum [30], wheat [31,32], and maize [33,34], and vegetables such as tomato [35]. Recently, with increased interest in transitioning from PTR to DSR, limited studies have been conducted on rice seed priming [36,37].

Seed priming is defined as a pre-sowing treatment that partially hydrates seeds without allowing emergence [38]. Priming often involves soaking the seed in pre-determined amounts of water, called hydropriming. Control of the imbibition rate by osmotic agents such as polyethylene glycol (PEG) is referred to as osmopriming. Similarly, the use of specific salts for priming is called halopriming, and the use of plant growth regulators for priming is known as hormopriming [39]. In rice, although limited studies have been conducted on priming, these studies primarily demonstrated the positive impact on germination/emergence, rate of emergence, root growth, early seedling vigor, and early growth [37,40,41], and a few studies also demonstrated the positive impact on grain yield and quality [36,38]. It has been reported that osmo-, hydro-, hormonal, and vitamin priming resulted in early and better crop establishment and early growth by enhancing amylase activity and total sugar in the seed [42]. Rice seed priming is, therefore, one of the most effective, pragmatic, and short-term approaches for increasing seed vigor and synchronization of germination under different stresses. Very limited information is available on the impact of seed priming on emergence and seedling growth and yield of DSR under Indian conditions where DSR is established using two methods—conventional and soil mulch DSR. To our knowledge, the impact of seed priming under *vattar*/soil mulch DSR has not been studied. Additionally, the majority of the previous seed priming studies were conducted under laboratory conditions with focus on germination/emergence and early growth, and very limited studies have evaluated the impact at grain yield [36,37]. Moreover, limited information is available on the impact of seed priming with KNO_3 and GA_3 on rice yield under DSR conditions. Therefore, research experiments were conducted with the objective to evaluate the effect of different types and durations of priming on germination, emergence, crop establishment, crop growth, and grain yield of rice under DSR conditions established by two methods.

2. Materials and Methods

2.1. Experimental Site

Experiments were conducted for two consecutive seasons (*kharif*/wet seasons (June to October/November) 2018 and 2019) at the Research Farm of Punjab Agricultural University, Ludhiana, India (30°56′ N latitude; 75°52′ E longitude; 247 m altitude) located in the Western Indo–Gangetic Plains (WIGPs). The climate of the experimental site is characterized as subtropical, semi-arid with an annual rainfall of 733 mm, of which about 80% is received during June to September [43]. The data on rainfall, sunshine hours, and maximum and minimum temperatures for the study period (2018 and 2019) were gathered at the agro–meteorological observatory of Punjab Agricultural University, Ludhiana, situated 200 m from the experimental site. Based on the initial soil analysis (0–15 cm depth) conducted at the beginning of the study, the experimental site was Typical Ustipsamment (Fatehpur sandy–loam) in texture, low in available N (225 kg ha^{-1}), and medium in available P (21.8 kg ha^{-1}), K (273 kg ha^{-1}), and soil organic carbon (0.42%). The soil pH (7.3) and electrical conductivity (0.25 dSm^{-1} at 25 °C) were within the normal range.

2.2. Experimental Details and Crop Management

2.2.1. Laboratory Study

Prior to the field experiment, a laboratory experiment was conducted in May 2018 to determine the effect of different priming treatments on the germination and vigor of rice seedlings. The experiment was conducted two times. Nine seed priming treatments were used, which were replicated four times in a randomized complete block design using the

PR 126 variety of rice. The seed priming treatments undertaken were: dry seed (control), hydropriming, osmopriming with polyethylene glycol (PEG) (−0.6 MPa osmotic potential), halopriming with 2.0% potassium nitrate, and hormopriming with 50 ppm gibberellic acid (GA_3). Seed priming was undertaken for two durations, i.e., 12 and 24 h. Before initiating germination studies, the required number of paddy seeds was surface sterilized using 0.1% mercuric chloride for 2 min, followed by thorough washing with distilled water to protect against any fungal infection. Seed germination was tested (one hundred seeds in each replication) using the "between paper" (BP) method in an incubator at 25 °C, keeping a day and night duration of 12 h [44].

2.2.2. Field Study

The same sets of nine treatments tested in the laboratory study were replicated thrice under field conditions during *kharif* 2018 in a randomized complete block design (RCBD). In 2018, seed priming treatments were evaluated under only the conventional DSR method (seeding in dry soil followed by irrigation). During *kharif* 2019, the seed priming treatments (factor 1) were evaluated under two DSR methods (factor 2): conventional DSR and *vattar*/soil mulch DSR in a factorial randomized complete block design. The solution of 50 ppm GA_3 was prepared by dissolving 50 mg of GA_3 in ethyl alcohol (2 mL) followed by dilution to 1.0 L using distilled water. Potassium nitrate (KNO_3) solution of 2.0% was prepared by dissolving 20 g of KNO_3 in 1.0 L distilled water. To prepare the solution with osmotic potential (OP) of −0.6 MPa, 21 g of PEG (polyethylene glycol) was dissolved in 1 L of water following the equation of Michaelis and Menten (1913) [45]. Hydropriming was performed by soaking one kg seed in one liter distilled water. Seed priming was performed for 12 and 24 h per treatment followed by drying of seed to its original moisture level before seeding. Short duration rice genotype PR 126 with 1000-grain weight 21.8 g was used and sown by conventional DSR and *vattar*/soil mulch DSR. For both methods, seeds were sown manually in rows. In the conventional DSR method, seeds were sown in well-prepared dry soil followed by irrigation immediately after sowing to facilitate crop emergence. For sowing, first rows/furrows were made using a hand plough, and then seeds were sown in furrows and covered with soil. In case of *vattar*/soil mulch DSR, pre-sowing irrigation was applied in a well-prepared soil followed by shallow tillage when the field reached the *vattar* (field capacity) condition and then rice sowing was conducted. Sowing was done using a hand-pulled plough where seeds were dropped at a depth of 1.5–2.0 cm through a funnel attached behind the plough while pulling it in a single operation. The layout and time of field operations in each year is presented as Supplementary Materials (Supplementary Figure S1 and Table S1).

In both methods, rice was sown at row spacing of 20 cm using a seed rate of 20 kg ha^{-1} in plots measuring 10.8 m^2. After sowing, the first post-sowing irrigation was applied 21 days after sowing (DAS) in *vattar*/soil mulch DSR, whereas in conventional DSR, post-sowing irrigations were applied at 0, 6, 14, and 21 DAS. Subsequent irrigations to both crops (conventional and *vattar*/soil mulch DSR) were scheduled and applied on similar days as per the crop demand. All other production and protection technologies were followed as per Punjab Agricultural University's recommendations [14]. The recommended dose of fertilizer (N, 150 kg ha^{-1} and $ZnSO_4$ (21%), 25 kg ha^{-1}) was applied to the crop. Nitrogen was applied through urea in three equal splits at 30, 45, and 63 days after sowing (DAS). Whole of the $ZnSO_4$ was applied basal at the last field preparation. Due to sufficient P and K levels in the soil, these nutrients were not applied to the experiment crops.

