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Influence of Planting and Irrigation Levels as Physical Methods on Maize Root Morphological Traits, Grain Yield and Water Productivity in Semi-Arid Region

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Abstract: Assessing the impact of planting methods and irrigation levels is needed to determine the effects on maize root morphological traits, grain yield, and water productivity in semi-arid regions. A study was initiated on maize (*Zea mays* L.) from 2015 to 2016, including three planting methods [i.e. broad bed and furrow (BBF), shallow and narrow furrow (SNF) and deep and wider furrow (DWF)] and four irrigation levels [i.e. irrigation once in ten days (I_{10D}), irrigation at 40% depletion of available soil moisture (DASM, I_{40}), irrigation at 50% DASM (I_{50}) and irrigation at 60% DASM (I_{60})] arranged in a split-plot design with three replications. Results reveal that the DWF method has increased root length, root volume, root surface area and root dry weight compared to SNF and BBF ($p < 0.05$). DWF and SNF resulted in higher grain yield than BBF, although the DWF grain yield was non-significant with SNF but resulted in 22.40% higher irrigation application. Irrigation at I_{50} had a significant effect on root length, root surface area, and grain yield, regardless of planting methods. Therefore, where irrigation has been a costly and limited farm input, the practice of SNF and deficit irrigation (I_{50}) could be a viable option for greater water saving and higher grain yields of maize.

Keywords: deficit irrigation; planting methods; root morphology; water productivity; maize

1. Introduction

Roots are indispensable for plant growth and productivity and perform several functions such as anchoring plants, nutrient and water uptake, engaging in symbiotic relationships with other biological entities and acting as a storage structure [1,2]. Further, roots help in soil structure formation and ecosystem functioning through a variety of physical, chemical and biological processes by adding approximately 60% of organic carbon into the soil [3–6]. Thus, they act as a natural conduit for organic compounds addition to the soil [7]. According to a study, root length, weight, diameter and the number of root tips are the major morphological traits directly influencing the functionality of the whole root system [8]. In general, root systems can be influenced by agronomic practices such as tillage [9], planting methods [10], nutrient management [11], irrigation scheduling [12] and planting density [13].

Maize (*Zea Mays* L.) is one of the highly cultivated cereals in the world, contributing 36% to the global food grain production next to rice and wheat [14]. Generally, maize is largely grown throughout the year in both rainfed and irrigated areas; however, both of these areas are facing the problem of water shortage due to erratic rainfall patterns under changing climate. In this context, several management practices have been tried in maize to manipulate soil moisture content and input use efficiency, especially in summer-grown maize. Modifications in planting methods and irrigation levels certainly influence the phenological stages, seed setting and grain yield of maize [15,16]. Previous studies have shown that changes in agronomic management practices (especially planting methods and irrigation levels) can influence the maize root system, water and nutrient use efficiency, and grain yield [10,11,17,18]. Therefore, understanding roots dynamics is of greater importance to explore crop water-saving mechanisms.

Improved planting methods help in better crop establishment and enhance the use of applied inputs. It has been reported that maize planted on ridges had greater root and crop growth, nutrient uptake and yield compared with that flat- and bed-planted [19,20]. Maize sown on ridges resulted in higher grain yield (5.45 t ha^{-1}) and water use efficiency (WUE, 1.34 kg m^{-3}) compared to crops under flat (4.86 t ha^{-1} and 1.22 kg m^{-3}, respectively) and bed-sown (5.13 t ha^{-1} and 1.28 kg m^{-3}, respectively) systems in a sandy clay loam soil [10]. Likewise, greater yield (7.8 t ha^{-1}) and phosphorus uptake (37.5 kg ha^{-1}) in maize planted on shallow furrows were found compared with that in a bed system (6.5 t ha^{-1} and 30.1 kg ha^{-1}, respectively) in a clay soil [21]. Higher N content (1.24%), N uptake by the stem (90.39 kg ha^{-1}) and grains of sorghum (34.39 kg ha^{-1}) were found with ridge and furrow methods as compared to the flat bed method in medium black soils of Dharwad [22].

Irrigation is also an important factor that can influence root development, crop growth and yield in arid and semi-arid regions [23,24]. Specifically, maize is highly sensitive to modifications in irrigation scheduling; water stress during the critical stages hampers grain production substantially [25,26]. Studies have been reported that maize can tolerate water deficits without much yield loss [27,28]. A study conducted in China suggested that alternate furrow irrigation increased the root tip number of maize by 32% and the surface area of fine roots by 35% and promoted deeper roots (10 cm greater) compared with maize under conventional furrow-irrigated treatment in a sandy loam soil [29]. In another study, a mild soil water deficit (50–60%) had the highest root to shoot ratio (0.18) and developed a longer lateral roots in maize [30,31]. Similarly, a high soil water deficit in maize decreased the root dry weight by 49.8–39.6 g $plant^{-1}$ [32].

Currently, very few studies so far have been attempted to investigate the additive effect of planting methods and irrigation levels on root morphology, grain yield and water productivity in summer maize [19,33]. Further, the growth and yield of a crop is dependent on the interaction of many field management practices. Presently, irrespective of crop needs, deep and wider furrow irrigation (WUE 30–50%) is the common practice in maize growing regions, although water shortage is prevailing, and this has led to higher seasonal water consumption [16,21]. Therefore, a study was initiated on regulated water applications and planting methods in a semi-arid region of Karnataka, which is one of the leading maize-producing (17.6% of production) states in India, with 34.4% of its area under irrigation [34]. Our hypothesis for this study was that the additive effect of deficit irrigation and planting methods may favor the root growth and water productivity of maize without much reduction in grain yield. The objective of this study was to evaluate the influence of planting methods and irrigation levels on root morphological traits, grain yield and water productivity of summer maize in a semi-arid region.

2. Materials and Methods

2.1. Study Location Details

A field experiment was conducted at the University of Agricultural Sciences, Dharwad, India (15°29′20.71″ N and 74°59′3.35″ E and 678 m above mean sea level) in summer 2015 and 2016. The study site is located in the Southern Plateau and Hill Zone of India (semi-arid with monsoon rainfall). The mean annual (past 65 years) rainfall of the experimental site was 772.73 mm. The maximum rainfall was received in July (155.92 mm), followed by October (126.50 mm). The mean maximum temperature varied from 27.3 (July and August) to 36.6 °C (April), whereas the mean minimum temperature ranged from 14.5 (December) to 21.6 °C (June). Meanwhile, the total rainfall received during the study season (February to May) was 247.8 mm in 2015 and 105.8 mm in 2016. The average maximum temperature was recorded in April in 2015 (35.5 °C) and 2016 (38.6 °C) and the lowest was recorded in February in 2015 (13.9 °C) and 2016 (16.2 °C) (Table 1). The soil of the study site is clayey in texture with 47.3% clay, 18.8% sand and 33.9% silt, a bulk density of 1.26 g cm^{-3} (0–30 cm), pH of 7.83, electrical conductivity of 0.24 dS m^{-1}, organic carbon at 0.62%, medium available nitrogen (320.3 kg ha^{-1}) and phosphorus (33.32 kg ha^{-1}) and high available potassium (426.5 kg ha^{-1}). The soil moisture content of the study site was 32.4% at field capacity and 18.0% at the permanent wilting point.

