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Water Stress Induced Changes in Root Traits and Yield of Irrigated Rice under Subtropical Condition

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Abstract: The presence of water or the degree of soil saturation has a direct impact on the root development and function in rice. In this regard, a pot investigation was performed to test the response of root traits and yield components of *boro* (irrigated) rice. Three *boro* rice varieties named Binadhan-10, Hira-2 and BRRI dhan 29 were grown at four irrigation regimes, viz. continuous flooding (CF), saturation (S), 75% S and 50% S at Bangladesh Agricultural University, Mymensingh, Bangladesh, throughout the *boro* period of 2020–2021. The study was replicated three times by employing a completely randomized design (CRD) method. The study revealed a drastic decline in root attributes at 75% and 50% S. A significant increase in root number (RN), root length (RL), root volume (RV), total dry matter (TDM) and grain yield (GY) under S condition followed by CF was observed. Binadhan-10 exhibited the largest scores of RN (359.00), RL (1577.83 cm) and RV (8.34 cm^3 $hill^{-1}$) at 80 DAT under S condition. Root attributes and GY were found to be substantially and positively associated in all observations. Binadhan-10 performed best with regard to seed output (26.13 g pot^{-1}) under S condition. S condition increased the yield of Binadhan-10 in CF, 75% S and 50% S by 4.06%, 23.72% and 46.00%, respectively.

Keywords: root porosity; leaf area index; total dry matter; correlation matrix; harvest index

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1. Introduction

Only 11% of the world's land surface is agriculturally arable, but it uses around 70% of the water extracted globally [1]. The competition between food requirements and freshwater supply is becoming more and more intense because of demographic expansion and climate changes [2,3]. Water is becoming very limited, and Asia's per-capita water sources are forecasted to decline by around 15 to 45% by 2025 compared to the levels found in 1990 [4]. Rice (oryza sativa L.) is a key food stuff for a significant percentage of the global population, and requires a huge amount of water for its production [5]. Irrigated lowland rice, the primary base of rice availability, continues to be crucial to global food security [6]. Asian countries generate over 90% of global rice, while over 90% of the irrigation water is consumed there [7]. For the sustainability of agriculture and water-food security, "more rice with less water" is essential [8]. The real amount of water needed to grow rice is substantially less than what has historically been used for this purpose [9]. Around 2000 litres of fresh water is required to produce 1 kg of paddy grains [10]. Consequently, agricultural water saving is a crucial and effective method of reducing water stress, especially in arid and semi-arid countries where there is a significant water shortage [11,12].

The root systems are essential to plant growth, which controls the growth of the shoots and the yield [13]. The primary function of a plant's roots is to take up water and minerals from the soil [14]. Root development, viability, functionality, and plant growth are all significantly influenced by water stress [15]. Understanding water stress, its occurrence, its acquisition, and water stress adaptation and tolerance are all greatly aided by the study of rice roots [16]. Roots with higher penetration rates are better able to get water from deeper soil layers [17]. Increased rooting depth, root shoot ratio, root density, root number, and ability to penetrate through hardpans all play a role in the rice root systems' ability to withstand drought [18]. Rice root systems are significantly affected by water management strategies. Occasional irrigation was reported to have a positive impact on root length and entire root biomass [19,20]. Furthermore, the root impedance, the types of competing crops already present, and the amount of growing area available are all strongly correlated with root size [21]. In addition, roots also directly contribute to a plant's health, development and survivability by absorbing moisture and minerals [22,23]. Furthermore, roots serve as a site for hormone production and consumption, which affects the hormonal regulation of the entire plant [24,25]. Rice grown under flooded conditions produces significantly more roots than rice grown under supplemental irrigation but without flood, at least throughout reproductive growth [26].

Flooded rice typically produces higher yields and productivity. However, the productivity of irrigated paddy starts to decrease as soon as the field's moisture levels go below saturation [27]. Several studies have investigated how ground moisture regimes regulate the overall morphology of the root scheme. These investigations proved that the root system morphology and soil water uptake are connected [28,29]. Under upland agriculture, the dispersal of rice roots is generally lower in the surface soil and higher in the subsoil compared to under conventional flooding irrigation [30]. But, under submerged conditions, proper percolation increases rice root porosity, which is linked to longer roots, a rise in the root and shoot biomass, and a greater level of nutritional composition in aboveground parts [31]. Farmers prefer to regularly flood their fields as a precaution against water shortages. In addition, the practice of systems of rice intensification technique in rice cultivation has resulted in a yield increase of 20% in rice and net income of 44.50% above the usual cultivation [32]. However, when rice was cultivated under a saturated soil condition, a decreased yield and production losses of 16–34% was reported [33,34]. Insufficient water during vegetative growth had no substantial impact on rice yields, whereas water scarcity during reproductive growth reduced the yields of flooded rice by 20–70% [35].

One of the keys to enhancing rice output in paddy fields is effective water management. Rice plants that experience water stress will produce less rice. Rolling and burning of rice foliage, declined rice tillers, stunted crops, late blooming, and unfilled grains are typical signs of moisture stress [36]. Accordingly, we need to consider how to replace the current irrigation system for rice production so that we can continue to grow rice while using less water. In water-conserving or water-scarce rice lands, rooting ability and successive plant establishment therefore becomes crucial. Even though numerous investigations have been attempted to evaluate lowland water and soil productivity in non-inundated, water-saving situations [37,38], research on rooting capacity, specifically on genetic heterogeneity worldwide, is rare. In this experiment, our principal goal is to ascertain how well rice cultivars can generate roots under different irrigation regimes, followed by an assessment of how rooting potential influences growth indices and rice yield.