2.3. Data Collection

2.3.1. Laboratory Study

Root and shoot lengths and seedling biomass were collected at termination of the experiment (14 DAS). Ten seedlings from each replication were measured using a centimeter scale and expressed in cm for measuring the root and shoot lengths. For dry matter accumulation (DMA), ten seedlings were dried in an oven at 65 ± 2 °C until attainment of constant weight and were expressed in grams per 10 seedlings. Seedling vigor index I and II were calculated by the formulae given below as described by [46]:

$$\text{Seedling vigor index I} = \text{Germination percentage} \times \text{Total seedling length (Root + Shoot) in cm}$$

$$\text{Seedling vigor index II} = \text{Germination percentage} \times \text{Dry weight of ten seedlings in g}$$

2.3.2. Field Study

Daily emergence counts until the plant population became constant were recorded from each plot, from two rows marked at 1 m on each side of the plot from the third row, to estimate days to first rice seedling emergence, synchrony of emergence (number of days for complete emergence), and total emergence, and time taken to 50% emergence (T_{50}). T_{50} was calculated using the following formula:

$$T_{50} = t_i + \frac{\left(\frac{N}{2} - n_i\right)\left(t_j - t_i\right)}{\left(n_j - n_i\right)}$$

where N is the number of final emerging seedlings, and n_j and n_i are the cumulative numbers of rice seedlings emerging by adjacent count at times t_j and t_i, respectively, when $n_i < N/2 < n_j$.

The final plant population estimated at 25 DAS was expressed as number of plants per square meter. Plant height was recorded at crop maturity by randomly selecting five plants in each experimental unit, and it was measured from the ground level to the tip of panicle, excluding awns and expressed in centimeters. Days to 50% flowering were noted based on visual observations from each plot. The SPAD reading was noted at 50% flowering stage from 4 fully expanded apical leaf at 2/3 position [47] from 10 rice plants in each plot, using a KONICA MINOLTA SPAD-502 PlusS/N:20001083 VER: 1.00.0501 Model. Root mass density was assessed at the anthesis stage (83 to 90 DAS depending on year and DSR method). For calculating root mass density, soil core samples were taken layer-wise (0–15 and 15–30 cm) using a root sampling pipe with an internal diameter of 15 cm. For this, five samples were taken continuously from 0.75 m row length per experimental unit. The soil samples thus obtained were washed in thin nylon mesh of one mm sieve in running water. The washed roots were picked up and then dried at 65 °C in an oven until reaching a constant weight. The root density was expressed as the weight of roots per unit volume of soil and calculated as follows:

$$\text{Rooting density } (\text{g/cm}^3) = \frac{\text{Total root weight in particular depth (g)}}{\text{Total soil volume from which roots were collected } (\text{cm}^3)}$$

Total and effective tillers were counted from one meter row length from two locations at each plot and were expressed as tillers m^{-2} and panicles m^{-2}. Five panicles were randomly selected from each experimental unit for recording panicle weight, and number of filled and unfilled grains per panicle. From the bulk samples, 1000 grains were counted and weighed on an electronic balance to obtain the 1000-seed weight. For estimating grain yield, a net area of 8.0 m^2 (4.0 m × 2.0 m) was harvested from each plot and then threshed, sun dried, winnowed, cleaned, and weighed on an electronic balance. For valid comparison of different treatments, moisture in grains was estimated using a digital moisture meter (Kett's RICETER J Handheld grain moisture meter). Grain yield was adjusted at 14% moisture and expressed as t ha^{-1}. The weight of straw from each net plot was also recorded three days after harvest for estimation of straw yield, which was expressed as t ha^{-1}.

2.4. Statistical Analysis

Data were subjected to 2-way analysis of variance (ANOVA) using the Proc GLM procedure of SAS software (SAS 9.3.) for laboratory study and 2018 field study using RCBD design and 3-ways analysis for 2019 field study using factorial RCBD design. For laboratory study, there was no treatment by run interaction; therefore, data of both runs were pooled and analyzed. For field study, data were analyzed year wise. The multiple comparisons among treatment means were carried out using Tukey's honest significance difference (HSD) test ($p \leq 0.05$).

3. Results

3.1. Weather Parameters

Maximum air temperature varied from 31.3 to 37.6 °C and 30.6 to 40.4 °C, and minimum from 17.1 to 27.2 °C and 18.4 to 26.8 °C during *kharif* 2018 and 2019, respectively (Figure 1). The maximum temperature of study years was almost similar to the long-term average, whereas minimum temperature of study years was slightly higher, especially during 2019, than the long-term average. Total seasonal rainfall was similar in both years (843.0 mm in 2018 and 844.5 mm in 2019) but both years varied in rainfall distribution during the growing season. For example, there was more rainfall in June and July in 2018 than in 2019, whereas in August, it was higher in 2019 than in 2018. In September, the rainfall was almost similar in both years (251 mm in 2018 and 265 mm in 2019). Similar to rainfall, total sunshine hours were also almost equal in both years (1015 and 1017 h in 2018 and 2019, respectively), but varied during the season, with higher sunshine hours in 2018 than in 2019 in the month of July, September, and October whereas it was the reverse in June and August. Overall, both seasons recorded above normal rainfall and below normal sunshine hours. The higher rainfall during September coincided with the grain filling period of the crop.