Table 1. Maximum and minimum temperature and rainfall data of the experimental site during the cropping season.

Crop Stage (DAS *)	2015			2016		
	Max. Temp (°C)	Min. Temp (°C)	Rainfall (mm)	Max. Temp (°C)	Min. Temp (°C)	Rainfall (mm)
0–15 (Feb 1FN *)	30.9	13.9	0.0	32.6	16.2	0.0
15–30 (Feb IIFN)	32.9	15.4	0.0	34.7	19.6	0.2
30–45 (Mar IFN)	31.5	18.2	105	35.3	20.3	0.0
45–60 (Mar IIFN)	34.8	20.4	0.2	37.0	20.9	2.4
60–75 (Apr IFN)	34.6	19.9	0.0	37.5	21.6	8.6
75–90 (Apr IIFN)	35.5	20.8	13.2	38.6	21.7	11.8
90–105 (May IFN)	35.4	21.3	91.0	38.3	21.4	61.0
105–120 (May IIFN)	34.0	22.4	38.4	33.9	22.5	21.8

* DAS—days after sowing; FN—fortnight.

2.2. Experimental Details

Treatments of this study were planting methods and irrigation levels. Three types of planting methods [i.e. broadbed and furrow (BBF), shallow and narrow furrow (SNF), and deep and wider furrow (DWF)] and four levels of irrigation [i.e. irrigation once in ten days (I_{10D}), irrigation at 40% depletion of available soil moisture (DASM) (I_{40}), and irrigation at 50% DASM (I_{50}), irrigation at 60% DASM (I_{60})] were studied. The treatments were arranged in a split-plot design by randomly placing planting methods in main plots and irrigation levels in sub-plots and all the treatments were replicated thrice. The plot size of the main and sub-plots was 23.2 × 7.0 and 6.0 × 5.4 m, respectively. The furrow depth was 0.12 m for BBF, 0.10 m for SNF and 0.25 m for DWF (Figure 1). The hybrid maize "Pinnacle" (Monsanto, Hyderabad- 501501, India) was planted on the side of the ridges with a spacing of 60 × 20 cm (83, 3333 plants ha^{-1}) on 7 February in 2015 and 1 February in 2016. The crop was fertilized with 150 kg N [$CO(NH_2)_2$], 75 kg P_2O_5 [$Ca (H_2PO_4)_2$] and 37.5 kg K_2O (KCl) ha^{-1}. In total, 50% of total N and 100% of P and K were applied at the time of sowing and the remaining 50% N was applied as a top-dressing in two splits, one at 30 DAS (days after sowing) (V9 stage) and the second at 60 DAS (tasseling stage).

Weeds were controlled using the pre-emergence application of atrazine (1.0 kg ai ha^{-1}) and a hand weeding at 30 DAS.

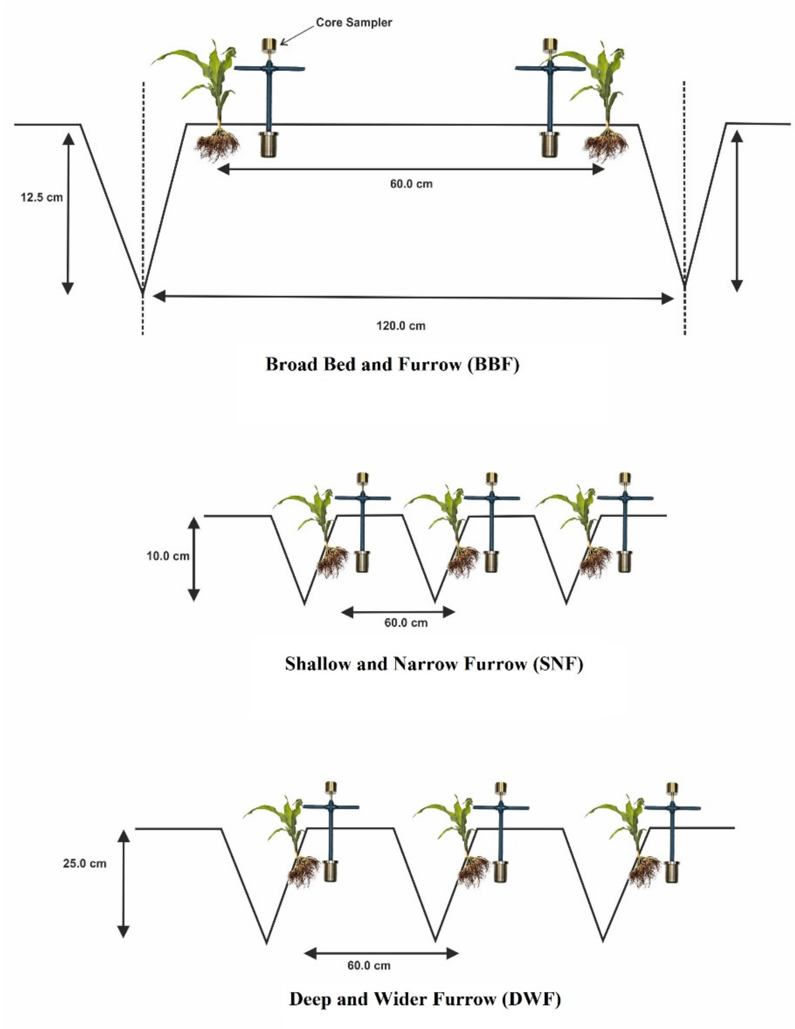

Figure 1. Field view of the planting methods.

2.3. Irrigation Scheduling

Based on the DASM values, irrigation was scheduled under different planting methods throughout the crop growth stage. This approach typically measures the moisture content of the soil in response to plant and climatic demands. The soil moisture content was measured using the rapid method; theta probe (MPKit-406 Soil Moisture Instant Reading Kit, ICT International, Spectra Agritec, New Delhi-110008, India). Random soil samples were taken between maize plants in all the treatments at the time of each irrigation. For calibration purposes, the probe readings were compared and adjusted with a standard gravimetric method. It has three needles (4 mm diameter) with a compact body, and the needles were inserted into the root zone with the help of a coarse sampler. The soil water status was regularly monitored using the theta probe and irrigation was given when the soil moisture content coincided with the respective lower limit of depletion (40%, 50% and 60% in the respective treatments). Common irrigation was applied up to 20 DAS for uniform crop establishment and later on, irrigations were scheduled based on the DASM. The soil moisture content (%) at each depletion point was calculated using the formula given by [35]. This method of withholding irrigation to allowable soil moisture depletion was similar to [36].

$$\text{Moisture content } (\%) = \frac{(\text{FC} - \text{PWP}) \times \text{Depletion } (\%)}{100} + \text{PWP} \quad (1)$$

where: FC—field capacity; PWP—permanent wilting point.