2. Materials and Methods

2.1. Experimental Site and Plant Materials

The study was executed at the net house of the Agronomy Department, Bangladesh Agricultural University, Mymensingh, Bangladesh (latitude: 24°42′55″, longitude: 90°25′47″) throughout the *boro* period of 2020–2021. The area is situated within the Old Brahmaputra

Floodplain Agro-ecological Zone (AEZ 9) and contains non-calcareous dark grey floodplain soil [39]. Three *boro* rice varieties–BRRI dhan29 (V_1, inbred), Binadhan-10 (V_2, inbred) and Hira-2 (V_3, Hybrid)—were used as research material and purchased from Bangladesh Rice Research Institute (BRRI), Bangladesh Institute of Nuclear Agriculture (BINA) and the domestic markets, respectively. These varieties were grown from January to May in the year cited.

2.2. Experimental Design and Crop Management

The investigation was carried out using the completely randomized design (CRD) with four different irrigation regimes (treatments), i.e., I_1—continuous flooding (CF), I_2—saturation (S), I_3—75% S and I_4—50% S, and three replications. Individual plastic containers (30 L with 35 cm width) were filled with 25 kg of sun-dried, crushed, and well-mixed soil. To maintain saturation, a pot with soil was weighed at the beginning, then a pot containing soil with pores was put in a bowl containing water for the whole night. Afterwards, the weight was taken, and a calculation was carried out for absorbing water, and was treated as saturation. After that, water was calculated for 75% and 50% S. Before transplanting the seedlings in the pot, irrigation treatments were applied in a drip system and continued up to harvest, maintaining different saturation levels on a daily weight basis (gravimetric method). For the pot experiment, the respective doses of urea, triple super phosphate (TSP), muriate of potash (MoP), gypsum and $ZnSO_4$ of 8.14, 2.5, 3.25, 2.81 and 0.09 g pot^{-1} [40] were applied. One-third of urea and the entire amount of the other fertilizers were spread after preparing the pot. The leftover urea (5.43 g) was applied through the top dressing method at 20 and 40 days after transplanting (DAT). The studied varieties were placed in random order to avoid bias. The seedlings of the specified varieties were transplanted into the pot after being cultivated in a nursery bed for 40 days. Weeds were occasionally seen during the vegetative phase, particularly during the beginning phases, and were manually removed. There were no noxious insects identified.

2.3. Determination of Root Phenological and Physiological Traits

Root phenological traits were examined at 20, 40, 60 and 80 DAT and harvest phases. Three plants per pot were pulled up and the calculated values of various attributes were averaged.

2.3.1. Root Number (RN)

After watering, deep digging was carried out around the base of the plants to uproot them. After being put in a 1 mm mesh sieve, the soil was washed away by rinsing the root samples with flowing tap water [41]. Manual counting was carried out to calculate RN plant^{-1} at 20, 40, 60 and 80 DAT and harvest stages.

2.3.2. Root Length (RL, cm)

RL was measured at 20, 40, 60 and 80 DAT DAT and the harvest phase from raw specimens [42].

2.3.3. Root Volume (RV, cm^3 hill^{-1})

The root masses were put into a measuring tube filled with a predetermined quantity of water to determine RV at 20, 40, 60 and 80 DAT and harvest stages [43]. The increment in water height was quantified and stated as cm^3 hill^{-1}.

2.3.4. Root Porosity (RP, %)

The roots, sealed in airtight polythene bags, were stored in water to maintain their original temperature. The pycnometer vials with and without water were weighed and recorded. The vial with water was checked for temperature. The roots were carefully wiped with tissue paper to transfer excess water to the blotting paper. Using an electronic weighing scale, the weight of the roots was taken. The sample roots were immersed in a vial containing freshwater. Submerged roots in the vial were managed with the sterilized needle to discharge the trapped air effervescence. After weighing the water and entire fresh roots with an electronic weighing scale, the roots were taken out of the vial and blended with a glass mortar and pestle. The pycnometer vial was then entirely saturated with the total homogenate. The homogenate and vial were weighed after being brought to ambient temperature. Porosity was determined by the procedure described below [44]:

$$\%\ \text{porosity} = \frac{W_{hr+w} - W_{fr+w}}{W_w + W_{fr} - W_{fr+w}} \tag{1}$$

Here, W_{hr+w} = weight of blended roots and water carrying pycnometer vial, W_{fr+w} = weight of fresh roots and water carrying pycnometer vial, W_w = water carrying pycnometer vial, W_{fr} = weight of fresh roots.

2.3.5. Plant Physiological Traits

The leaves of three different plants were taken, rinsed with water, and afterwards dried with tissue paper, in order to calculate LAI. An estimate of the area of newly-formed green leaves using a leaf area meter (Model LICOR 3000, USA) was presented in cm^2 $plant^{-1}$.When the leaves were arranged on the roller, extra attention was paid to ensure that none of them overlapped. The following formula [45] was used to calculate LAI.

$$\text{LAI} = \frac{\text{Total leaf area } (\text{cm}^2)/\text{plant}}{\text{Ground area } (\text{cm}^2)\ /\text{plant}} \tag{2}$$

The crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate (NAR) were assessed depending on the dry mass deposited by plants over the time the methods were carried out [46].

Crop Growth Rate (CGR, gm^{-2} day^{-1})

The following formula was used to calculate the CGR.

$$\text{CGR} = \frac{1}{\text{SA}} \times \frac{\text{Wii} - \text{Wi}}{\text{Tii} - \text{Ti}} \tag{3}$$

Here, Wi and Wii indicate dry mass (g $hill^{-1}$) during the period Ti and Tii, respectively. SA = Surface area covered by the plant.

Relative Growth Rate (RGR, mg g^{-1} day^{-1})

RGR was estimated with the following procedure:

$$\text{RGR} = \frac{\text{loge Wii} - \log e\text{Wi}}{\text{Tii} - \text{Ti}} \tag{4}$$

Here, Wi and Wii indicate dry mass (g $hill^{-1}$) during period Ti and Tii, respectively. Loge (Natural logreading) = 2.3

Net Assimilation Rate (NAR, mg m^{-2} day^{-1})

The standardized methods mentioned below were used to calculate NAR:

$$\text{NAR} = \text{CGR} \times \frac{\text{loge Lii} - \text{loge Li}}{\text{Lii} - \text{Li}} \tag{5}$$

Here, Li and Lii indicate leaf area (m^2) during the period Ti and Tii, respectively. CGR = crop growth rate (g m^{-2} day^{-1}).

