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Research Article

Effect on Photosynthetically Active Radiation Interception and Yield in Rice by Microclimate Modification Through Row Spacing under Punjab Conditions

SHUBHAM ANAND, L.K. DHALIWAL* AND KARUNA

Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana-141004, Punjab

ABSTRACT

The field experiments were conducted at the Research Farm, Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana during *kharif* seasons of 2017 and 2018. Rice varieties were transplanted on 15th June (D_1) and 30th June (D_2) during *kharif* 2017 and on 20th June (D_1) and 30th June (D_2) during *kharif* 2018. The varieties were transplanted under three spacing (25 cm × 12 cm, 20 cm × 15 cm and 30 cm × 10 cm) during both the years. The photosynthetically active radiation (PAR) was recorded in different treatments. PAR interception was higher in wider spacing (30 cm × 10 cm) followed by closer spacing (20 cm × 15 cm and 25 cm × 12 cm). Correlation coefficients were worked out between periodic number of tillers and temperature (maximum and minimum) and sunshine hours.In first date of transplanting, maximum temperature showed a significant negative correlation with tiller number during 2018. The sunshine hours showed a positive and significant correlation under different treatments in first date of transplanting during *kharif* 2017 and 2018. During both the years, the first date of transplanting reported higher mean grain yield (59.16 q/ha) as compared to second date of transplanting (56.11 q/ha) and also higher mean grain yield (59.88 q/ha) was recorded in rice varieties transplanted under wider spacing (30 cm × 10 cm)in comparison to closer spacing of 20 cm × 15 cm (57.85 q/ha) and 25cm × 12cm (55.15 q/ha). So, by modification in spacing the rice yield can be increased without any extra cost.

Key words: Rice, Dates of transplanting, Spacing, PAR interception, Microclimate modification

Introduction

Rice (*Oryza sativa* L.) is widely cultivated under diverse ecosystems of tropical and sub-tropical regions of the world. It occupies an area of approximately 44 million hectares in India at the end of fiscal year 2019. Rice was the most produced food grain across the South Asian nation during 2020 (FAO, 2020). In Punjab, rice crop covers 31.42 lakh hectares area with an annual production of 189.18 lakh tonnes in 2019-20. The average yield of paddy recorded was 60.21 quintals per hectare during 2019-20 (Anonymous, 2021). The maximum yield potential of a rice crop is usually achieved when the crop is exposed to most appropriate temperature range, which can be controlled by transplanting at proper time. Optimum date of transplanting influences rice production in three ways- by ensuring favourable temperature and sunshine hours at vegetative growth, warmest minimum temperature at cold sensitive stage and milder autumn temperature at grain filling stage for better quality of grain (Patel *et al.,* 2019).

*Corresponding author,
Email: dhaliwal1969@pau.edu

Planting geometry of a crop effects the interception of solar radiation, crop canopy coverage, dry matter accumulation and crop growth rate. The closer planting geometry causes competition among plants for light, water and nutrients which consequently slow down growth as well as grain yield. Optimum planting geometry ensures proper growth of aerial as well as underground plant parts by effective utilization of solar radiation, nutrients and water (Anwar *et al.,* 2011). Similarly, the tillering capacity and spikelet formation per panicle are also influenced by the planting geometry, which effects yield of rice. So, the date of transplanting and plant spacing should be optimized by keeping in mind the different aspects of crop management techniques (Miah *et al.,* 1990). As climate change continues to affect agricultural systems worldwide, strategies that enhance crop resilience to changing environmental conditions become increasingly important. Understanding how microclimate modifications through row spacing influence crop performance can contribute to the development of climate-resilient farming practices. Keeping this in view, the present study was carried out to investigate the influence of different dates of transplanting and plant spacing on growth and yield of different varieties.