For the surface irrigation method, the water discharge was measured (4.3 l s^{-1}) using a 7.5 cm throat section Parshall flume (Hydro Flow-Tech Engineers, India, Maharashtra-422005) with the help of a calibrated table as suggested by [35]. Both sides of the furrow were regularly irrigated in SNF and DWF, whereas, all the time, only one side of the furrow was irrigated in the BBF method. To facilitate the water application into individual furrows, a gated pipe was laid along with the head of furrows. Care was taken to avoid lateral movement of the water between the different plots by preparing separate irrigation channels between the main plots. The depth of the irrigation water was quantified based on the discharge, time taken to irrigate and the number of irrigations. Likewise, the amount of rainfall was also included in computing the total water applied (Table 2). Meanwhile, the irrigation water was analyzed for different quality parameters such as pH (6.90), electrical conductivity (1.27 dS m^{-1}), sodium adsorption ratio (5.72) and residual sodium carbonate (-5.80 me L^{-1}); overall, the quality of water was normal for irrigation. After 24 h of irrigation, the lateral wetting area/zone (Supplementary Table S1) of soil around the maize plants was measured (cm) in all the treatments [37].

Table 2. Irrigation water and total water applied in a season under different planting methods and irrigation levels to maize.

Treatments *	**Irrigation Applied (mm)**	**Total Water (mm)**
Planting method		
BBF	260.4	372.5
SNF	341.9	454.0
DWF	440.6	552.9
Irrigation level		
I_{10D}	347.7	459.8
I_{40}	405.3	517.7
I_{50}	347.7	459.8
I_{60}	289.8	401.8

* BBF, broad bed and furrow; SNF, shallow and narrow furrow; DWF, deep and wider furrow; I_{10D}, irrigation once in 10 days; I_{40}, irrigation at 40% depletion of available soil moisture (DASM); I_{50}, irrigation at 50% DASM; and I_{60}, irrigation at 60% DASM.

2.4. Root Observation

Maize root length, diameter, surface area, volume, number of root tips and forks per plant were recorded at the peak growth stage of maize (tasseling), as recommended by [38]. The root samples were drawn from the maize rhizosphere using a core sampler (0.000754 m^3core size). Collected core samples were washed under running water, the washed roots were stained using $KMnO_4$ for 1 h and then placed in a root scanner tray attached toa computer system (Regent-STD 1600 + WinRHIZO^{TM} 2013, Regent instrument, Canada, Quebec). The scanner view of the comparative maize root morphology in selected treatments is depicted in Figure 2. In addition, the number of crown roots and brace roots was counted and then the root to shoot ratio was computed. To determine the shoot dry weight and total biomass, plant samples were dried at 63 °C for 72 hin a hot air oven. Further, root length density (RLD) and root weight density (RWD) were computed following the formula given by [15,24].

$$\text{RLD } (\text{cm cm}^{-3}) = \frac{\text{Total root length in a core}}{\text{Volume of a core}} \quad (2)$$

$$\text{RWD}\ (\text{mg cm}^{-3}) = \frac{\text{Total root dry weight in a core}}{\text{Volume of a core}} \quad (3)$$

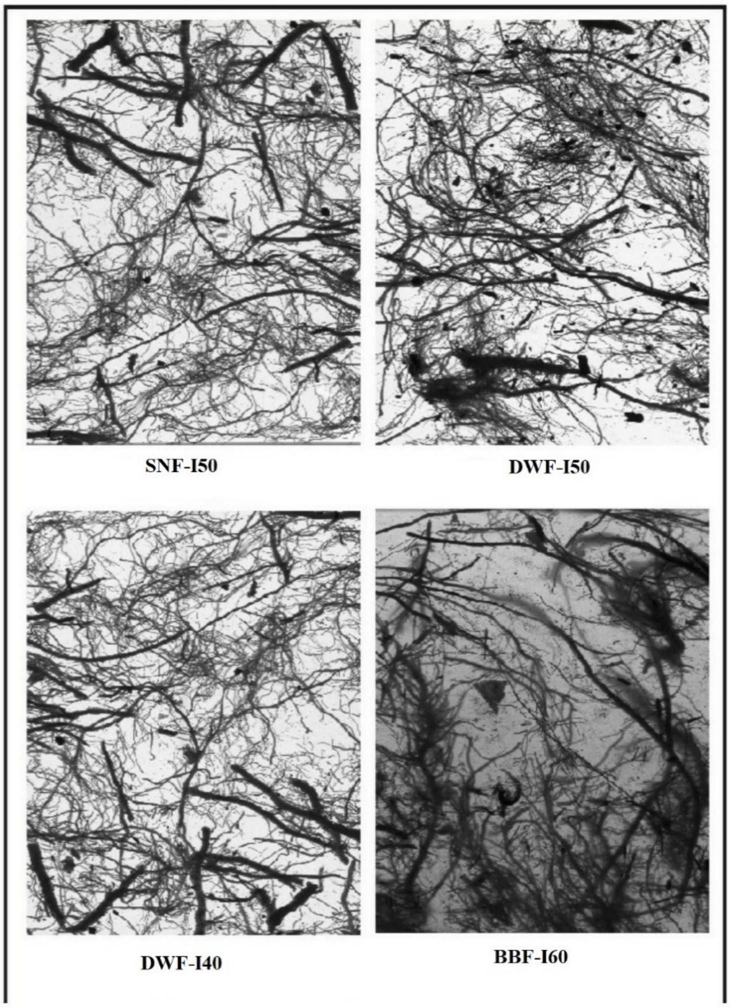

Figure 2. Comparative view of maize root morphology for selected treatments (scanner image) in response to planting method and irrigation level.

2.5. Maize Yield Parameters

The crop was harvested at physiological maturity, and after harvesting, the cob and stalk yield was estimated and the grain yield was expressed in t ha^{-1}.

2.6. Water Productivity

The water productivity was estimated by taking the ratio of grain yield and total water applied in a season [30,39].

$$\text{Water productivity}\ \left(\text{kg m}^{-3}\right) = \frac{\text{Kernal yield}\ \left(\text{kg ha}^{-1}\right)}{\text{Water applied}\ (\text{m}^{-3}\ )} \quad (4)$$

2.7. Data Analysis

All the data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS (V 9.3 SAS Institute Inc, Cary, NC, USA) in assistance of colleagues from King Saud and Princess Nourah bint Abdulrahman Universities. Before ANOVA, all the data were tested for normality using PROC Univariate analysis. In the analysis, planting methods (PM) and irrigation levels (IL) were considered as fixed effects and replication and year as random effects. The posthoc test for each variable was performed using the Tukey procedure ($\alpha = 0.05$). To predict the effect of selected root morphological traits (root length, root diameter, root volume and crown root number) on grain yield, a multiple linear regression was performed using R software (v 4.0.2).

3. Results and Discussion

Interaction of planting methods–by–irrigation levels was significantly ($p < 0.05$) influenced in root length, root surface area, root volume, root tip numbers, crown root numbers, shoot dry weight, root dry weight, root to shoot ratio, root length density, root weight density and grain yield of maize (Table 3). However, the interaction of planting methods–by–irrigation levels did not significantly ($p > 0.05$) influenced the root diameter, brace root numbers, stover yield, and water productivity (Table 3). For root diameter, brace root numbers, stover yield, and water productivity presented only the individual effect of planting methods and irrigation levels because interaction effect was non-significant ($p > 0.05$).