Total Dry Matter (TDM)

Three plants per treatment were picked at their individual growing periods. Separated leaves, stalks and panicles were oven-dried and then the weight was measured using an electronic balance. The recorded dry mass of leaves, culms, and panicles was then calculated to get mean data (g plant^{-1}). TDM was determined by adding the dry masses of plant components.

2.4. Yield and Yield Components

The rice plants in the pots were harvested, while 90% of the seeds were ripened. After adjusting 14% moisture content, the rice seed weight was evaluated and recorded as g pot^{-1}. Data for plant height (PH), number of effective tiller plant^{-1}(ET), panicle number (PN), panicle length (PL), number of grain panicle^{-1} (GP), 1000-grain weight (TGW), grain yield (GY) and straw yield (SY) for each plant were recorded. The harvest index (HI, %) was assessed at the reaping phase of the plants by dividing the grain biomass into the entire grain biomass plant^{-1} [47]

2.5. Statistical Analysis

The two-way analysis of variance (ANOVA) test was carried out using the statistical package JMP Pro 16 (SAS Institute Inc., Cary, NC, USA), and the mean differences were compared through Tukey's honestly significant difference (HSD) post hoc test at $p < 0.05$ and $p < 0.01$ probability levels. Sigma Plot v14 (Systat Software, Inc., San Jose, CA, USA, www.systatsoftware.com, (accessed on 30 August 2022) and R (R for windows 4.1.2) software were used for the data visualization and correlation matrix [48].

3. Results

3.1. Root Morphological Traits, Total Dry Matter and Leaf Area Index

The irrigation regimes exerted a substantial impact on the RN of the three rice varieties (Figure 1). RN increased from the beginning of the crop stage and continued up to maturity. The maximum increase of RN was found at 60–80 DAT. Binadhan-10 yielded the highest number of roots of 36.67, 110.83, 188.83, 287.83 and 289.25 at 20, 40, 60, 80 DAT and at the harvest stage, respectively. Under S condition, the highest number of roots of 43.33, 137.00, 226.67, 352.78 and 353.22 was found at 20, 40, 60, 80 DAT and the harvest stage, respectively. RN was significantly affected by the interaction effect of irrigation regime and variety. At 80 DAT, the RN with S condition for Binadhan-10 was 4.87, 33.00 and 98.34% higher, respectively, than CF, 75% and 50% S.

Similar to RN, irrigation regimes also had significant effects on the RL of the three rice varieties (Figure 1). The greatest RL was observed in Binadhan-10, and were 100.25, 542.75, 891.83, 1266.67 and 1268.67 cm at 20, 40, 60, 80 DAT and at harvest stage, respectively. The highest RL of 122.11, 663.11, 1090.67, 1569.22 and 1572.22 cm was found at 20, 40, 60, 80 DAT and at harvest under S condition, respectively, whereas the lowest value was observed at 50% S. In the case of interaction, at 80 DAT, the RL with S condition for Binadhan-10 was 2.05, 34.20 and 105.29% higher than CF, 75% and 50% S, respectively.

The greatest value of RP was observed in Binadhan-10 and was 13.97, 15.44, 18.58, 21.34 and 21.35% at 20, 40, 60, 80 DAT and at the harvest stage, respectively. RP varied significantly under different irrigation regimes. CF produced the highest value of root porosity at every observation, whereas the lowest value was observed in 50% S. In the case of interaction, Binadhan-10 with CF had the highest value of RP and were 16.80, 20.17, 23.79, 24.24 and 24.28% at 20, 40, 60, 80 DAT and at the harvest stage, respectively.