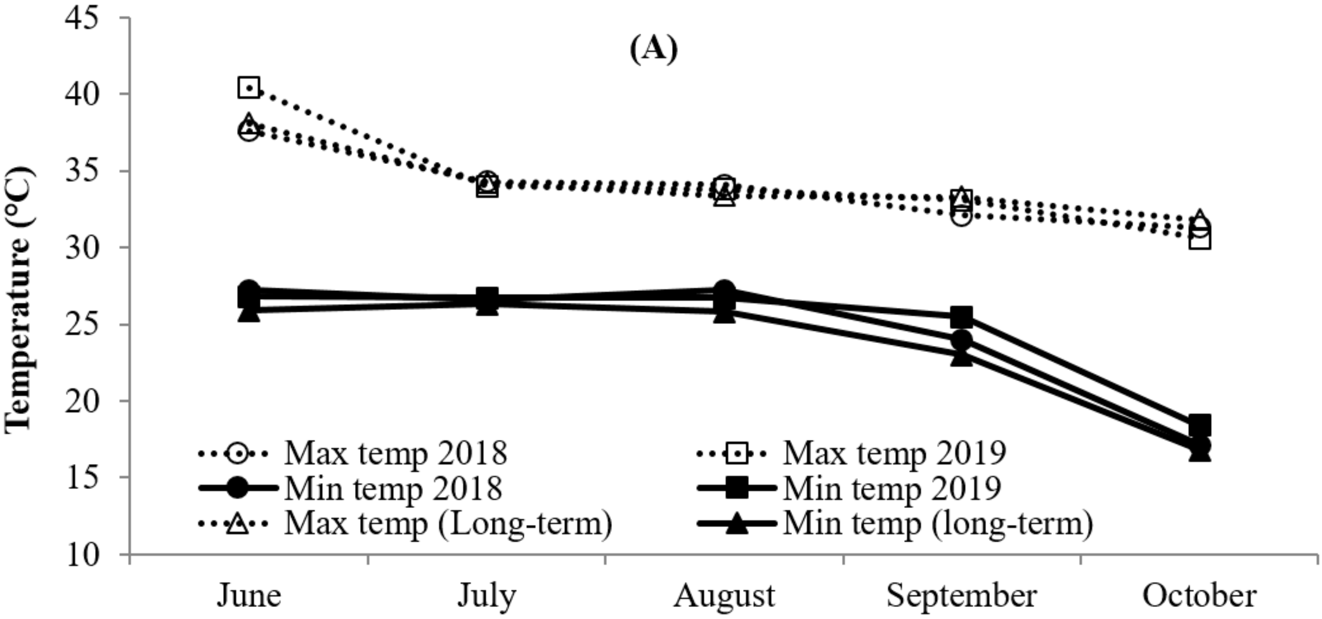

Figure 1. *Cont.*

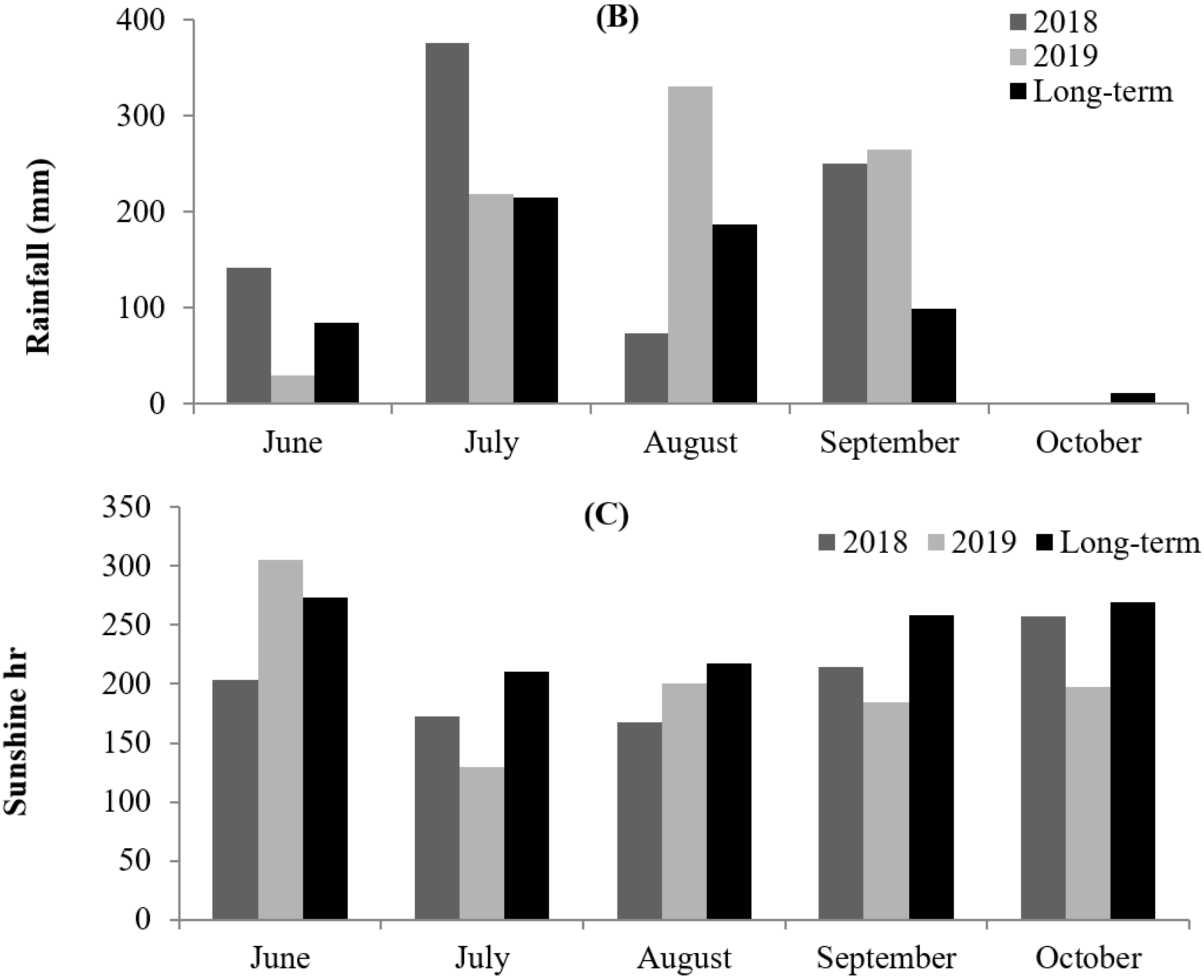

Figure 1. Mean monthly (**A**) temperature (minimum, maximum, and mean), (**B**) rainfall, and (**C**) sunshine hours during the study period (2018 and 2019 season) and of 10 year long-term average.

3.2. Laboratory Study

Results show that halopriming of seed with 2.0% potassium nitrate or hormopriming with 50 ppm GA_3 enhanced seed germination by 3–4% compared to non-primed dry seed (control), whereas hydropriming and osmopriming with PEG did not affect seed germination (Table 1). Compared to the control (dry seed), all priming treatments except hydropriming had a positive impact on root growth with 20–27% increment in the root length. Only hormopriming with GA_3 positively impacted shoot length with 21–22% higher shoot length compared to the control (dry seed). Hormopriming treatments had higher shoot length than the remaining treatments except halopriming treatments. Similar to root length, all priming treatments except hydropriming treatments improved the total seedling length. Priming treatments also significantly influenced vigor index 1 and vigor index 2. Osmopriming, halopriming, and hormopriming had a higher index vigor 1 than the control (dry seed) and hydropriming, whereas only halopriming and hormopriming had a higher vigor index 2 than the control, hydropriming, and osmopriming. There was improvement in root length, shoot length, and vigor indices, but it was not reflected in seedling dry matter accumulation within a short study period of 14 days. Duration of priming (12 or 24 h) in all priming treatments (hydro-, osmo-, halo-, and hormopriming) was not significant for any of the growth parameters.

Table 1. Effect of different seed priming techniques on germination, root and shoot length, dry weight (DW) accumulation, and vigor index of paddy seedlings (laboratory studies, average of two runs) [1].

Treatment	Germination (%)	Root Length (cm)	Shoot Length (cm)	DW of 10 Seedlings (g)	Vigor Index 1	Vigor Index 2
Control (dry seed)	89 ± 0.1 b	12.8 ± 0.2 c	12.1 ± 0.3 b	0.086 ± 0.002 a	2219 ± 10.7 e	7.7 ± 0.04 b
Hydropriming 12 h	89 ± 0.7 b	13.1 ± 0.2 bc	12.4 ± 0.1 b	0.088 ± 0.001 a	2267 ± 6.3 e	7.8 ± 0.03 b
Hydropriming 24 h	89 ± 0.6 b	13.3 ± 0.3 bc	12.6 ± 0.2 b	0.087 ± 0.002 a	2302 ± 28.3 de	7.7 ± 0.03 b
Osmopriming12 h	89 ± 0.7 b	16.3 ± 0.3 a	12.6 ± 0.4 b	0.088 ± 0.002 a	2560 ± 25.7 c	7.8 ± 0.01 b
Osmopriming 24 h	88 ± 0.6 b	16.1 ± 0.1 a	12.2 ± 0.3 b	0.088 ± 0.002 a	2496 ± 3.1 cd	7.7 ± 0.01 b
Halopriming 12 h	92 ± 0.3 a	15.0 ± 0.3 ab	13.3 ± 0.6 ab	0.091 ± 0.002 a	2619 ± 39.6 bc	8.4 ± 0.03 a
Halopriming 24 h	92 ± 0.6 a	15.7 ± 0.8 a	13.4 ± 0.6 ab	0.092 ± 0.001 a	2676 ± 92.3 abc	8.5 ± 0.04 a
Hormopriming 12 h	93 ± 0.6 a	15.3 ± 0.8 ab	14.7 ± 0.4 a	0.091 ± 0.001 a	2790 ± 95.6 ab	8.4 ± 0.02 a
Hormopriming 24 h	93 ± 0.6 a	15.9 ± 0.3 a	14.8 ± 0.4 a	0.091 ± 0.003 a	2852 ± 30.4 a	8.5 ± 0.02 a

[1] Within column, means followed by the same letter are not different at the 0.05 level of probability using Tukey's honest significance difference (HSD) test.