Material and Methods

The field experiments were conducted at the Research Farm, Department of Climate Change and Agricultural Meteorology, Punjab Agricultural University, Ludhiana during *kharif* seasons of 2017 and 2018. Two rice varieties *viz*. PR 122 (V_1) and PR 124 (V_2)were transplanted on 15th June (D_1) and 30th June (D_2) during *kharif* 2017. PR 121 (V_1) and PR 126 (V_2) were transplanted on 20th June (D_1) and 30th June (D_2) during *kharif* 2018.The varieties were transplanted under three spacing (25cm × 12cm, 20cm × 15cm and 30cm × 10cm) during both the years. The experiment was laid out in Split-Split Plot Design with four replications. Line Quantum Sensor was used to take diurnal cycles of photosynthetically active radiation (PAR) from 1000 hours to 1600 hours at maximum tillering stage. The per cent PAR interception by the crop was calculated by using the following formula:

$$\text{PAR interception (\%)} = \frac{[\text{PAR(I)} - \text{PAR(R)} - \text{PAR(T)}]}{\text{PAR(I)}} \times 100$$

where,

PAR (I) – Photosynthetically active radiation incident above the canopy

PAR (T) – Photosynthetically active radiation transmitted to the ground

PAR (R) – Photosynthetically active radiation reflected from the canopy

The periodic number of tillers were counted in different treatments. Correlation coefficients were worked out between periodic number of tillers and different meteorological parameters (maximum temperature, minimum temperature and sunshine hours). The yield and yield attributing characteristics were recorded at the time of harvesting. The data collected was statistically analyzed by using CPCS-1 software.

Results

Photosynthetically active radiation interception

Photosynthetically Active Radiation (PAR) is the amount of light in the wavelength range of 0.4-0.7μ useful for photosynthesis. Biomass production largely depends on intercepted PAR. The quantum of biomass production and harvest index regulates rice yield (Huang *et al*., 2016). The growth and yield of the plant largely depends on the radiation interception and efficiency of plant to use all resources and it is strongly influenced by micro-climate of crop stand (West *et al.,* 2008). The PAR interception is influenced by canopy geometry and morphology such as leaf area, angle and orientation (DeCosta *et al.,* 2006). The PAR interception was recorded in different rice varieties transplanted on different dates under different plant spacing during maximum tillering stage. During this stage, vegetative growth of plant takes place and reach its maximum. The soil is shaded by the crop and it hardly gets any direct insolation.

During maximum tillering stage, the PAR interception was higher in variety PR 122 (85.9 per cent) followed by variety PR 124 (83 per cent) under 30cmx10cm while it was 84.7 per cent and 83.8 per cent in variety PR 122 under 20 cm × 15 cm and 25 cm × 12cm spacing respectively (Fig. 1 and Fig. 2).

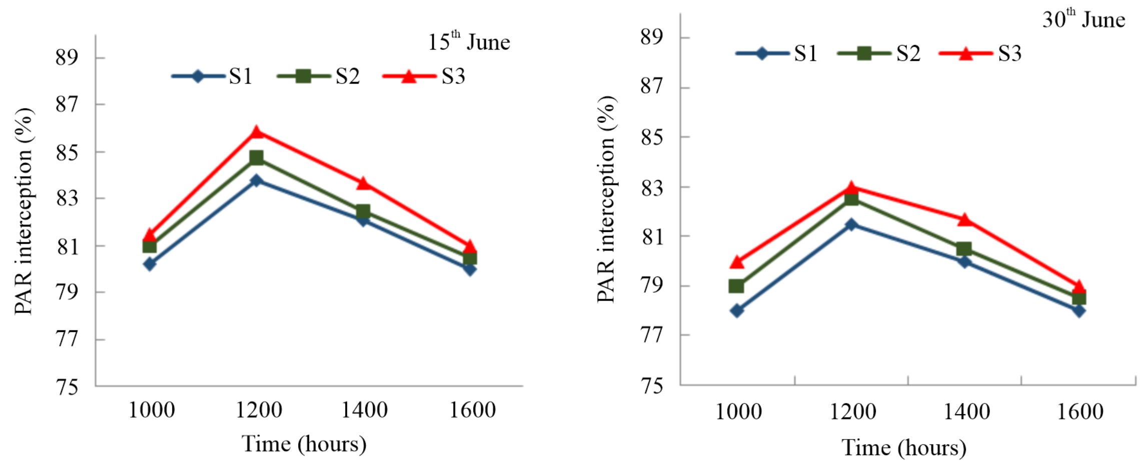

Fig. 1. PAR interception at maximum tillering stage under different spacing in PR 122 during *kharif* 2017