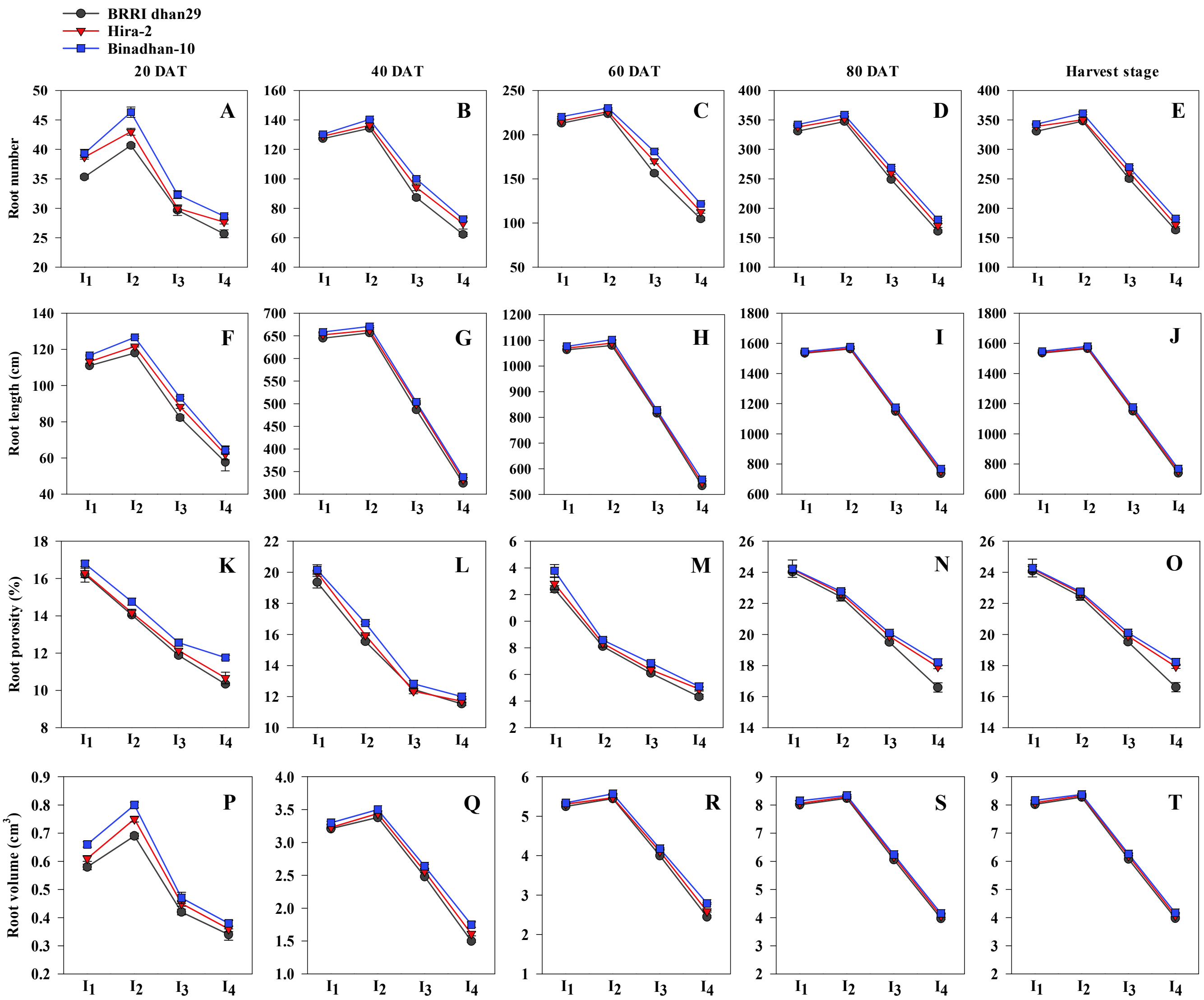

Figure 1. Variable root morphological attributes of three rice cultivars at four irrigation regimes during 20 DAT to harvest stage. I_1—Continuous flooding, I_2—Saturation, I_3—75% of saturation, I_4—50% of saturation; (**A**–**E**) represent root number; (**F**–**J**) represent root length; (**K**–**O**) represent root porosity; (**P**–**T**) represent root volume.

The RV of three tested varieties under four irrigation regimes varied significantly. This value increased from the first stage and continued up to the harvest stage. With respect to variety, Binadhan-10 generated the largest score of RV at every observation, whereas the S condition had the highest root volume at every observation for irrigation treatment. In both cases, BRRI dhan29 and 50% S had the lowest value of RV. In the case of interaction, Binadhan-10 had the greatest root volume at S condition, and was 0.80, 3.50, 5.57, 8.34 and 8.37 cm^3 hill^{-1} at 20, 40, 60, 80 DAT and at the harvest stage, respectively. At 80 DAT, the RV under S condition for Binadhan-10 was 2.33, 33.65 and 100.96% higher than CF, 75% and 50% S, respectively.

The impact of the irrigation regime and variety on LAI and TDM at different DAT is presented in (Figure 2). TDM varied significantly with varieties and irrigation regimes. A gradual increase of TDM was observed during the initial phases of development and afterwards enhanced quickly with the increase in plant age. The exponential rise in TDM in the latter phases was presumably caused by the production of a substantial number of late tillers, PH, and LA. At 80 DAT, Binadhan-10 exhibited the greatest TDM (19.59 g plant^{-1}), whereas the lowest (19.10 g plant^{-1}) was found in BRRI dhan29. Under S condition the highest TDM (24.25 g plant^{-1}) was obtained, whereas the lowest (11.75 g plant^{-1}) was produced at 50% S at 80 DAT. When interactions occurred, Binadhan-10 yielded the biggest TDM (24.41 g plant^{-1}) at 80 DAT under S conditions, whereas BRRI dhan29 yielded the minimum values of TDM (11.41 g plant^{-1}) at 50% S.