Table 3. Analysis of variance (ANOVA) for all the root morphological traits, grain yield and water productivity under different planting methods (PM) and irrigation levels (IL) in maize.

Variance *	DF	RLNT	RDIA	RSFA	RVOL	RTIP	RFOR	CRNR	BRCR	SHDW	RTDW	RSRT	RLD	RWD	GRY	STY	WP
PM	2	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0047	<0.0001
IL	3	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0066	0.0019
PM × IL	6	<0.0001	NS	<0.0001	<0.0001	<0.0001	<0.0001	0.0363	NS	0.0004	0.0002	<0.0001	<0.0001	0.0002	<0.0500	NS	NS

* DF, degree of freedom; PM, planting methods; IL, irrigation levels; RLNT, root length; RDIA, root diameter; RSFA, root surface area; RVOL, root volume; RTIP, root tips; RFOR, root forks; CRNR, crown roots; BRCR, brace roots; SHDW, shoot dry weight; RTDW, root dry weight; RSRT, root to shoot ratio; RLD, root length density; RWD, root weight density; GRY, grain yield; STY, stover yield; WP, water productivity, NS, non-significant at $p < 0.05$.

3.1. Effect of Planting Methods and Irrigation Levels on Maize Root Morphology

3.1.1. Root Length, Surface Area, Volume and Number of Tips

Maize root length, root surface area, root volume and root tip numbers were influenced by planting methods and irrigation levels (Table 4). The planting method DWF resulted in a higher root length (566.7 cm plant^{-1}), surface area (168.8 cm^2 plant^{-1}), volume (5.03 cm^3 plant^{-1}), and root tip numbers (4887 plant^{-1}) compared to the BBF and SNF systems (Table 4). The greater root length (50–107.8 cm plant^{-1}), surface area (23.2–34.5 cm^2 plant^{-1}), volume (1.15–2.2 cm^3 plant^{-1}) and root tip numbers (1728–3171 plant^{-1}) were recorded in irrigation at I_{50} compared to I_{10D}, I_{40} and I_{60}, but the root volume of treatment I_{40} (4.93 cm^3 plant^{-1}) was on par with I_{50} (4.88 cm^3 plant^{-1}). Concerning the interaction effect of planting methods and irrigation levels, the treatment DWF + I_{50} recorded higher root length (632 cm plant^{-1}), surface area (191.1 cm^2 plant^{-1}), volume (6.14 cm^3 plant^{-1}) and root tip numbers (8370 plant^{-1}), followed by SNF + I_{50} and DWF + I_{40} (Table 4). It was speculated that adequate aeration and better availability of soil moisture and nutrients under DWF and SNF could be reasons for the higher root length, surface area, volume and root tip numbers. In a previous study, primary root length (48% and 20% greater), number of lateral roots (17% and 33%) and root growth rate (14% and 29%) were greater in ridge-sown maize than that when bed- and flat-sown, respectively [19]. Likewise, a moderate soil water deficit, resulting in the promotion of shoot elongation and expansion of the root forage area in search of soil moisture, led to greater root growth. Findings also supported that root length, root surface area and root activity were improved by a moderate water deficit over asevere deficit in grain crops in [40]. Meanwhile, the lower growth of the above-mentioned root parameters under the treatment combination of BBF and I_{60} could be attributed to less water application (50.73% lower) on one side of the plant compared to DWF and SNF (Figure 1). Therefore, planting maize on deeper or shallow furrows with moderate water deficit (I_{50}) conditions may favor the root growth and development.

Table 4. Maize root length, surface area, volume and root tips number in response to different planting methods and irrigation levels.

Treatment *		Root Length (cm Plant^{-1})	Root Surface Area (cm^2 Plant^{-1})	Root Volume (cm^3 Plant^{-1})	Root Tips Plant^{-1}
Planting methods					
BBF		393.5 (±13.15 **) c	115.4 (±1.92) c	2.65 (±0.32) c	2587 (±225) c
SNF		531.6 (±14.35) b	136.68 (±6.62) b	4.48 (±0.45) b	3091 (±321) b
DWF		566.7 (±12.76) a	168.8 (±4.57) a	5.03 (±0.40) a	4887 (±610) a
p value		<0.0001	<0.0001	<0.0001	<0.0001
Irrigation levels					
I_{10D}		483.4 (±25.37) c	133.2 (±8.46) c	3.73 (±0.53) b	2961 (±146) c
I_{40}		504.1 (±17.63) b	138.7 (±7.35) b	4.93 (±0.39) a	3614 (±139) b
I_{50}		554.7 (±34.13) a	161.9 (±10.73) a	4.88 (±0.62) a	5342 (±780) a
I_{60}		446.9 (±30.16) d	127.4 (±6.25) d	2.68 (±0.36) c	2171 (±345) d
p value		<0.0001	<0.0001	<0.0001	<0.0001
Interaction effect					
BBF	I_{10D}	386.2 (±4.31) j	110.0 (±2.13) e	2.09 (±0.59) g	2716 (±0.57) h
	I_{40}	441.9 (±4.28) h	121.6 (±2.14) de	3.80 (±0.54) de	3127 (±0.66) f
	I_{50}	418.8 (±4.31) i	120.1 (±1.55) de	2.77 (±0.54) f	3175 (±0.66) f
	I_{60}	326.9 (±4.39) k	109.9 (±3.19) e	1.94 (±0.55) g	1331 (±0.57) k
SNF	I_{10D}	507.3 (±4.09) f	123.8 (±1.70) d	4.10 (±0.54) d	2623 (±0.57) i
	I_{40}	507.3 (±4.39) f	126.8 (±1.70) d	5.47 (±0.54) bc	3621 (±1.20) d
	I_{50}	613.2 (±4.10) b	174.5 (±1.02) b	5.72 (±0.73) ab	4481 (±1.15) b
	I_{60}	498.4 (±4.21) g	121.6 (±0.93) de	2.63 (±0.54) f	1641 (±28.3) j
DWF	I_{10D}	556.3 (±3.86) d	165.7 (±3.17) b	4.99 (±0.73) c	3546 (±1.15) e
	I_{40}	563.1 (±4.21) c	167.7 (±2.22) b	5.51 (±0.54) b	4093 (±1.15) c
	I_{50}	632.0 (±4.18) a	191.1 (±0.51) a	6.14 (±0.73) a	8370 (±1.20) a
	I_{60}	515.4 (±4.39) e	150.5 (±4.80) c	3.49 (±0.59) e	3542 (±1.15) e
p value		<0.0001	<0.0001	<0.0001	<0.0001

* BBF, broad bed and furrow; SNF, shallow and narrow furrow; DWF, deep and wider furrow; I_{10D}, irrigation once in 10 days; I_{40}, irrigation at 40% DASM; I_{50}, irrigation at 50% DASM; and I_{60}, irrigation at 60% DASM. ** Standard error of mean. Means followed by the same letter (s) within a column are not significantly differed.