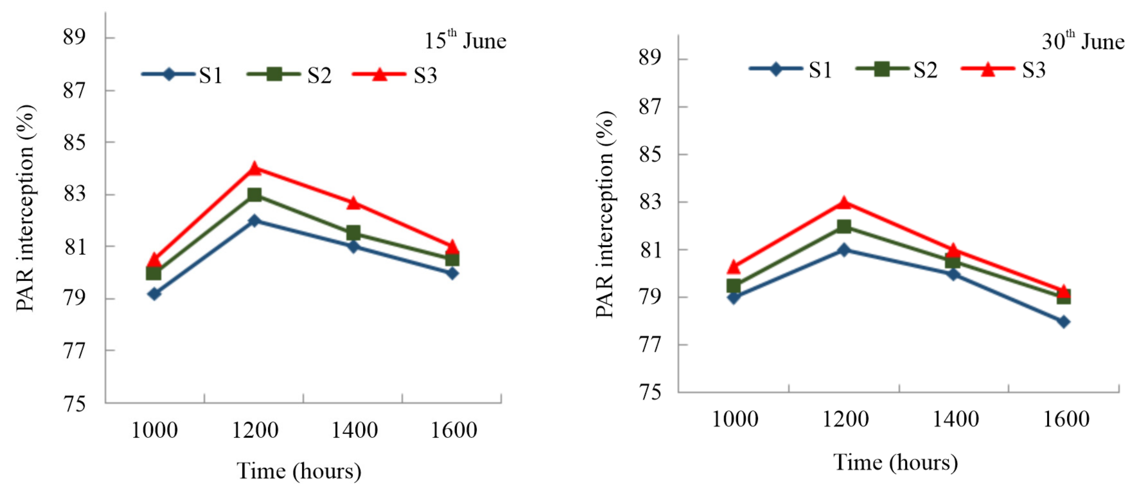

Fig. 2. PAR interceptions at maximum tillering stage under different spacing in PR 124 sown on 15th June and 30th June during *kharif* 2017

S_1 = 20cm×15cm, S_2 = 25cm×12cm, S_3 = 30cm×10cm

In 15th June transplanted crop PAR interception was more as compared to 30th June transplanted crop.It was higher in variety PR 121 (83.17 per cent) compared to variety PR 126 (82.47 per cent) under 30 cm × 10 cm spacing while it was 82.20 per cent and 81.10 per cent in variety PR 121 under 20 cm × 15 cm and 25 cm × 12cm spacing respectively. In 20th June transplanted crop, PAR interception was more as compared to 30th June transplanted crop. PAR interception was more under 30 cm × 10 cm spacing in comparison to 20 cm × 15 cm and 25 cm × 12 cm spacing. Similarly Xu *et al.* (2020) reported that, the different row and interplant spacing values of rice individuals during the optimization process affected the light microclimate around the leaves, thus light interception of the individuals was influenced, leading to more light interception at larger plant spacing within a certain range, and vice versa.

During 2018, the PAR interception in 20th June transplanted rice was higher in variety PR 121 (84 per cent) in comparison to variety PR 126 (83.26 per cent) under 30 cm × 10 cm spacing while it was 82.77 per cent and 81.56 per cent in variety PR 121 under 20 cm × 15 cm and 25 cm × 12 cm spacing respectively at maximum tillering stage (Fig.3 and Fig. 4). The PAR interception in 30th June transplanted crop was also higher in variety PR 121 (83.75 per cent) than variety PR 126 (83.26 per cent) under 30 cm × 10 cm spacing while it was 82.77 per cent and 81.56 per cent in variety PR 121 under 20