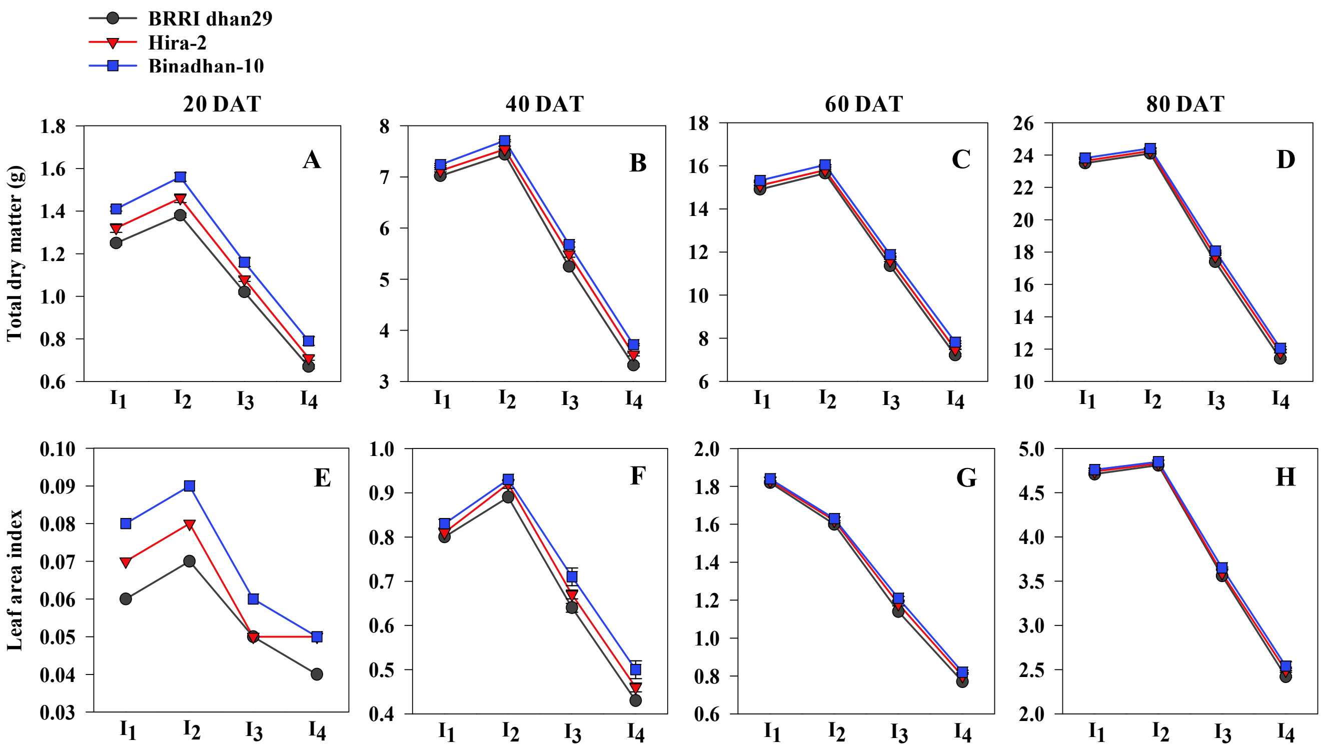

Figure 2. Total dry matter (TDM) and leaf area index (LAI) of three rice cultivars at four irrigation regimes during 20 DAT to 80 DAT. I_1—Continuous flooding, I_2—Saturation, I_3—75% of saturation, I_4—50% of saturation; (**A**–**D**) represent TDM; (**E**–**H**) represent LAI.

LAI increased progressively from the beginning and peaked at 80 DAT, and then decreased, irrespective of the variety and irrigation regime. Binadhan-10 had the highest LAI (3.95) at 80 DAT, and the lowest value (3.88) was observed in BRRI dhan29. With regard to the irrigation regime, the S condition gave the highest value of LAI (4.83) and the lowest (2.48) was observed in 50% of S at 80 DAT. In terms of interaction, Binadhan-10 with S condition gave the highest value of LAI (4.85) at 80 DAT, and the minimum (2.42) value was observed in BRRI dhan29 with 50% S.

3.2. Growth Parameters

The CGR, RGR and NAR of tested varieties at various irrigation regimes at 20–40 DAT (1st), 40–60 DAT (2nd) and 60–80 DAT (3rd) are presented in Figure 3. At 60–80 DAT, the highest value of CGR (7.54 g m^{-2} day^{-1}) was observed under CF level whereas BRRI dhan29 produced the lowest CGR of 6.15 g m^{-2} day^{-1} 60–80 DAT. At 40–60 DAT, the highest (7.83 g m^{-2} day^{-1}) readings of CGR was noticed in Binadhan-10 with S condition while the minimum (6.67 g m^{-2} day^{-1}) was documented in BRRI dhan29 under 50% S. Analysis of the LAI and CGR data reveals that, in line with the rise in leaf area with time, CGR also increased up to 60 to 80 DAT and afterwards decreased.

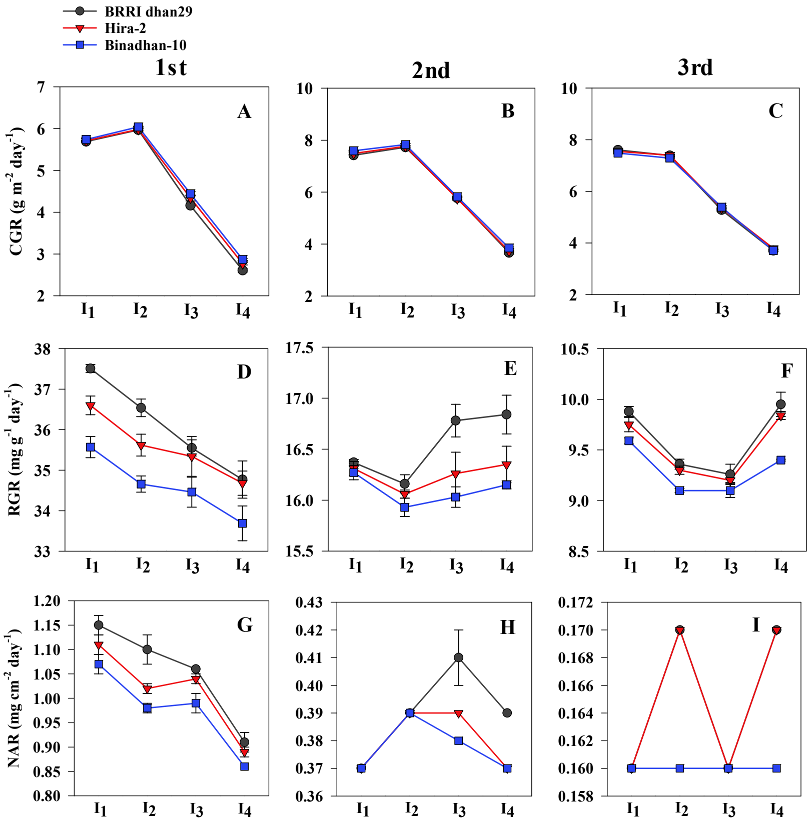

Figure 3. CGR, RGR and NAR of three rice cultivars at four irrigation regimes at 20–40 DAT (1st), 40–60 DAT (2nd) and 60–80 DAT (3rd). I_1—continuous flooding, I_2—Saturation, I_3—75% of saturation, I_4—50% of saturation. (**A**–**C**) represent CGR; (**D**–**F**) represent RGR; (**G**–**I**) represent NAR.

At 60–80 DAT, the highest (9.74 mg g^{-1} day^{-1}) value of RGR was found under CF, while the lowest (9.18 mg g^{-1} day^{-1}) was observed at 75% S. The highest value (9.61 mg g^{-1} day^{-1}) of RGR was obtained in BRRIdhan29 andthe lowest (9.76 mg g^{-1} day^{-1}) was found in Binadhan-10 at 60–80 DAT. In terms of interactions, it was found that BRRI dhan29 had the highest (9.88 mg g^{-1} day^{-1}) RGR at 60–80 DAT under CF, and the lowest (9.10 mg g^{-1} day^{-1}) was observed in Binadhan-10 with both S condition and 75% S. RGR rose irrespectively under all irrigation regimes in the initial phase (20–40 DAT), and afterwards tended to decline with the increase in crop age.