3.3. Field Study

3.3.1. Rate of Crop Emergence and Crop Establishment

Both priming and DSR methods influenced time taken to 50% emergence (T_{50}), and days taken to start and completion of emergence. However, priming × DSR method interaction was non-significant for all of these parameters, suggesting that the effect of priming did not differ with DSR establishment methods (Tables 2 and 3). In both years, the rice emergence was faster in treatments with halopriming and hormopriming compared to the control (dry seeds without priming) as demonstrated by minimum value (days taken) for T50, and days taken to start and complete crop emergence. T_{50} was 1 day faster in halopriming and hormopriming compared to the control in 2018, and 2 days faster in 2019. Similarly, the time to start of emergence was 1 to 1.3 days earlier in 2018 and 1.5 to 2.0 days earlier in 2019 in halopriming and hormopriming than the control. The time to completion of rice emergence was 2 to 3 days earlier in both years in halopriming and hormopriming treatments compared to the control (dry seeds without priming). Other priming treatments did not differ from the control for these parameters.

Table 2. Time taken to 50% emergence (T50), days taken to start and completion of emergence, and final plant population as affected by different seed priming in conventional direct-seeded rice (DSR) establishment method during 2018 at Ludhiana, India.

Treatment	Time Taken to 50% Emergence (T50)	Days Taken to Start of Emergence	Days Taken to Completion of Emergence	Plant Population (No. m^{-2})
Control (dry seed)	10.3 ± 0.2 a	6.3 ± 0.3 a	13.0 ± 0.6 a	85 ± 0.1 a
Hydropriming 12 h	9.8 ± 0.3 ab	5.7 ± 0.2 ab	11.7 ± 0.7 ab	88 ± 0.7 a
Hydropriming 24 h	9.8 ± 0.3 ab	5.7 ± 0.3 ab	12.3 ± 0.7 ab	87 ± 0.6 a
Osmopriming12 h	9.9 ± 0.4 ab	6.3 ± 0.3 a	11.7 ± 0.7 ab	88 ± 0.7 a
Osmopriming 24 h	9.9 ± 0.5 ab	6.3 ± 0.3 a	11.0 ± 0.6 ab	88 ± 0.6 a
Halopriming 12 h	9.3 ± 0.1 b	5.3 ± 0.3 b	10.7 ± 0.3 ab	87 ± 0.3 a
Halopriming 24 h	9.3 ± 0.1 b	5.3 ± 0.3 b	10.3 ± 0.3 b	87 ± 0.6 a
Hormopriming 12 h	9.2 ± 0.1 b	5.0 ± 0.1 b	10.0 ± 0.1 b	86 ± 0.6 a
Hormopriming 24 h	9.2 ± 0.1 b	5.0 ± 0.1 b	10.0 ± 0.1 b	87 ± 0.6 a

Within column, means followed by the same letter are not different at the 0.05 level of probability using Tukey's HSD test.

In 2019, T_{50}, and time to start and completion of rice emergence was 1 day faster in conventional DSR than in *vattar*/soil mulch DSR (Table 3). The final plant population did not differ by priming treatment in 2018 but was 6% to 8% higher in halopriming and hormopriming treatments compared to the control treatment. In both years, the final plant population in hydropriming and osmopriming was not different from the control treatment.

Table 3. Time taken to 50% emergence (T50), days taken to start and completion of emergence, and final plant population as affected by different seed priming and DSR establishment methods during 2019 at Ludhiana, India.

Treatment	**Time Taken to 50% Emergence (T50)**	**Days Taken to Start of Emergence**	**Days Taken to Completion of Emergence**	**Plant Population (No. m^{-2})**
(A) Priming treatment				
Control (dry seed)	10.7 ± 0.4 a	7.7 ± 0.6 a	13.7 ± 0.3 a	74.8 ± 3.5 d
Hydropriming 12 h	9.9 ± 0.3 abc	6.8 ± 0.3 ab	12.7 ± 0.3 abcd	76.8 ± 3.5 bcd
Hydropriming 24 h	9.8 ± 0.4 bc	6.8 ± 0.3 ab	12.8 ± 0.4 abc	76.0 ± 3.3 bcd
Osmopriming12 h	10.0 ± 0.4 ab	7.0 ± 0.4 ab	13.3 ± 0.5 ab	75.3 ± 3.6 cd
Osmopriming 24 h	9.9 ± 0.5 abc	7.0 ± 0.4 ab	13.3 ± 0.5 ab	75.8 ± 3.5 bcd
Halopriming 12 h	9.2 ± 0.5 cd	6.2 ± 0.3bc	11.5 ± 0.5 bcde	79.3 ± 3.2 ab
Halopriming 24 h	8.7 ± 0.3 d	6.0 ± 0.3 bc	11.0 ± 0.5 cde	79.0 ± 3.3 abc
Hormopriming 12 h	8.6 ± 0.3 d	5.7 ± 0.2 c	10.8 ± 0.5 de	81.1 ± 2.9 a
Hormopriming 24 h	8.5 ± 0.4 d	5.7 ± 0.3 c	10.7 ± 0.4 e	81.0 ± 2.8 a
(B) DSR method				
Conventional DSR	8.9 ± 0.1 b	6.0 ± 0.1 b	11.7 ± 0.3 b	85 ± 0.5 a
Soil mulch DSR	10.1 ± 0.2 a	7.1 ± 0.2 a	12.7 ± 0.3 a	71 ± 0.6 b
ANOVA (*p*-value)				
Priming (P)	<0.0001	<0.0001	<0.0001	<0.0001
DSR method (M)	<0.0001	<0.0001	0.002	<0.0001
P × M interaction	NS	NS	NS	NS

Within column for each factor, means followed by the same small letter are not different at the 0.05 level of probability using Tukey's HSD test.

3.3.2. Crop Growth and SPAD Value

In both years, seed priming treatments did not influence rice plant height and days to 50% flowering but both parameters were significantly influenced by the DSR methods (Tables 4 and 5). The plant height was 2 cm higher in *vattar*/soil mulch DSR than in the conventional DSR method. In addition, days to 50% flowering under *vattar* DSR was delayed by 4 days compared to the conventional DSR method.

Table 4. Plant height, tiller number, days to flower and SPAD value as affected by different seed priming in conventional DSR establishment method during 2018 at Ludhiana, India.

Treatment	**Plant Height (cm)**	**Tillers (Number m^{-2})**	**Days to Flowering (Days)**	**SPAD Value**
Control (dry seed)	95 ± 3.1 a	512 ± 1.2 c	82 ± 0.3 a	35.4 ± 0.2 b
Hydropriming 12 h	96 ± 0.5 a	512 ± 2.3 c	81 ± 1.0 a	35.6 ± 0.3 b
Hydropriming 24 h	96 ± 1.1 a	511 ± 2.6 c	81 ± 0.6 a	35.6 ± 0.3 b
Osmopriming12 h	98 ± 0.4 a	517 ± 5.5 bc	82 ± 0.3 a	37.7 ± 0.3 a
Osmopriming 24 h	98 ± 0.8 a	517 ± 3.3 bc	82 ± 0.3 a	37.5 ± 0.3 a
Halopriming 12 h	99 ± 2.0 a	540 ± 3.1 ab	80 ± 0.6 a	37.4 ± 0.2 a
Halopriming 24 h	100 ± 1.7 a	550 ± 8.1 a	80 ± 0.9 a	37.5 ± 0.6 a
Hormopriming 12 h	99 ± 1.6 a	539 ± 3.3 ab	80 ± 0.3 a	37.4 ± 0.1 a
Hormopriming 24 h	100 ± 1.3 a	541 ± 7.4 ab	80 ± 1.2 a	37.4 ± 0.8 a

Within column, means followed by the same letter are not different at the 0.05 level of probability using Tukey's HSD test.