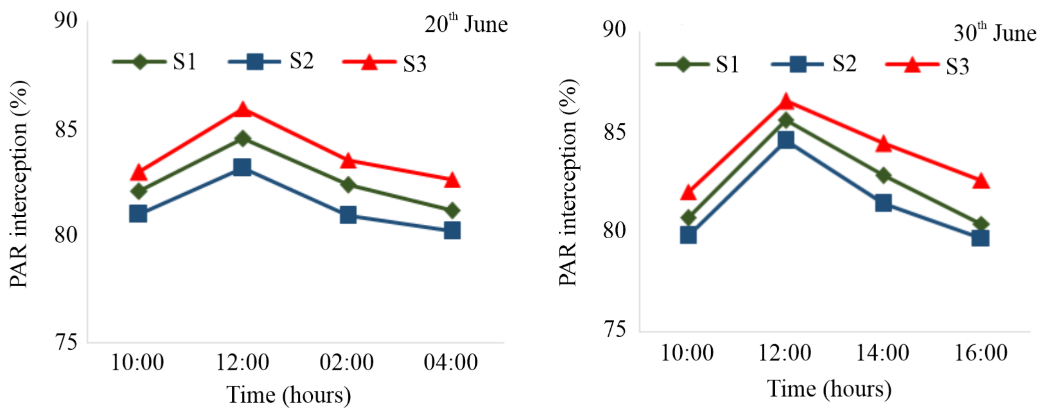

Fig. 3. PAR interception at maximum tillering stage under different spacing in variety PR 121 transplanted on 20th June and 30th June during *kharif* 2018

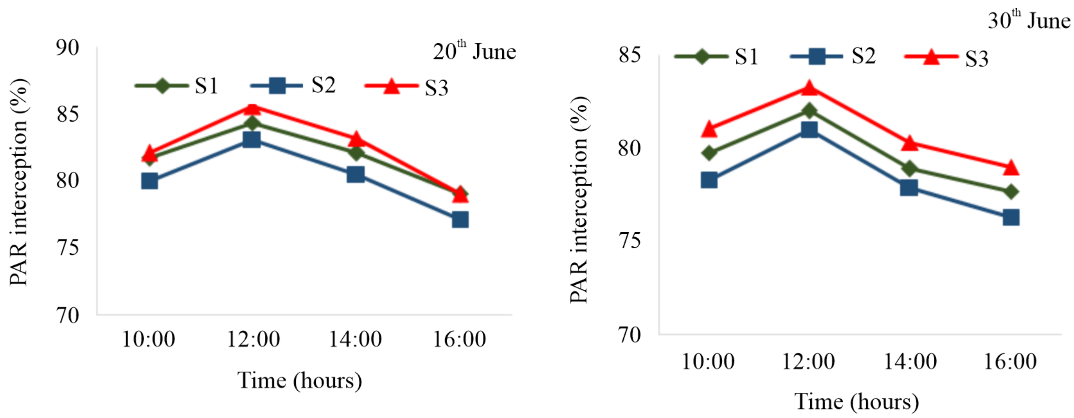

Fig. 4. PAR interception at maximum tillering stage under different spacing in variety PR 126 transplanted on 20th June and 30th June during *kharif* 2018S_1 = 20cm×15cm, S_2 = 25cm×12cm, S_3 = 30cm×10cm

cm × 15 cm and 25 cm × 12 cm spacing respectively. Kaur (2016) also found that PAR interception was higher in early transplanted crop than late transplanted crop as early transplanted crop has a long vegetative growth period. Thus, plant is able to harvest more of solar energy. Similar results were also reported by Sastri *et al.* (2000) and Singh *et al.* (2000). The geometry of crop stand is responsible for allowing radiation inside the crop for its absorption and its transmission to lower leaves. Due to dense stand and effective canopy, sunshine reaches the ground in patches only. Closer spacing increases competition among the plants for light which results in weaker plants. Optimum plant spacing ensures plant to grow properly with their aerial and underground parts by utilizing more solar radiation and nutrients. Mutual shading thus favours more straw yield than grain yield. Thus, more light penetration in wider spacing occurs as compared to closer spacing (Sultana *et al.,* 2012). Due to wider spacing and proper light penetration, the PAR interception was higher in 30 cm × 10 cm spacing in all phenological stages (Sharma *et al.,* 2011).

Relationship of periodic number of tillers with maximum and minimum temperatures

Temperature effects rate of tiller production and growth of rice crop. Under high temperature conditions, more tiller buds are produced. Although, tillering rate is boosted but tillering period is decreased which leads to production of less number of tillers (Sreenivasan, 1985). Thus, reduction in yield was observed under higher maximum and minimum temperatures conditions during tillering period (Sridevi and Chellamuthu, 2015). Under high temperature conditions, the maximum tillering stage was early as compared to normal temperature

Table 1. Correlation coefficients (r) between periodic number of tillers of rice and temperature (maximum and minimum) and sunshine hours/day