After 20–40 DAT, NAR started to decline in rice varieties independently of time and irrigation treatments. Nevertheless, varieties showed a decreasing trend of NAR from 40 to 60 DAT. At 60–80 DAT, BRRI dhan29 produced the greatest (0.17 mg cm^{-2} day^{-1}) NAR, whereas Binadhan-10 gave the smallest (0.16 mg cm^{-2} day^{-1}) amount of NAR. On the other hand, in the case of irrigation treatment under S condition, the largest (0.18 mg cm^{-2} day^{-1}) amount of NAR was documented, whereas CF had the lowest (0.16 mg cm^{-2} day^{-1}) value of NAR at 60–80 DAT. In terms of interactions, BRRI dhan29 generated the maximum (0.168 mg cm^{-2} day^{-1}) amount of NAR with 50% S, while Binadhan-10 yielded the smallest (0.159 mg cm^{-2} day^{-1}) amount of NAR, along with CF, at 60–80 DAT.

3.3. Grain Yield and Yield Component of the Rice Varieties

Yield components and output of rice were substantially affected by varieties and irrigation treatments (Table 1). The greatest value of ET (11.58), PL (21.59 cm), GP (100.67), TGW (23.78 g) and GY (21.31 g pot^{-1}) was observed in Binadhan-10, but the least value for all these parameters noticed in BRRI dhan29. Under a different irrigation regime, the S condition produced the largest score of ET (13.78), PL (23.67 cm), GP (120.11), TGW (24.25 g) and GY (25.13 g pot^{-1}), but the minimum value for the same parameters was observed in 50% S. Cultivars and irrigation schemes had a strong interaction effect on yielding components and yield (Figure 4). Binadhan-10 yielded the greatest amount of ET (14.67), PL (25.34 cm), GP (123.00), TGW (26.26 g) and GY (26.13 g pot^{-1}) with S condition, whereas the lowest value for the studied traits was observed in BRRI dhan29 with 50% S (Figure 4). In the case of Biandhan-10, the results revealed that grain yield with S condition was 4.23, 31.11 and 85.19% higher compared to CF, 75% and 50% S, respectively. In the case of BRRI dhan29 GY with S condition, this was 2.88, 29.58 and 88.16% higher compared to CF, 75% and 50% S, respectively, and finally for Hira-2 GY with S condition it was 4.87, 28.51, 83.87% higher compared to CF, 75% and 50% S, respectively.

Table 1. Yield attributes of the three rice cultivars under the four irrigation regimes.

Variety (V)	PH (cm)	ET (no.)	PL (cm)	GP	TGW (g)	GY (g pot^{-1})	SY (g pot^{-1})	HI (%)
V_1	75.83 b	9.92 c	19.64 b	93.58 c	21.17 b	19.90 c	20.15 c	49.65
V_2	71.17 c	10.50 b	20.28 b	96.58 b	22.39 ab	20.45 b	20.72 b	49.61
V_3	84.42 a	11.58 a	21.59 a	100.67 a	23.78 a	21.31 a	21.59 a	49.61
Irrigation (I)								
I_0	92.33 a	12.11 b	18.42 c	112.00 b	22.56 b	24.16 b	24.30 b	49.86 a
I_2	93.67 a	13.78 a	23.67 a	120.11 a	24.25 a	25.13 a	25.28 a	49.86 a
I_3	70.11 b	9.44 c	22.16 b	91.78 c	22.64 b	19.37 c	19.76 c	49.51 ab
I_4	52.44 c	7.33d	17.75 c	63.89 d	20.33 c	13.54 d	13.94 d	49.27 b
ANOVA								
V	**	**	**	**	**	**	**	NS
I	**	**	**	**	**	**	**	**
CV (%)	1.70	5.18	4.91	2.04	4.27	1.67	2.16	0.87

Notes: Within every column, means indicated by the identical letters were not substantially dissimilar. ** and NS denote significance at the 1% levels and non-significance, respectively, depending on the ANOVA.