3.1.2. Root Forks, Crown Roots, Shoot and Root Dry Weight

Compared to SNF and BBF, maize root fork numbers (31 and 62%, respectively) and shoot dry weight (10–18%, respectively) were greater in DWF (Table 5). However, both DWF and SNF had higher crown root numbers (25% higher) and root dry weight (33–39% higher) than BBF. Among irrigation levels, I_{50} had the highest root fork numbers (7019 plant^{-1}), shoot dry weight (72.29 g plant^{-1}) and root dry weight (16.77 g plant^{-1}), followed by I_{40} (6642 plant^{-1}, 67.86 g plant^{-1} and 13.36 g plant^{-1}), whereas crown root numbers were higher in both I_{40} and I_{50} over other irrigation levels (Table 5). Regarding the interaction effect, root fork numbers were 6–71% greater in the DWF + I_{50} treatment compared to other treatment combinations. However, crown root numbers, shoot dry weight and root dry weight were greater with DWF + I_{50}, SNF + I_{50} and DWF + I_{40} compared to other treatments. The greater number of root forks and crown roots resulting from the loose soil with greater nutrients solubility (organic carbon (OC), N and P) under the DWF system coupled with the moderate water deficit (I_{50}) might have enhanced the uptake of nutrients, resulting in higher root dry weight and shoot dry weight [41]. Meanwhile, the higher degree of moisture stress owing to the inadequate supply of water and nutrients was believed to be a reason for the poor development of fine roots and lower root dry weight under the BBF and I_{60} system. It was found that the application of adequate irrigation at the right time improved the root numbers and overall root activity compared to severely stressed maize plants [30,42]. Severe water stress led to preferential partitioning of photosynthates to the leaf area expansion rather than root growth and development, resulting in a lower root dry weight [31]. Similarly, it was found that moisture stress decreased maize root dry weight from 49.8 to 39.6 g plant^{-1} compared to that of the non-stressed treatment [32]. Therefore, it is evident from the present study that root forks and crown root growth play an important role in tolerating moisture stress and help in meeting the needs of crop water and nutrients requirements.

Table 5. Effect of planting methods and irrigation levels on root forks, crown roots, shoot dry weight and root dry weight in maize.

Treatment *		Root Forks Plant^{-1}	Crown Roots Plant^{-1}	Shoot Dry Weight (g Plant^{-1})	Root Dry Weight (g Plant^{-1})
Planting methods					
BBF		3223 (±181 **) c	12.89 (±0.81) b	59.34 (±0.75) c	9.24 (±0.54) b
SNF		5852 (±351) b	17.17 (±0.72) a	65.64 (±2.32) b	13.89 (±1.25) a
DWF		8508 (±415) a	17.26 (±0.98) a	72.71 (±1.60) a	14.64 (±1.22) a
p value		<0.0001	<0.0001	<0.0001	<0.0001
Irrigation levels					
I_{10D}		5416 (±721) c	14.53 (±0.74) b	61.99 (±1.47) c	11.22 (±0.61) c
I_{40}		6642 (±838) b	17.45 (±0.89) a	67.86 (±2.10) b	13.36 (±0.93) b
I_{50}		7019 (±891) a	17.95 (±1.35) a	72.29 (±2.78) a	16.77 (±1.76) a
I_{60}		4366 (±602) d	13.17 (±0.92) b	61.44(±2.49) c	9.01 (±0.72) d
p value		<0.0001	<0.0001	<0.0001	<0.0001
Interaction effect					
BBF	I_{10D}	2950 (±6.83) k	12.08 (±1.01) de	57.26 (±0.13) d	9.34 (±1.05) de
	I_{40}	3641 (±6.83) j	15.83 (±1.62) b–d	62.14 (±0.87) cd	10.37 (±0.43) b–d
	I_{50}	3923 (±6.83) i	13.50 (±1.01) c–e	61.24 (±0.58) cd	9.91 (±1.15) de
	I_{60}	2378 (±7.17) l	10.17 (±1.11) e	56.71 (±0.34) d	7.34 (±1.05) e
SNF	I_{10D}	5351 (±6.66) g	16.51 (±0.77) b–d	61.63 (±1.05) cd	11.94 (±0.62) b–d
	I_{40}	6843 (±6.83) e	18.17 (±2.19) a–c	66.84 (±0.28) bc	14.01 (±0.54) bc
	I_{50}	7033 (±6.83) d	18.51 (±1.61) ab	77.32 (±0.93) a	20.21 (±0.41) a
	I_{60}	4179 (±6.83) h	15.51 (±0.78) b–d	56.77 (±0.44) d	9.41 (±1.26) de
DWF	I_{10D}	7946 (±6.83) c	15.01 (±0.02) b–d	67.08 (±0.86) bc	12.37 (±0.62) b–d
	I_{40}	9442 (±11.83) b	18.34 (±0.43) ab	74.60 (±3.59) a	15.71 (±1.58) b
	I_{50}	10102 (±6.66) a	21.84 (±0.91) a	78.30 (±0.15) a	20.21 (±0.70) a
	I_{60}	6541 (±6.66) f	13.84 (±0.95) b–e	70.85 (±2.84) ab	10.27 (±1.16) c–e
p value		<0.0001	0.0363	0.0004	0.0002

* BBF, broad bed and furrow; SNF, shallow and narrow furrow; DWF, deep and wider furrow; I_{10D}, irrigation once in 10 days; I_{40}, irrigation at 40% DASM; I_{50}, irrigation at 50% DASM; and I_{60}, irrigation at 60% DASM. ** Standard error of mean. Means followed by the same letter (s) within a column are not significantly differed.

3.1.3. Root Length and Weight Density, and Root to Shoot Ratio

Maize root length density (0.78 cm cm^{-3}) and root to shoot ratio (0.25) were greater with DWF than SNF (0.67 cm cm^{-3} and 0.20, respectively) and BBF (0.52 cm cm^{-3} and 0.13, respectively) (Table 6). However, DWF (19.41 mg cm^{-3}) and SNF (18.51 mg cm^{-3}) had a comparable root weight density. The moderately water-stressed soil (I_{50}) treatment had a greater root length density (0.20–0.90 cm cm^{-3} greater), root weight density (4.52–10.17 mg cm^{-3} greater) and root to shoot ratio (0.07–0.14) than other soil water stress treatments (Table 6). In combination, the treatment DWF + I_{50} had a higher root length density (0.03–0.41 cm cm^{-3} higher) over other treatments, but root weight density and root to shoot ratio were greater with both DWF + I_{50} and SNF + I_{50} combinations than the other treatment combinations. An improvement in maize RLD (48.80%) and RWD (14.60%) was recorded as a result of the extension of the root forage area and size of roots in search of water under mild moisture stress [24]. Likewise, it was propounded that farmers can choose a mild water stress technique for averting the negative effect of severe water stress on stem elongation, the sensing ability of roots and the poor accumulation of photosynthates in roots [15,30]. Therefore, the practice of DWF along with I_{40} and I_{50} for maize can conserve the irrigation water along with the development of longer roots (RLD) and higher dry weight (RWD) in the upper soil layer.

Table 6. Influence of different planting methods and irrigation levels on maize root length density, root weight density and root to shoot ratio.