Treatments	Dates of transplanting											
	D_1						D_2					
	Tmax		Tmin		Ssh/day		Tmax		Tmin		Ssh/day	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
						V_1						
S_1	0.11	-0.92**	0.30	-0.05	0.55*	0.78**	-0.34	-0.22	0.04	-0.16	0.18	0.35
S_2	0.09	-0.74**	0.40	0.16	0.53*	0.74**	-0.22	0.07	0.24	0.18	0.31	0.38
S_3	0.09	-0.88**	0.40	0.06	0.55*	0.85**	-0.10	-0.01	0.51*	0.04	0.09	0.42
						V_2						
S_1	0.13	-0.95**	0.19	-0.12	0.50*	0.80**	-0.24	-0.28	0.41	-0.21	0.18	0.41
S_2	0.48	-0.54*	0.69*	0.45	0.60*	0.63*	-0.25	0.27	0.60*	0.39	0.31	0.28
S_3	0.13	-0.94**	0.52	-0.07	0.54*	0.89**	-0.13	-0.19	0.42	-0.12	0.09	0.58*

*Significant at the 0.05 level

**Significant at the 0.01 level

conditions due to production of more number of tillers per square meter during early development period. Panicle differentiation happens by and large at temperatures in the range of minimum temperature (18°C) and maximum temperature (30°C) (Oh-e *et al.,* 2007).

The periodic number of tillers were correlated with maximum temperature and minimum temperatures during *kharif* 2017 and 2018 (Table 1). In first date of transplanting, maximum temperature showed a significant negative correlation with tiller number during 2018. Yao *et al.* (2007) also found that photosynthetic production capability of rice is affected by higher temperature due to decrease in leaf photosynthetic velocity which ultimately affects grain yield. The fluctuation in maximum temperature and minimum temperature during the rice growing season leads to such results. Biswas (2008) also reported that temperature influenced the number of tillers which ultimately determines the yield by influencing the number of panicles per unit area.

Relationship between periodic number of tillers and sunshine hours

Solar radiation intercepted in rice canopy plays a major role in determining biomass and grain yield. Solar radiation requirements of a rice crop are different at different phenophases. It influences crop growth and productivity (Singh, 2005). Reduction in light intensity and duration causes reduction in photosynthesis. The shading of plants cause delay in tillering and reduced tillering rate and total dry matter production (Jagdish and Muthurajan, 2010). The sunshine hours play a major role during the vegetative phase of rice crop.

The periodic number of tillers were correlated with sunshine hours. The results indicate that sunshine hours showed a positive and significant correlation under different treatments in first date of transplanting during *kharif* 2017 and 2018. But in second date of transplanting, it showed non-significant results due to cloudiness and rainfall. Rani *et al.* (2011) also reported that during monsoon season the low light intensity is associated with lower incident radiation, low sunshine hours and more cloudiness. The sunshine hours were also found to be positively correlated with periodic number of tillers in first date of transplanting during *kharif* 2018 (Table 1). The sunshine hours showed a significant relationship with tiller number in first date of transplanting as compared to second date of transplanting. Physical capacity of rice is decided by tiller number per unit area. Since temperature and sunshine hours are correlated, they have profound effect on tiller rate (Sharma *et al.,* 2011). During vegetative stage low sunshine hours has little influence on grain yield as compared to reproductive stage. The vegetative lag phase is affected by less light stress and thus, tiller mortality occurs and panicles m^{-2} formed are less (Das, 2010).

Effect of dates of transplanting on yield and yield contributing characteristics

The yield contributing characteristics viz. plant height, number of effective tillers per plant, 1000-grain weight and grain yield is a function of total yield of rice crop. Varieties PR 122 and PR 124 showed significant differences in number of effective tillers, panicle length and 1000-grain weight except plant height and number of grains per panicle during *kharif* 2017 (Table 2). The yield contributing characteristics viz. plant height, number of effective tillers per plant, panicle length, number of grains per panicle and 1000-grain weight were more in 15th June transplanting as compared to 30th June transplanting.