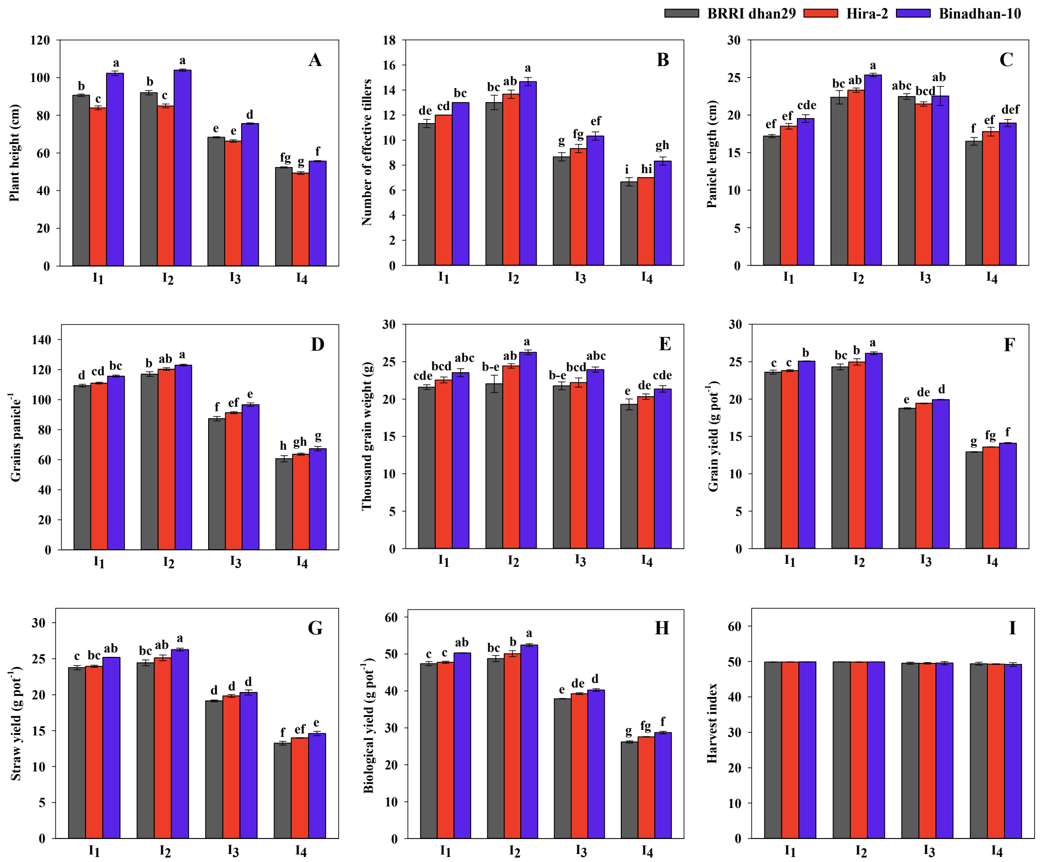

Figure 4. Yield and yield attributing traits of three rice cultivar under four irrigation regimes (**A**–**I**). I_1—Continuous flooding, I_2—Saturation, I_3—75% of saturation, I_4—50% of saturation.

3.4. Relationship among Root Traits, Growth Parameters, Yield and Yield Attributes

Figure 5 illustrates the correlation matrix of root parameters, development indices, yields, and yield parameters to investigate the relationship among them. GY showed a strong positive association with all root attributes. Yield contributing components such as ET, Pl, GP, TGW also had a positive and significant correlation with RN, RV, RL and RP. Again, root attributes and GY showed substantial and positive association with TDM and LAI.

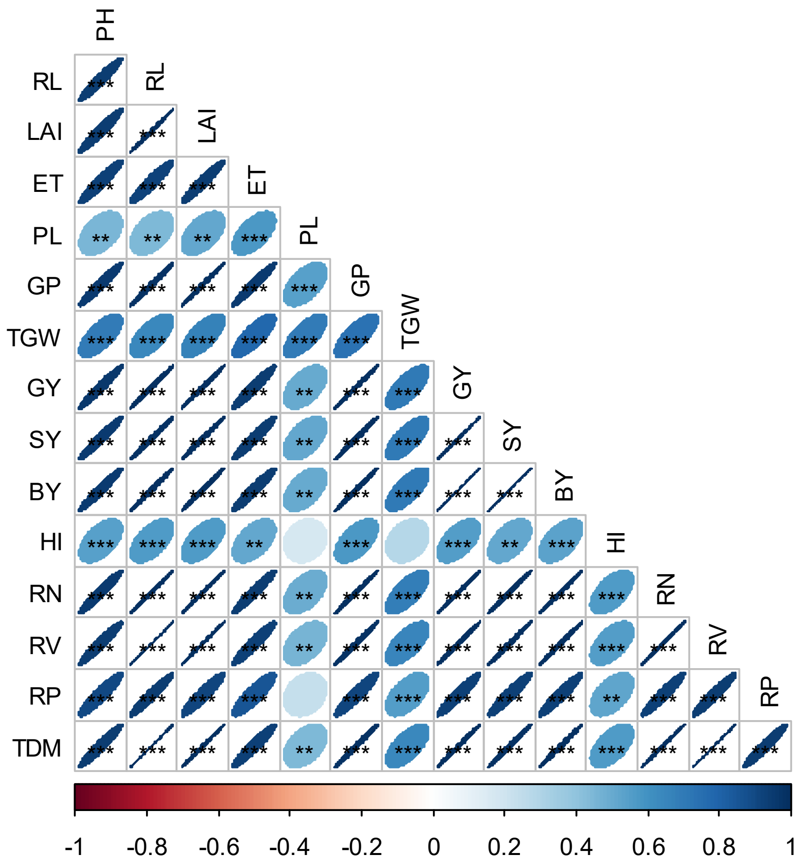

Figure 5. Correlation matrix and heatmap of the root parameters, growth attributes, yield parameters and yield. The ellipses in blue and red represent the positive and negative connections, accordingly. Greater color brightness exhibits the stronger coefficient. The ellipse's shape emphasizes the extent of homogeneity of the connections. ** and *** indicate 1% and 0.1% levels of significance, respectively. Traits descriptions: PH—plant height; No. ET—number of effective tillers; RN-root number; RL—root length; RP—root porosity (%); RV—root volume; TDM—total dry matter; PL—panicle length; GP—grains per panicle; TGW—thousand grain weight; GY—grain yield; SY—straw yield; BY-biological yield; HI—harvest index.

4. Discussion

The serious global issue of water shortage, also recognized as water stress or drought, has become the biggest obstacle to sustainable crop production in agriculture above all other issues. Rice productivity is severely hampered by the absence of irrigation water at the vegetative phase or reproductive phase [49]. Water and nutrients are absorbed primarily through the roots, which are crucial for plant physiological functions. The development of plant roots is intimately connected to soil environmental parameters such as moisture, air, temperatures, and productivity, of which moisture and productivity emerge as the most important parameters, and these are associated to and interactive with one another [50,51]. So, there is a relationship between rice roots, water and yield. According to the latest study, the response of varieties differed depending on the irrigation regimes. Variations in

TDM, crop growth, root traits and yield may be responsible for the performance variation of varieties.