Treatment *		Root Length Density (cm cm^{-3})	Root Weight Density (mg cm^{-3})	Root to Shoot Ratio
Planting methods				
BBF		0.52 (±0.01 **) c	12.25 (±0.71) b	0.13 (±0.01) c
SNF		0.67 (±0.01) b	18.51 (±1.61) a	0.20 (±0.02) b
DWF		0.78 (±0.01) a	19.41 (±1.62) a	0.25 (±0.02) a
p value		<0.0001	<0.0001	<0.0001
Irrigation levels				
I_{10D}		0.64 (±0.03) c	14.87 (±0.82) c	0.16 (±0.01) c
I_{40}		0.68(±0.03) b	17.72 (±1.23) b	0.21 (±0.01) b
I_{50}		0.70 (±0.03) a	22.24 (±2.34) a	0.28 (±0.03) a
I_{60}		0.61 (±0.04) d	12.07 (±0.92) d	0.14 (±0.01) c
p value		<0.0001	<0.0001	<0.0001
Interaction effect				
BBF	I_{10D}	0.51 (±0.01) j	12.38 (±1.40) de	0.15 (±0.01) de
	I_{40}	0.55 (±0.01) i	13.75 (±0.56) c–e	0.17 (±0.02) cd
	I_{50}	0.59 (±0.01) h	13.13 (±1.52) de	0.12 (±0.01) de
	I_{60}	0.43 (±0.01) k	9.73 (±1.40) e	0.10 (±0.01) e
SNF	I_{10D}	0.67 (±0.01) f	15.83 (±0.83) b–d	0.12 (±0.01) de
	I_{40}	0.68 (±0.01) e	18.57 (±0.72) bc	0.23 (±0.02) b
	I_{50}	0.67 (±0.01) f	26.80 (±0.55) a	0.35 (±0.01) a
	I_{60}	0.66 (±0.01) g	12.85 (±1.31) de	0.12 (±0.01) de
DWF	I_{10D}	0.75 (±0.01) c	16.41 (±0.83) b–d	0.20 (±0.01) bc
	I_{40}	0.81 (±0.01) b	20.83 (±2.09) b	0.25 (±0.01) b
	I_{50}	0.84 (±0.01) a	26.80 (±0.93) a	0.36 (±0.01) a
	I_{60}	0.74 (±0.01) d	13.62 (±1.55) c–e	0.19 (±0.01) bc
p value		<0.0001	0.0002	<0.0001

* BBF, broad bed and furrow; SNF, shallow and narrow furrow; DWF, deep and wider furrow; I_{10D}, irrigation once in 10 days; I_{40}, irrigation at 40% DASM; I_{50}, irrigation at 50% DASM; and I_{60}, irrigation at 60% DASM. ** Standard error of mean. Means followed by the same letter (s) within a column are not significantly differed.

3.1.4. Root Diameter and Brace Root Numbers

Maize root diameter and brace root numbers were influenced by planting methods and irrigation levels (Figure 3A–D). Compared to DWF, a 33.59–35.11% higher root diameter was observed in BBF and SNF systems (Figure 3B). The authors presume that the shorter roots with a higher diameter under the BBF system might be due to root hardening or root suberization because of the partial root drying. A study conducted in Canada observed that maize root growth and expansion were affected by severe water deficit conditions at the upper soil layer as a result of the partial closure of the stomata and reduction in the movement of photosynthates towards roots [43]. Among irrigation levels, I_{60} had a higher root diameter (0.2–0.45 mm greater) compared to other treatments (Figure 3D). The limited root extension might be a reason for the thicker roots in the case of I_{60} compared to I_{40} and I_{50}, with those recording deeper and thinner roots.

The maize brace root numbers were greater in DWF and SNF (18.43 and 17.19 number plant^{-1}, respectively), compared to the BBF (14.74 number plant^{-1}) system (Figure 3A). The uniform distribution of soil water in terms of the wetting zone (24–34% higher, Supplementary Table S1) and the deeper and loose soil around the maize plants might have induced the greater number of brace roots that emerged under DWF and SNF. However, very limited literature is available on the effect of planting methods on brace root numbers. Regarding irrigation levels, I_{60} recorded the lowest brace root number (1.22–7.56% lower) compared to that in I_{10D}, I_{40} and I_{50} (Figure 3C). As reported, longer lateral roots in maize under mild water deficit (50%) conditions were reported because of the optimum soil wetting and forage area as compared to higher and lower soil water deficit conditions [30,31]. Therefore, it is evident from the present investigation that modification in planting methods and regulated irrigation scheduling have a considerable effect on the maize root diameter and brace root development; indeed, these will influence the mechanical support to the crop.

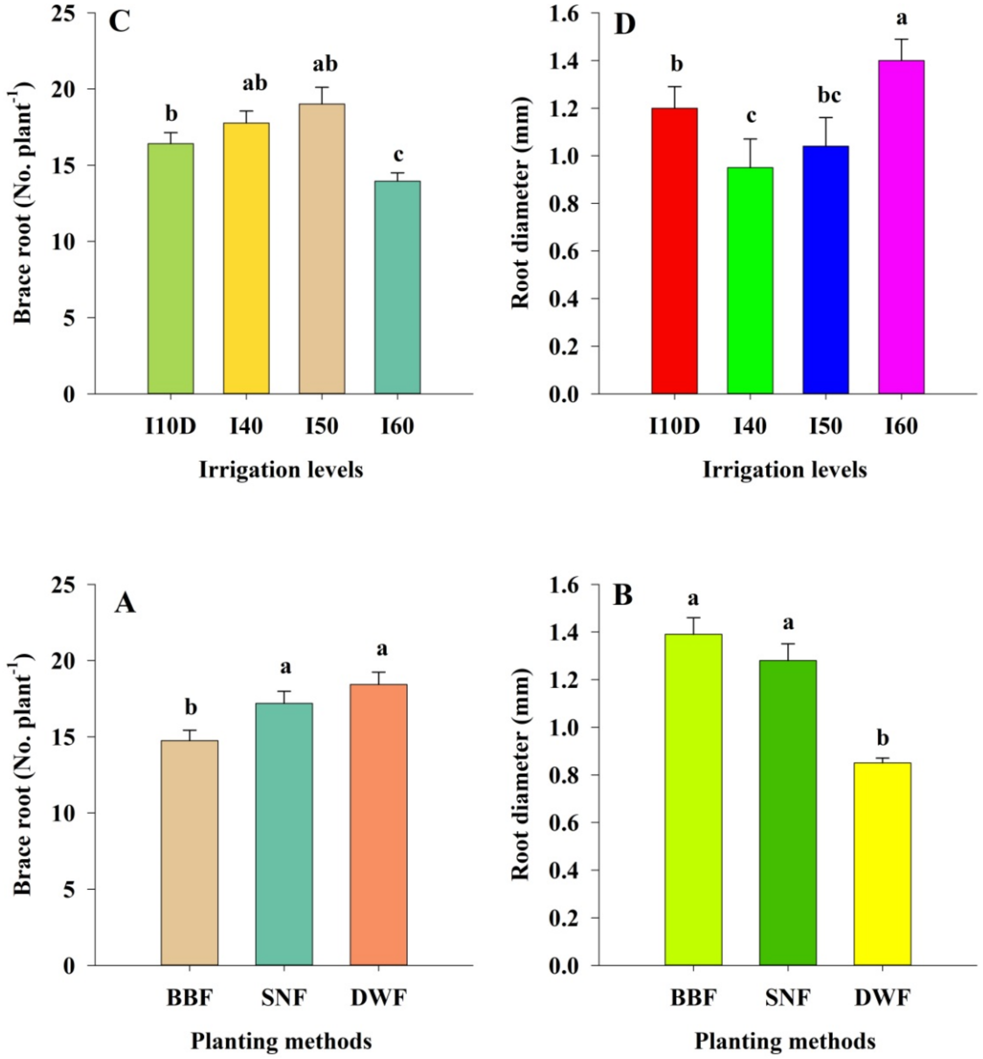

Figure 3. Planting methods and irrigation levels effect on brace root numbers (**A**,**C**) and root diameter (**B**,**D**) of maize. Means followed by the same letter (s) within the figure are not significantly differed.