The first date of transplanting (15th June) had higher number of effective tillers than second date of transplanting (30th June). The crop transplanted on 15th June had higher (12.70) number of effective tillers per plant compared to 30th June transplanted crop (10.10). Comparatively, panicle length was better in first date of transplanting (15th June) than second date of transplanting (30th June). Number of grains per panicle was 107.50 and 103.20 in 15th June and 30th June transplanted crop, respectively. The 1000-grain weight in 15th June transplanted crop was higher (25 g) than 30th June transplanted crop (21g). The variety PR 122 recorded higher grain, straw and biological yield as compared to variety PR 124. In 15th June transplanting, all the yield contributing characters were higher resulting in higher grain yield (60.4 q/ha) as compared to 30th June transplanting (58.3 q/ha) as presented in Table 2. Dhaliwal *et al.* (2006) also reported that higher grain yield was obtained in case of 15th June transplanted crop as compared to 30th June transplanted crop.

The number of effective tillers per plant was higher in variety PR 121 (11.87) and statistically different from variety PR 126 (10.80) during *kharif* 2018 (Table 2). In 20th June transplanting, the number of effective tillers per plant was higher (11.84) as compared to 30th June transplanting (10.83). In 20th June transplanting, panicle length was higher in variety PR 121 (22.10 cm) as compared to variety PR 126 (21.47 cm). Number of grains per panicle

Table 2. Yield and yield contributing characteristics of rice varieties under different transplanting dates and spacing during *kharif* 2017 and 2018

Treatments	Plant height (cm)		No. of effective tillers / plant		Panicle length (cm)		No. of grains per panicle		1000-grain weight (gm)		Biological yield (q/ha)		Straw yield (q/ha)		Grain yield (q/ha)	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Dates of transplanting																
D_1	87.00	79.49	12.70	11.84	28.20	22.10	107.50	116.36	25.00	25.40	146.9	137.92	85.2	80.01	61.7	57.91
D_2	84.60	77.95	10.10	10.83	22.65	21.47	103.20	106.12	21.50	24.29	138.0	129.10	81.0	75.13	57.0	53.93
CD (P=0.05)	0.25	NS	1.20	0.23	0.98	0.60	0.47	1.13	0.67	0.69	4.90	2.92	1.70	2.59	3.50	1.77
Varieties																
V_1	86.31	76.87	11.40	11.87	25.70	22.32	106.70	114.08	23.30	25.28	145.4	136.13	85.0	79.01	60.4	57.12
V_2	85.41	80.57	11.00	10.80	25.10	21.25	103.90	108.39	23.60	24.42	139.5	130.84	81.2	76.12	58.3	54.71
CD (P=0.05)	0.26	0.62	NS	0.35	NS	0.89	0.52	2.59	NS	NS	3.70	2.70	2.30	2.33	1.70	1.94
Spacing																
S_1	85.00	77.41	10.00	10.67	23.90	20.49	104.00	102.96	22.50	24.12	136.1	127.10	79.2	73.68	56.9	53.40
S_2	86.42	78.59	11.30	11.17	25.30	22.18	105.60	113.24	23.50	25.02	146.6	134.62	85.5	78.92	60.0	55.70
S_3	85.81	80.15	12.20	12.16	26.90	22.68	106.00	117.51	24.10	25.40	144.7	138.75	84.6	80.10	61.1	58.65
CD (P=0.05)	0.32	1.93	0.45	0.69	0.68	0.56	0.68	1.97	NS	0.80	4.50	2.21	2.90	3.44	2.50	2.1

were also higher in case of early transplanting as compared to late transplanting. The test weight showed non-significant differences among varieties PR 121 and PR 126. But it was higher in case of first date of transplanting than second date of transplanting. Thus, all the yield contributing characters were significantly higher in case of first date of transplanting compared tosecond date of transplanting. Similarly, Sharma *et al.* (2011) studied that the first date of transplanting (20^{th} June) is significantly better than second date of transplanting (30^{th} June) in terms of height of plant, length of panicle, numbers of grains per panicle, number of effective tillers and 1000 grain weight due to availability of favourable temperature during panicle initiation and grain formation period in 15^{th} June transplanted crop. The variety PR 121 recorded higher grain, straw and biological yield as compared to variety PR 126. In 20^{th} June transplanting, all the yield contributing characters were higher resulting in higher grain yield (57.91 q/ha) as compared to 30^{th} June transplanting (53.93 q/ha) (Table 2). Similar trend was observed in case of straw yield. The biological yield was also recorded higher in 20^{th} June transplanting (137.92 q//ha) which was statistically different from 30^{th} June transplanting (129.10 q/ha). Kaur (2016) also found that PAR interception was higher in first date of transplanting as compared to second date of transplanting due to longer vegetative growth period. Thus, plant is able to utilise more of solar energy. Similar results were also supported by Mahajan *et al.* (2009).