Both priming techniques and DSR methods influenced tiller density and SPAD value, but the effect of priming did not differ with DSR establishment method, as demonstrated by non-significant priming × DSR method interaction (Table 5). In both years, the tiller density in osmopriming and hydropriming treatments was similar to the control (dry and non-primed seed). Tiller density in halopriming and hormopriming treatments was 5–7% higher than control and hydropriming treatments in 2018, whereas in 2019, tiller density was 8–11% higher in halopriming and hormopriming treatments compared to osmopriming, hydropriming, and control treatments.

In both years, the SPAD value in all priming treatments except hydropriming was higher than the control. In 2018, SPAD values in control and hydropriming ranged from 35.4 to 35.6, whereas in other priming treatments, they ranged from 37.4 to 37.7. In 2019, they ranged from 34.7 to 34.8 in the control and hydropriming, and from 36.3 to 36.8 in the other priming treatments. In 2019, among DSR methods (Table 5), the SPAD value was higher in *vattar*/soil mulch DSR (37.1) than conventional DSR (34.8).

Table 5. Plant height, tiller number, days to flower and SPAD value as affected by different seed priming and DSR establishment methods during 2019 at Ludhiana, India.

Treatment	Plant Height (cm)	Tillers (Number m^{-2})	Days to Flowering (Days)	SPAD Value
		(A) Priming treatment		
Control (dry seed)	98 ± 1.1 a	421 ± 6.4 b	83 ± 0.8 a	34.7 ± 0.7 b
Hydropriming 12 h	98 ± 1.1 a	425 ± 6.6 b	82 ± 0.8 a	34.7 ± 0.6 b
Hydropriming 24 h	97 ± 0.9 a	425 ± 7.2 b	82 ± 0.8 a	34.8 ± 0.7 b
Osmopriming12 h	98 ± 0.8 a	429 ± 7.3 b	82 ± 0.8 a	36.4 ± 0.6 a
Osmopriming 24 h	98 ± 0.9 a	426 ± 5.8 b	83 ± 0.8 a	36.3 ± 0.6 a
Halopriming 12 h	99 ± 0.6 a	463 ± 4.8 a	82 ± 0.8 a	36.5 ± 0.6 a
Halopriming 24 h	99 ± 1.0 a	463 ± 3.4 a	81 ± 0.8 a	36.6 ± 0.5 a
Hormopriming 12 h	101 ± 1.3 a	462 ± 5.6 a	81 ± 0.8 a	36.8 ± 0.5 a
Hormopriming 24 h	101 ± 1.3 a	469 ± 5.1 a	81 ± 0.9 a	36.7 ± 0.5 a
		(B) DSR method		
Conventional DSR	98 ± 0.5 b	452 ± 3.3 a	80 ± 0.2 b	34.8 ± 0.2 b
Soil mulch DSR	100 ± 0.5 a	433 ± 5.0 b	84 ± 0.2 a	37.1 ± 0.2 a
		ANOVA (*p*-value)		
Priming (P)	NS	<0.0001	NS	<0.0001
DSR method (M)	<0.0001	<0.0001	<0.0001	<0.0001
P × M interaction	NS	NS	NS	NS

Within column for each factor, means followed by the same small letter are not different at the 0.05 level of probability using Tukey's HSD test.

3.3.3. Root Mass Density

Priming techniques and DSR methods influenced root mass density at both depths (0–15 cm and 15–30 cm) but the interaction between priming and DSR method was non-significant (Tables 6 and 7). In 2018, the root mass density of conventional DSR at 0–15 cm depth was highest in osmopriming for 24 h (4.85 mg cc^{-1}) which was at par with halopriming and hormopriming for 24 h, but was higher than halopriming and hormopriming for 12 h treatments. The lowest root mass density was in control and hydropriming treatments (3.39 to 3.45 $mgcc^{-1}$) and was lower than all other priming treatments. At 15–30 cm depth, root mass density in osmopriming, halopriming, and hormopriming treatments was higher (ranging from 0.410 to 0.428 $mgcc^{-1}$) than control and hydropriming treatments (ranging from 0.324 to 0.334 mg cc^{-1}). In 2019, a similar trend was observed in root mass density at both depths to that observed in 2018. In 2019, root mass density was higher in *vattar*/soil mulch DSR than conventional DSR at both depths (Table 7) (4.6 versus 3.8 mg cc^{-1} at 0–15 cm and 0.40 versus 0.37 mg cc^{-1} at 15–30 cm depth).

Table 6. Root mass density of rice under different seed priming techniques in conventional DSR establishment method during 2018 at Ludhiana, India.

Treatment	Root Mass Density (mg/cc) in Different Layers	
	0–15 cm	15–30 cm
Control (dry seed)	3.39 ± 0.04 c	0.324 ± 0.01 b
Hydropriming 12 h	3.39 ± 0.02 c	0.334 ± 0.02 b
Hydropriming 24 h	3.45 ± 0.06 c	0.327 ± 0.03 b
Osmopriming12 h	4.66 ± 0.02 ab	0.428 ± 0.01 a
Osmopriming 24 h	4.85 ± 0.02 a	0.424 ± 0.01 a
Halopriming 12 h	4.27 ± 0.13 b	0.410 ± 0.01 a
Halopriming 24 h	4.42 ± 0.04 ab	0.416 ± 0.01 a
Hormopriming 12 h	4.31 ± 0.01 b	0.414 ± 0.01 a
Hormopriming 24 h	4.51 ± 0.24 ab	0.420 ± 0.02 a

Within column, means followed by the same letter are not different at the 0.05 level of probability using Tukey's HSD test.

Table 7. Root mass density of rice under different seed priming techniques and DSR establishment methods during 2019 at Ludhiana, India.

Treatment	**Root Mass Density (mg/cc) in Different Layers**	
	0–15 cm	**15–30 cm**
	(A) Priming treatment	
Control (dry seed)	3.47 ± 0.22 d	0.33 ± 0.01 b
Hydropriming 12 h	3.47 ± 0.21 d	0.33 ± 0.01 b
Hydropriming 24 h	3.49 ± 0.25 d	0.33 ± 0.01 b
Osmopriming12 h	4.66 ± 0.16 ab	0.42 ± 0.01 a
Osmopriming 24 h	4.70 ± 0.16 a	0.42 ± 0.01 a
Halopriming 12 h	4.44 ± 0.16 bc	0.40 ± 0.01 a
Halopriming 24 h	4.54 ± 0.15 abc	0.40 ± 0.01 a
Hormopriming 12 h	4.42 ± 0.17 c	0.40 ± 0.01 a
Hormopriming 24 h	4.47 ± 0.17 bc	0.40 ± 0.01 a
	(B) DSR method	
Conventional DSR	3.79 ± 0.1 b	0.37 ± 0.01 b
Soil mulch DSR	4.59 ± 0.1 a	0.40 ± 0.01 a
	ANOVA (p-value)	
Priming (P)	<0.0001	<0.0001
DSR method (M)	<0.0001	<0.0001
P × M interaction	NS	NS

Within column for each factor, means followed by the same small letter are not different at the 0.05 level of probability using Tukey's HSD test.

3.3.4. Yield and Yield Attributes

In both years, hydropriming and osmopriming did not differ from control in panicle numbers (Tables 8 and 9). In contrast, halopriming and hormopriming did not differ between themselves but had 7–11% higher panicle numbers than control, hydropriming, and osmopriming treatments in both years. Overall, panicle numbers were higher in 2018 than in 2019 (505 versus 418 m^{-2}), and also in the conventional DSR method than in *vattar*/soil mulch DSR in 2019 (431 versus 404 m^{-2}).

Table 8. Yield attributes (panicle no., panicle weight, and 1000-grain weight) of rice as affected by different seed priming in conventional DSR establishment method during 2018 at Ludhiana, India.