3.2. Grain and Stover Yield

Grain yield of maize was significantly (p < 0.05) influenced by the interaction of planting methods and irrigation levels (Table 3). Whereas the stover yield of maize was non significantly influenced by the interaction of planting methods and irrigation levels (p > 0.05); however, the individual effect of planting methods and irrigation levels was significant (p < 0.0001). Compared to BBF, higher grain yield was recorded in DWF (14.58%) and SNF (10.57%) (Figure 4A). Among four irrigation levels, both I_{40} and I_{50} had significantly higher grain yields compared to I_{10D} and I_{60} (Figure 4B). The stover yield seems to follow the same pattern as does the grain yield (Figure 4C,D). The higher grain and stover yield of maize under DWF and SNF were mainly as a result of improved maize root morphological traits such as root length, root surface area, volume, number of crown roots, fine roots, and final root dry weight. Furthermore, severe moisture stress due to reduction in irrigation water under I_{60} has led to poor root morphological traits, as discussed earlier. It was speculated further that under severe moisture stress conditions maize plants could not able to synthesize and accumulate more photosynthates, this might have resulted in poor translocation of assimilates towards the sink might have affected the grain and stover yield. It is also evident from the multiple linear regression between root morphological traits (root length, root diameter, root volume and, number of crown roots) and maize grain yield (Figure 5). The root length, root diameter, root volume, and number of crown roots were positively related to the grain yield of maize (adjusted r^2 = 0.51). However, only root length (p < 0.0001) and root diameter (p < 0.01) were significant among the root morphological traits for predicting the grain yield. Hence these aforementioned root morphological traits can impact the grain yield of maize by the extent of 51%. While the lack of optimum soil moisture can affects the growth and development of roots, and grain yield [32,44–46]. Likewise, irrigation at 60% depletion under the BBF method adversely affected the leaf area (16.46%), cob weight (23.72%), uptake of nutrients such as N, P, and K in maize compared to 40% depletion under DWF [21,47]. Therefore, a higher maize grain and stover yield can be obtained from the DWF and SNF method of planting with allowable moisture depletion (I_{40} and I_{50}). Thus it can be an alternate option in water-scarce semi-arid regions without affecting the grain yield.

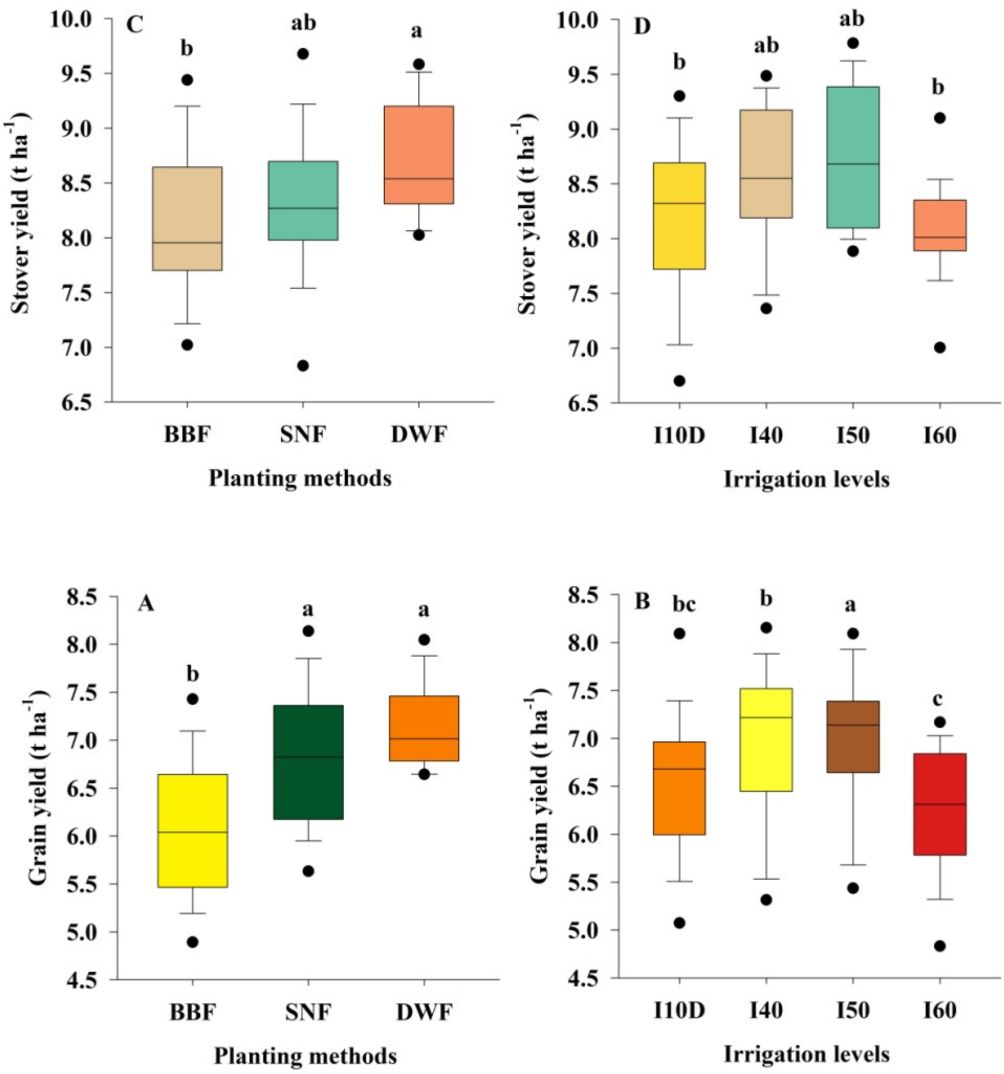

Figure 4. Planting methods and irrigation levels effect on grain (**A**,**B**) and stover yield (**C**,**D**) of maize. Means followed by the same letter (s) within the figure are not significantly differed.