As leaves are the main photosynthetic organ, they are an important target for enhancing morphological features in order to maximize carbon assimilation [52]. Erect leaflets in rice plants produce greater LAI, which boosts the efficiency of nitrogen utilization and light absorption during photosynthetic carbon assimilation [53]. In this study, rice grown under S condition generated the greatest LAI. The proliferation of tillers and the expansion of leaf size are the two widely acknowledged principal factors that greatly influence the leaf area index. Higher LAI was found under S condition compared with CF, 75% and 50% S. This might be caused by the impact of moisture on activating cell multiplication and enlargement, which is stated by Abu El-Ezz [54]. Reduced LAI reading at 75% and 50% S because of moisture deficit decreases the leaf initiation rate and also lowers the leaf surface of pre-existing foliage, resulting in a lower photosynthesis rate in the affected foliage. Lower LAI was the result of continuous and prolonged flooding [55]. In this experiment, the highest LAI was found in the S condition in Binadhan-10 at all observations.

In the present study, Binadhan-10 grown under S condition produced greater TDM. TDM may indicate a robust capability for nutrient and water uptake, leading to high grain yield. In general, increasing irrigation increased TDM. A gradual increase of TDM was observed during the initial phases of development, which then enhanced quickly with the increase in plant age. The exponential growth in TDM in the latter phases was presumably caused by the generation of a substantial quantity of late tillers, PH, and LA. The observations of our research are in harmony with other research [56]. The variety Binadhan-10 produced the highest TDM at all observations compared to other varieties. This may be due to the considerable variation in photosynthetic rates among rice cultivars, and dry matter accumulation may vary [57]. Dissimilarities in TDM deposition in several races was also observed [58]. The cultivar Binadhan-10 may uptake higher minerals from the soil, which improved growth, increased LAI, and produced larger TDM. According to other, earlier findings on the impacts of ceasing flooding, rice grain yield and dry matter production both significantly decline in unsaturated environments [59,60]. It might have occurred because of the nitrification and denitrification processes that cause soil nitrogen to be lost [61].

Crop growth rate (CGR) means had been significantly lower in the stressed treatment than the S condition and CF. CGR changes resembled each other in all treatments, but CF and S condition were superior to that of the stressed treatment during all stages. Under stressed treatments, extreme water deficit condition limits plant development owing to a reduction in stomata opening, which restricts carbon dioxide absorption and subsequently lowers photosynthesis [62]. Stomata may entirely close at moderate-to-extreme stress based on the frequency and duration of stress. Cell enlargement decreases or stops when exposed to moisture deficit conditions, which limits the development of plants. The probable cause of CGR decline in moisture deficit treatments might be owing to a decrease in the LAI and NAR [63,64]. CF produced the maximum values for relative growth rate (RGR), while stressed conditions generated the least values. The smaller TDM and CGR may be responsible for the significant decrease in RGR. The above findings are corroborated by other researchers [64,65]. Net assimilation rate refers to the physiological capacity to turn TDM into seed output. NAR is an indicator of measuring photosynthesis rates, excluding respiration losses [66]. NAR peaked between 0–20 DAT, dropped immediately between 60–80 DAT, and continued to decline up to the harvest stage, irrespective of treatment and variety.

The irrigation regimes exerted a substantial impact on RN at several developmental phases. RN generally enhanced over time and rice, particularly cultivated under S condition and CF, produced the highest RN at maturity. In contrast, RN under 75% and 50% S were lower in all observations. The reduced number of roots in arid soil (75% and 50% S condition) was also observed [67]. The RN enhancement under continuous flooding and saturated water environments contributed to the rise in root development throughout the time following heading. Moreover, there was little variation between the total RN of CF and that of under S at all developmental phases. In the case of RL, rice grown under 75% nd 50% S produced lower RL than rice raised in S condition and CF. The reduction in RL at 75% and 50% S condition could be explained by an increase in soil mechanical impedance because the land gets harder and more compacted in comparison to the soil that is continuously flooded and saturated with water. The finding that soil mechanical impedance affects the total RL is also supported [68]. RL exhibited a substantial quadratic trend when crop maturity increased between 40–60 DAT, but showed a regular trend at the blooming phase [69]. Our results also followed the same trend. In this study, Binadhan-10 produced maximum RL under S condition at all observations.

In case of RV, S condition performed best result. In CF, results showed a very similar trend to S condition. At 75% and 50% S, however, the value of RV decreased drastically. This may have occurred due to a very low amount of water which inhibits root growth properly. The greater RV is regarded as an adaptation strategy that enables plants to use the groundwater captured, and obtain groundwater at deeper levels [70,71]. The value of RP refers to the number of aerenchyma formation, which facilitates the moving of vital gases from shoot sections to the root parts [72]. The abundance and size of aerenchyma (air chambers that contain gas-filled pockets) in the roots are affected by a variety of irrigation regimes, such as flooded (anoxic) or hypoxic situations. In this study, the highest value of RP was observed in CF which is consistent with the result [73] that the generation of aerenchyma is necessary for plants to survive in waterlogged environments because it facilitates the transfer of oxygen from roots to shoots and vice-versa. Both aerobic acclimated and wetland cultivars produced aerenchyma up to a limited level in water deficit situations than in waterlogged situations [74].

The correlation between yield and yield attributes with RN, RL and RV was significant and positive. The correlation test among root attributes and yield revealed a stronger effect on the significance of roots in boosting seed output. There was a positive connection between root trait and yield [75–77]. Larger roots and greater RV indicate enhanced root activities, which then boosted TDM synthesis and mineral absorption [78], and ultimately produced a higher yield. In this study, varieties under S condition performed best, followed by CF, but at 75 and 50% S all growth indices, root traits and finally yield reduced drastically. Insufficient water limits the supply of minerals, and photosynthetic activity, and subsequently reduces the distribution of assimilates to the root parts [79,80] and ultimately reduced yield, our findings also followed the statement.

5. Conclusions

Varieties responded to water stress with decreased root attributes, development indices, yield parameters and yield. Among the four irrigation regimes, S condition performed best with regard to root traits and yield, followed by CF. The majority of yield attributed traits showed a significant positive association with root traits, highlighting the importance of root traits for higher yield. Out of three varieties, Binadhan-10 produced the maximum score of root attributes and yield, followed by Hira-2 and BRRI dhan29 under S condition.

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