Treatment	**Panicles (No. m^{-2})**	**Panicle Weight (g)**	**1000-Grain Weight (g)**
Control (dry seed)	480 ± 4.6 b	3.08 ± 0.11 a	21.7 a ± 0.2
Hydropriming 12 h	485 ± 2.7 b	3.08 ± 0.08 a	21.7 a ± 0.2
Hydropriming 24 h	481 ± 0.7 b	3.11 ± 0.06 a	21.7 a ± 0.03
Osmopriming12 h	489 ± 5.8 b	3.15 ± 0.01 a	21.7 a ± 0.2
Osmopriming 24 h	487 ± 3.7 b	3.16 ± 0.01 a	21.7 a ± 0.2
Halopriming 12 h	523 ± 2.7 a	3.13 ± 0.04 a	21.7 a ± 0.7
Halopriming 24 h	524 ± 4.7 a	3.11 ± 0.02 a	21.7 a ± 0.9
Hormopriming 12 h	523 ± 5.3 a	3.11 ± 0.11 a	21.6 a ± 0.6
Hormopriming 24 h	525 ± 4.7 a	3.11 ± 0.07 a	21.7 a ± 0.3

Within column, means followed by the same letter are not different at the 0.05 level of probability using Tukey's HSD test.

The panicle weight and 1000-grain weight were not affected by priming treatments in both years (Tables 8 and 9). In 2019, (Table 9), 1000-grain weight was also not affected by DSR methods but panicle weight was influenced by DSR methods with 17% higher panicle weight in *vattar*/soil mulch DSR than conventional DSR (3.30 versus 2.83 g·panicle^{-1}).

Filled grains per panicle only in 2019, and unfilled grains and sterility in both years, were significantly affected by priming treatments (Tables 10 and 11). These parameters were also significantly influenced by DSR methods; however, the interaction effect (priming × DSR method) was non-significant (Table 10). In 2019, filled grains per panicle in osmopriming, halopriming, and hormopriming treatments were 3% to 6% higher than in control and hydropriming treatments. Filled grains per panicle were also higher (22 grains panicle^{-1} or 18%) in *vattar*/soil mulch DSR than in the conventional DSR method (Table 11).

Table 9. Yield attributes (panicle no., panicle weight, and 1000-grain weight) of rice as affected by different seed priming and DSR establishment methods during 2019 at Ludhiana, India.

Treatment	Panicles (No. m^{-2})	Panicle Weight (g)	1000-Grain Weight (g)
	(A) Priming treatment		
Control (dry seed)	400 ± 9.1 b	3.00 ± 0.12 a	21.4 ± 0.1 a
Hydropriming 12 h	399 ± 7.1 b	3.00 ± 0.12 a	21.4 ± 0.3 a
Hydropriming 24 h	404 ± 7.1 b	2.99 ± 0.13 a	21.4 ± 0.2 a
Osmopriming 12 h	402 ± 5.0 b	3.16 ± 0.11 a	21.6 ± 0.2 a
Osmopriming 24 h	401 ± 9.9 b	3.17 ± 0.1 a	21.5 ± 0.3 a
Halopriming 12 h	438 ± 5.2 a	3.06 ± 0.15 a	21.5 ± 0.3 a
Halopriming 24 h	436 ± 7.1 a	3.07 ± 0.15 a	21.5 ± 0.2 a
Hormopriming 12 h	439 ± 7.2 a	3.08 ± 0.12 a	21.4 ± 0.3 a
Hormopriming 24 h	441 ± 6.1 a	3.07 ± 0.13 a	21.5 ± 0.4 a
	(B) DSR method		
Conventional DSR	431 ± 3.5 a	2.83 ± 0.02 b	21.3 ± 0.1
Soil mulch DSR	404 ± 4.6 b	3.30 ± 0.04 a	21.6 ± 0.1
	ANOVA (*p*-value)		
Priming (P)	<0.0001	NS	NS
DSR method (M)	<0.0001	<0.0001	NS
P × M interaction	NS	NS	NS

Within column for each factor, means followed by the same small letter are not different at the 0.05 level of probability using Tukey's HSD test.

Table 10. Yield attributes (filled and unfilled grains per panicle and sterility %) of rice as affected by different seed priming in conventional DSR establishment method during 2018 at Ludhiana, India.

Treatment	Number of Filled Grain Per Panicle	Number of Unfilled Grain Per Panicle	Sterility (%)
Control (dry seed)	140 ± 3.7 a	25 ± 1.0 a	15 ± 0.7 a
Hydropriming 12 h	141 ± 4.5 a	25 ± 1.2 a	15 ± 1.0 ab
Hydropriming 24 h	140 ± 1.6 a	26 ± 0.4 a	15 ± 0.1 a
Osmopriming12 h	146 ± 1.3 a	20 ± 0.6 b	12 ± 0.2 bc
Osmopriming 24 h	146 ± 0.6 a	20 ± 0.4 b	12 ± 0.2 c
Halopriming 12 h	144 a ± 6.9	21 ± 1.9 ab	13 ± 0.5 abc
Halopriming 24 h	144 ± 5.3 a	21 ± 1.2 ab	13 ± 0.7 abc
Hormopriming 12 h	145 ± 4.8 a	20 ± 0.8 b	12 ± 0.5 bc
Hormopriming 24 h	144 ± 1.7 a	20 ± 1.4 b	12 ± 0.9 bc

Within column, means followed by the same small letter are not different at the 0.05 level of probability using Tukey's HSD test.

Unfilled grains panicle^{-1} was 20% lower in osmopriming and hormopriming treatments compared to control and hydropriming treatments in 2018, whereas halopriming treatments did not differ from any of the priming treatments and the control (Tables 10 and 11). In 2019, unfilled grains panicle^{-1} was >30% lower in osmopriming treatments, and 25% lower in halopriming and hormopriming treatments compared to control and hydropriming treatments. Unfilled grains panicle^{-1} was 23% lower in *vattar*/soil mulch DSR than in the conventional DSR method.

Sterility % was the highest in control and hydropriming treatments (15% in 2018, and 15–16% in 2019), whereas it was significantly lower in osmopriming (12% in 2018, and 10% in 2019) and hormopriming (12% in both years). Halopriming treatments did not differ in sterility % from the control and hydropriming in 2018 but sterility was lower in halopriming treatments than in control and hydropriming in 2019. Like unfilled grain, sterility % was 33% lower in *vattar*/soil mulch DSR than in the conventional DSR method. Grain, straw yield, and harvest index was not affected by the DSR establishment method (*vattar*/soil mulch DSR and conventional DSR) but during both years, priming treatments significantly affected rice yields (Tables 12 and 13). In both years, halopriming and hormopriming, irrespective of duration of priming (12 or 24 h), produced higher rice yields than the control. In 2018, compared to the control (dry and non-primed seed), halopriming and hormopriming treatments resulted in 7–11% higher yields and osmopriming treatments resulted in 4% higher yield. Like 2018, rice yields in 2019 were also 9–11% higher under halopriming and hormopriming treatments than the control. In contrast, rice yields under osmopriming treatments did not differ from that of the control. In both years, the yields of hydropriming treatments and the control did not differ. Overall, yields were higher in 2018 compared to 2019 (8.5 versus 7.4 tha^{-1}). The interaction effects of priming treatments and DSR establishment methods were non-significant (Table 13).

Table 11. Yield attributes (filled and unfilled grains per panicle and sterility %) of rice as affected by different seed priming and DSR establishment methods during 2019 at Ludhiana, India.