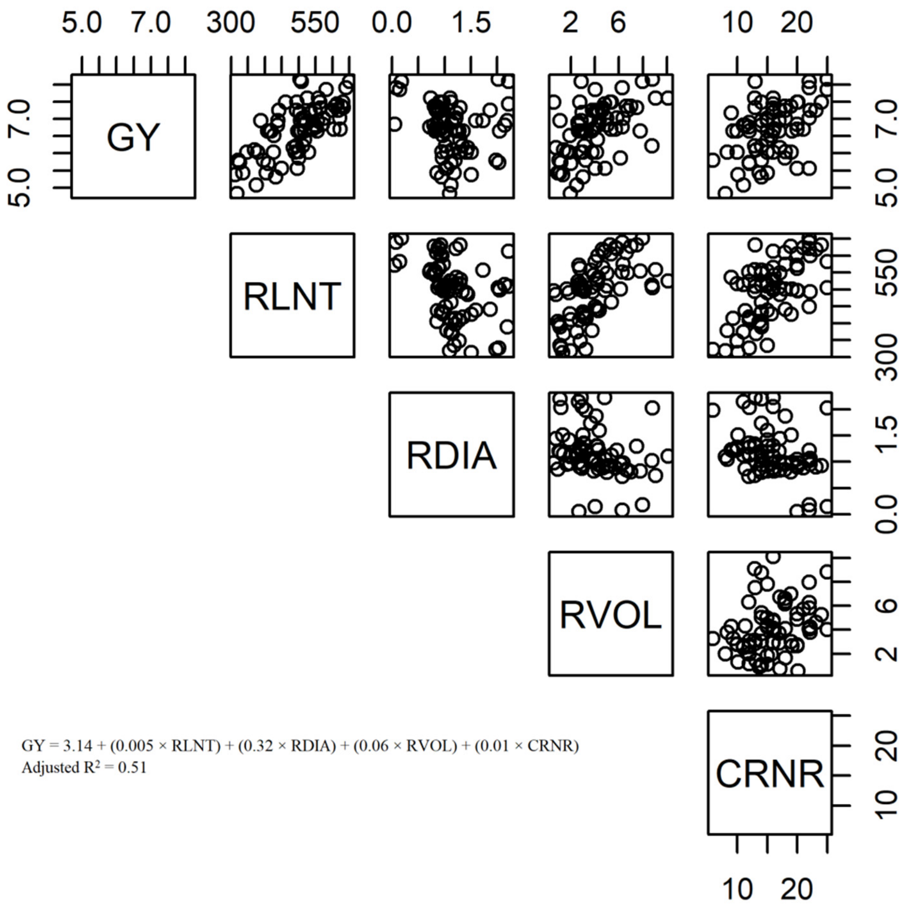

Figure 5. Multiple linear regression between selected root morphological traits [root length (RLNT), root diameter (RDIA), root volume (RVOL) and crown roots number (CRNR)] and grain yield (GY) of maize (N = 72).

3.3. Water Productivity

In maize, root growth and water application rate was regulated by planting methods and irrigation levels; therefore, water productivity varied among planting methods and irrigation levels (Figure 6). However, the two-way interaction of planting methods and irrigation levels did not significantly affect the water productivity ($p > 0.05$). Water productivity ranged from 1.29 to 1.63 kg m^{-3} in different planting methods and 1.37 to 1.57 kg m^{-3} under various irrigation levels. The highest water productivity was recorded in both BBF (1.63 kg m^{-3}) and SNF (1.53 kg m^{-3}) systems compared to DWF (1.29 kg m^{-3}). For the irrigation levels, greater water productivity was recorded under I_{60} (1.57 kg m^{-3}) and I_{50} (1.54 kg m^{-3}), followed by I_{10D} (1.45 kg m^{-3}). It was noticed that the higher water productivity under the BBF system was mainly because of a reduction in the total water consumption (32.62% and 17.88% lesser, Table 2) and considerable grain yield (6.09 t ha^{-1}) compared to DWF and SNF. Meanwhile, alternate partial rootzone irrigation saved 38.4% irrigation water and enhanced the canopy WUE by 24.3% compared to regular furrow irrigation [48]. Similar findings were reported previously wherein water productivity was 13.63% greater under moderate deficit irrigation than full irrigation in maize grown in a clay loam soil [49].

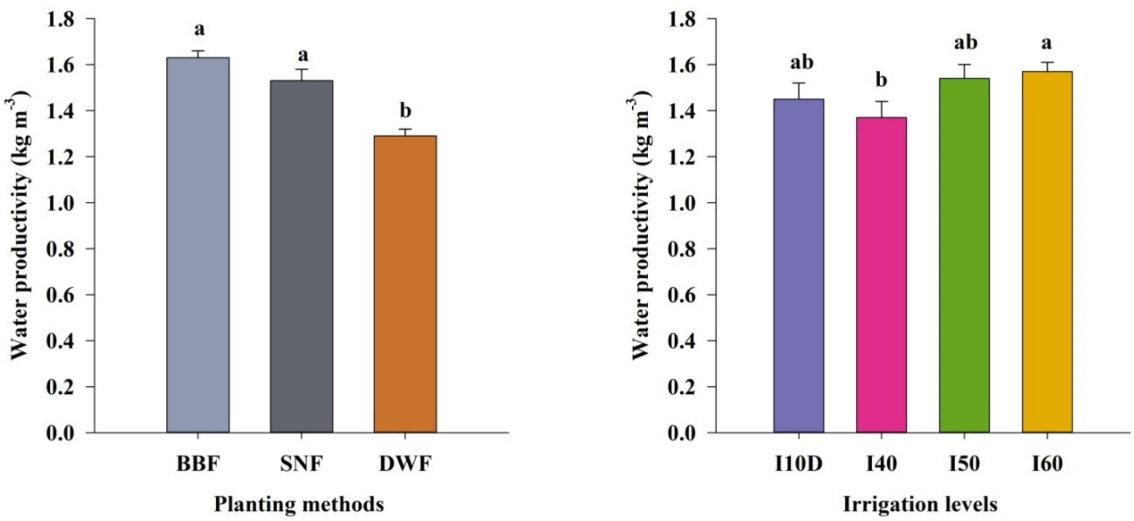

Figure 6. Water productivity of maize under different planting methods and irrigation levels. Means followed by the same letter (s) within the figure are not significantly differed.

4. Conclusions

In conclusion, this study is among the few studies performed so far that assessed the different planting methods' and irrigation levels' effect on root morphological traits, grain yield and water productivity of maize in a semi-arid region. The planting method DWF and deficit irrigation (I_{50}) resulted in higher root morphological traits and crop yield compared to other planting methods (BBF and SNF) and irrigation levels (I_{10D}, I_{40} and I_{60}). Further, the combination of deficit irrigation (I_{50}) with SNF resulted in higher root morphological traits, grain yield and water productivity, although DWF recorded a similar grain yield to SNF but resulted in 22.40% higher irrigation application because of the larger wetting area. However, for a better understanding of the crop root morphological traits and grain yield of maize, investigations on the additive effect of nutrient management under various planting methods and deficit irrigation in vertisols of semi-arid regions can be helpful to enhance the input use efficiency. Therefore, under assured irrigation, farmers can practice DWF and I_{50} for a higher grain yield of maize, whereas for a limited water situation, SNF and I_{50}could be an alternate option for higher water productivity and obtaining a higher grain yield of maize.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4395/11/2/294/s1, Table S1: Lateral wetting area around maize plants influenced by planting method and irrigation level. Table S2: Grain yield of maize due to interaction of planting methods and irrigation levels.

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