Treatment	Number of Filled Grain Per Panicle	Number of Unfilled Grain Per Panicle	Sterility (%)
(A) Priming treatment			
Control (dry seed)	131 ± 5.4 b	24 ± 1.8 a	16 ± 1.4 a
Hydropriming 12 h	130 ± 5.2 b	24 ± 1.5 a	15 ± 1.3 a
Hydropriming 24 h	130 ± 5.3 b	24 ± 1.5 a	15 ± 1.2 a
Osmopriming12 h	138 ± 4.9 a	16 ± 1.2 b	10 ± 1.0 b
Osmopriming 24 h	138 ± 4.6 a	15 ± 1.3 b	10 ± 1.0 b
Halopriming 12 h	135 ± 4.8 a	18 ± 1.0 b	12 ± 1.0 b
Halopriming 24 h	136 ± 5.6 a	18 ± 1.4 b	12 ± 1.2 b
Hormopriming 12 h	135 ± 5.9 a	18 ± 1.3 b	12 ± 1.2 b
Hormopriming 24 h	136 ± 5.2 a	18 ± 1.3 b	12 ± 1.1 b
(B) DSR method			
Conventional DSR	124 ± 0.9 b	22 ± 0.7 a	15 ± 0.5 a
Soil mulch DSR	146 ± 1.0 a	17 ± 0.7 b	10 ± 0.4 b
ANOVA (*p*-value)			
Priming (P)	0.0069	<0.0001	<0.0001
DSR method (M)	<0.0001	<0.0001	<0.0001
P × M interaction	NS	NS	NS

Within column for each factor, means followed by the same small letter are not different at the 0.05 level of probability using Tukey's HSD test.

Table 12. Grain yield, straw yield and harvest index of DSR as affected by different seed priming in conventional DSR establishment method during 2018 at Ludhiana, India.

Treatment	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Harvest Index (%)
Control (dry seed)	8.1 ± 0.04 d[2]	10.3 ± 1.1 a	44 ± 2.2 a
Hydropriming 12 h	8.2 ± 0.04 cd	10.4 ± 0.7 a	44 ± 1.8 a
Hydropriming 24 h	8.3 ± 0.03 cd	10.5 ± 1.1 a	44 ± 2.1 a
Osmopriming12 h	8.4 ± 0.03 bc	10.6 ± 0.3 a	44 ± 0.7 a
Osmopriming 24 h	8.4 ± 0.12 bc	10.5 ± 0.3 a	45 ± 0.4 a
Halopriming 12 h	8.9 ± 0.08 a	10.8 ± 1.1 a	45 ± 2.8 a
Halopriming 24 h	9.0 ± 0.04 a	10.9 ± 1.0 a	45 ± 2.5 a
Hormopriming 12 h	8.7 ± 0.1 ab	10.8 ± 1.0 a	45 ± 2.7 a
Hormopriming 24 h	8.9 ± 0.07 a	10.9 ± 0.9 a	45 ± 1.8 a

Within column, means followed by the same small letter are not different at the 0.05 level of probability using Tukey's HSD test.

Table 13. Grain yield, straw yield and harvest index of DSR as affected by different seed priming and DSR establishment methods during 2019 at Ludhiana, India.

Treatment	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Harvest Index (%)
(A) Priming treatment			
Control (dry seed)	7.0 ± 0.08 c	9.0 ± 0.6 a	44 ± 1.3 a
Hydropriming 12 h	7.2 ± 0.09 c	9.1 ± 0.4 a	44 ± 1.2 a
Hydropriming 24 h	7.2 ± 0.06 c	8.9 ± 0.2 a	45 ± 0.7 a
Osmopriming12 h	7.3 ± 0.03 bc	9.1 ± 0.1 a	45 ± 0.3 a
Osmopriming 24 h	7.3 ± 0.05 bc	9.1 ± 0.1 a	45 ± 0.5 a
Halopriming 12 h	7.6 ± 0.05 ab	9.3 ± 0.2 a	45 ± 0.6 a
Halopriming 24 h	7.7 ± 0.06 a	9.4 ± 0.2 a	45 ± 0.5 a
Hormopriming 12 h	7.7 ± 0.07 a	9.4 ± 0.2 a	45 ± 0.6 a
Hormopriming 24 h	7.8 ± 0.06 a	9.5 ± 0.3 a	45 ± 0.6 a
(B) DSR method			
Conventional DSR	7.5 ± 0.05 a	9.4 ± 0.1 a	44.4 ± 0.3 a
Soil mulch DSR	7.4 ± 0.07 c	9.0 ± 0.1 a	45.1 ± 0.3 a
ANOVA (*p*-value)			
Priming (P)	<0.0001	NS	NS
DSR method (M)	NS	NS	NS
P × M interaction	NS	NS	NS

Within column for each factor, means followed by the same small letter are not different at the 0.05 level of probability using Tukey's HSD test.

4. Discussion

Seed priming is a pre-sowing treatment that modifies the seed's physiological and metabolic state and enables seed to germinate more efficiently and tolerate abiotic stresses better, leading to improved emergence, uniform and faster crop establishment, and higher early vigor [40]. Risks of poor and uneven crop establishment and higher weed infestations leading to lower yields are major bottlenecks in wide-scale adoption of DSR [9,20]. Therefore, seed priming techniques were evaluated to identify options that can reduce the risk of poor or uneven crop establishment, leading to improved performance of DSR. Although priming effect has been studied widely in different crops, limited studies have been conducted in DSR under Indian conditions where DSR is established using two methods—conventional DSR and *vattar*/soil mulch DSR. Moreover, the majority of the previous seed priming studies were conducted under laboratory conditions with a focus on seed germination/emergence attributes, and early growth and vigor, but very limited studies have evaluated priming impact at later stages of growth and on grain yield [48]. This study examined the impact of priming treatments, not only on germination/emergence and early growth parameters, but also on yield attributes and rice grain yield. Furthermore, to our knowledge, this is the first study which has assessed the effect of priming on *vattar*/soil mulch DSR.

4.1. Laboratory Study

Results from laboratory experiments showed that halopriming with 2% KNO_3 and hormopriming with 50 ppm of GA_3 improved seed germination, root and shoot length, and seedling vigor index 1 and 2, but seedling dry weight at 14 DAS was not affected compared to the control (non-primed dry seed) (Table 1). The reason for no effect of halopriming and hormopriming on seedling dry weight despite positive impact on root and shoot length could be that the experimental duration was too short (14 days) to reflect impact on dry weight; if the experiment was longer, the effects could have been reflected in dry weight. An increasing tendency in dry weight in these priming treatments can be noted (Table 1), although it was not statistically different within the 14 days of the experimental period. In this study, hydropriming did not affect any of these parameters, whereas osmopriming improved root and vigor index 1 but did not affect germination, shoot length, total dry weight, and vigor index 2 (Table 1). Similar to our results, another study from the same geography (Punjab, India) also reported no significant effect of hydropriming on time taken to 50% germination of rice [49], whereas in other research, hydropriming resulted in rapid germination of both coarse and fine-rice varieties [50]. The possible cause of no response of hydropriming in this study could be because the seed used in the study was of good quality with low dormancy and high germination percentage (89%) even without any priming treatment. By comparison, the study that found higher germination rate and germination percentage reported that the improved germination in their study could be attributed to breakdown of dormancy by hydropriming because fresh seeds were used in the experiment [50]. In contrast to our results, other studies reported a positive impact of hydropriming on radical length and seedling vigor [49,50]. Similar to our study, many other researchers also observed the positive impact of halopriming with KNO_3 and hormopriming with GA_3 on seed germination, root and shoot length, and early vigor in rice [51–53]. In general, many other studies have reported positive effects of seed priming treatments on rice seed germination under normal and stress conditions [37,41,46,53,54].

4.2. Field Study

Results of the field study suggest that halopriming with 2.0% potassium nitrate and hormopriming with 50 ppm GA_3 have good potential to improve crop establishment (Tables 2 and 3), growth (Tables 4 and 5), and yields of rice (Tables 12 and 13) in DSR systems. The higher rice yields in halopriming and hydropriming were attributed to rapid emergence, higher establishment, better root and crop growth, and improvement in yield attributes compared to the non-primed control treatment (Tables 2–11). The faster, uniform, and higher seedling emergence and growth are crucial in DSR, and determine crop establishment, crop–weed competition, and yield [20,48,49]. It has been reported that rapidly germinating seedlings could emerge and produce a deep root system leading to uniform and good crop establishment for attaining potential yield levels [23]. Rapid, uniform, and good crop establishment with early vigor can also improve the competitiveness of rice against weeds leading to better yield, especially in DSR where weeds are one of the major constraints in attaining optimal DSR yields [9,55]. Many researchers have reported advantages of seed priming in terms of faster emergence, early vigor, crop establishment, crop growth, and yields in rice under weed stress [55], chilling stress [48], flooding stress [56] and normal/no stress conditions [37,40,41,49]. The improvement in germination or emergence, early vigor, and higher tolerance to stress conditions (drought, salinity, cold, etc.) was reported because of improved activities of α-amylase, superoxide dismutase (SOD), catalase (CAT), and scavenger reactive oxygen species, resulting in carbohydrate mobilization and decrease in lipid peroxidation [37,42,55], and increase in cell division and expansion of embryonic axis [40,57,58].

The increase in root length and shoot biomass due to hydropriming (24 h soaking) has been reported [59]. Similarly, others also reported a significant effect of hydropriming on growth and rice yield [49,60]. In our study, however, no significant enhancement in germination/emergence, growth, or yield was observed under hydropriming treatment. This may be because the hydropriming technique may result in an unequal degree of seed hydration, thus leading to lack of simultaneous metabolic activation within seeds followed by unsynchronized emergence, as reported by other researchers [61]. These results also highlight the important of evaluating priming treatments under different locations to generate more consensus and evidence.

Osmopriming with PEG in this study showed variable results with improvement in rice yield (4%) in 2018 only (Table 12), whereas its effect was consistent in both years on improvement in root mass density (Tables 6 and 7), SPAD value (Tables 4 and 5), reduction in spikelet sterility, and unfilled grain panicle^{-1} (Tables 10 and 11), and showed no effect on crop emergence rate and final crop establishment (Tables 2 and 3). The higher SPAD value in osmopriming treatment could be attributed to higher root mass density, which might have improved the availability of resources including water and nutrients to crop plants through higher uptake compared to the control treatment (non-primed dry seed). The improvement in root growth, and uptake of water and nutrients leading to higher SPAD value, may have reduced the spikelet sterility. This enhancement in root mass density is likely attributed to the stress imprints imposed during seed osmopriming on reduced availability of water to seeds. Other researchers have also reported positive impact of osmopriming with PEG on better root growth [59,62], and on germination, emergence, and seedling establishment in several crops, including rice [28,62–67] under stress conditions. Osmopriming improves stress tolerance by strengthening the antioxidant system (e.g., ascorbate peroxidase (APX), peroxidase (POD), CAT, and SOD) and osmotic regulation [27]. Our study was conducted under fully irrigated conditions which could be the reason that we did not observe an osmopriming effect on emergence and early growth (Tables 1–3). DSR can experience some mild moisture stress even under irrigated systems because the fields in DSR are not kept flooded, as is the case in transplanted rice. This could be one of the reasons for the positive impact of osmopriming on root growth and SPAD value.

Similar to our results, many other researchers also observed a positive impact of halopriming using KCl, $CalCl_2$, and KNO_3, and of hormopriming using GA_3 on germination and emergence attributes, early growth, and grain yield in rice and other crops under normal and stress (salinity, drought) conditions [37,65,68,69].The higher emergence in hormopriming with GA_3 could partially be because it stimulates elongation of mesocotyl and coleoptile, and thereby withstands adverse conditions, such as deeper seeding or flooding stress during emergence [52,54]. In this study, across all priming treatments, we did not find a significant effect of priming duration (12 or 24 h). This may be ascribed to the fact that soaking of seed for 12 h in priming material might be sufficient to bring about the necessary changes in physiological processes responsible for the beneficial effect of priming.

4.3. Conventional DSR versus Vattar/Soil Mulch DSR

Irrespective of priming treatments, total emergence was lower in *vattar*/soil mulch DSR than conventional DSR. Additionally, rate of emergence, time to start and completion of emergence (Table 3), and days taken to 50% flowering (Table 5) were slower/delayed in *vattar* DSR compared to conventional DSR. This could be due to lower moisture in *vattar* DSR than conventional DSR at the early crop establishment phase because the first irrigation was withheld for 21 days in *vattar*/soil mulch DSR. The lower tiller density (Table 5 in *vattar* DSR compared to conventional DSR could be due to the overall lower plant population (71 versus 85 m^{-2}; Table 2). In contrast, SPAD value in *vattar*/soil mulch DSR was higher than that in conventional DSR (Table 5). This could be attributed to higher root mass density (Table 7), which may be due to low soil moisture in *vattar*/soil mulch DSR in the first 20 days compared to conventional DSR, leading to more root development and higher uptake of nutrients and water. Despite lower tiller density in *vattar*/soil mulch DSR than conventional DSR, grain yield of *vattar*/soil mulch DSR did not differ from that of conventional-DSR. This was because lower tiller density was compensated for by higher filled grain $panicle^{-1}$, lower unfilled grain $panicle^{-1}$, lower spikelet sterility, and higher panicle weight compared to conventional DSR. These results suggest that both conventional DSR and *vattar* DSR are equally productive but *vattar*/soil mulch DSR offers more potential to save irrigation water by reducing early irrigation requirements for the first 20 days by conserving soil moisture [16,17]. It has also been reported that *vattar*/soil mulch DSR reduces early weed pressure by 40–60% compared to conventional DSR [16]. Therefore, *vattar*/soil mulch DSR should be promoted over conventional DSR to conserve irrigation water and to minimize risk of weed infestation in DSR.

5. Conclusions

Our results demonstrated that halopriming with 2% KNO_3 and hormopriming with 50 ppm GA_3 can improve the performance of DSR by improving crop establishment (faster and higher crop emergence), seedling vigor, root density biomass, yield attributes, and grain yield compared to DSR without seed priming. These results also indicate that halopriming and hormopriming can help overcome the problem of poor and uneven crop establishment in DSR systems, thereby helping attain optimal yield of both conventional DSR and *vattar*/soil mulch DSR. Osmopriming with PEG increased root mass density and crop growth (higher SPAD value), and reduced spikelet sterility and unfilled grains, but its impact on yield was inconsistent, with a positive impact in 2018 but no effect in 2019.These findings indicate that halopriming and hormopriming—an easy and affordable technique—should be promoted to make DSR more successful. Further research to quantify the positive impact of priming techniques, especially in farmers' fields under varying conditions (favorable and stress), would help scaling these seed invigoration techniques in DSR-based systems in India.

Supplementary Materials: The supplementary materials are available online at https://www.mdpi.com/article/10.3390/agronomy11050849/s1, Supplementary Figure S1: Experimental layout in 2018 (A) and 2019 (B); Supplementary Table S1: Summary of crop management and field operations in field study during 2018 and 2019,

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Abbreviations

h	hour
DSR	direct-seeded rice
Conv-DSR	conventional dry direct-seeded rice

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