Effect of plant spacing on yield and yield contributing characterstics

Optimum row spacing is one of the most important factor determining the yield of rice crop. The growth, development and yield of rice crop are significantly influenced by row and plant spacing under field conditions. Closer spacing hinders intercultural operations, increases competition among the plants for nutrients, air, light, which results in weaker plants, mutual shading thus favours more straw yield than grain yield. Optimum plant spacing ensures plant to grow properly with their aerial and underground parts by utilizing more solar radiation and nutrients (Sultana *et al.,* 2012). The various yield contributing characters are also affected by different spacing and consequently affect grain, straw and biological yield.

Different plant spacing showed significant differences among number of effective tillers, 1000-grain weight, plant height, panicle length and number of grains per panicle. All these yield contributing characteristics were higher in 30 cm × 10 cm spacing as compared to that of 20 cm × 15 cm spacing and 25 cm × 12 cm spacing. During *kharif* 2017, wider spacing (30 cm × 10 cm) recorded higher number of effective tillers per plant (12.20) as compared to closer spacing 20 cm × 15 cm and 25 cm × 12 cm which were 11.30 and 10.00 respectively. Under wider spacing (30 cm × 10 cm), panicle length was found to be higher (26.90 cm) than that of other spacing viz. 20 cm × 15 cm (25.30 cm) and 25 cm × 12 cm (23.90 cm). The number of grains per panicle among the three spacing, 30 cm × 10 cm spacing (106) and 20 cm × 15 cm spacing (105.60) were statistically at par but differed significantly from 25 cm × 12 cm spacing (104). In 15^{th} June and 30^{th} June transplanted crop the highest grain yield (61.1 q/ha) was recorded in 30 cm × 10 cm due to more spacing between plants and less competition fornutrients, light and air. Similarly straw and biological yield was highest in 30 cm × 10 cm spacing followed by 20 cm × 15 cm and 25 cm × 12 cm spacing (Table 2).

During *kharif* 2018, wider spacing (30 cm × 10 cm) recorded higher number of effective tillers per plant (12.16) as compared to closer spacing 20 cm × 15 cm (11.17) and 25 cm × 12 cm (10.67) as presented in Table 3. Under wider spacing (30 cm × 10 cm), panicle length was found to be higher than that of other two spacing viz. 20 cm × 15 cm (22.68 cm) and 25 cm × 12 cm (22.18 cm). The test weight among the three spacing, 30 cm × 10 cm spacing (25.40 g) and 20 cm × 15 cm spacing (25.02 g) were statistically at par but differed significantly from 25 cm × 12 cm spacing (24.12 g). The wider spacing 30 cm × 10 cm spacing recorded higher grain yield (55.70 q/ha) in comparison to 20 cm × 10 cm spacing (58.65 q/ha) and 25 cm × 12 cm spacing (53.40 q/ha). In general, during both the years, the first date of transplanting reported higher mean grain yield (59.16 q/ha) as compared to second date of transplanting (56.11 q/ha) and also higher mean grain yield (59.88 q/ha) was recorded in rice varieties transplanted under wider spacing (30 cm × 10 cm) in comparison to closer spacing of 20 cm × 15 cm (57.85 q/ha) and 25 cm × 12 cm (55.15 q/ ha). The wider spacing of 30 cm × 10 cm resulted in a grain yield increase of approximately 3.50% compared to the closer spacing of 20 cm × 15 cm. Similarly, compared to the closer spacing of 25 cm × 12 cm, the wider spacing exhibited a grain yield increase of approximately 8.58%. Among the spacing, the highest seed yield was recorded by 40 × 40 cm^2 while it was at par between 20 × 20 cm^2 and 30 × 30 cm^2. The increase in seed yield under 40 × 40 cm^2 might be due to better root development and more sunlight interception which might have led to more nutrient uptake to the source and ultimately to greater grain yield (Zhimomi *et al.,* 2021). Most of the traits were found superior in 25 cm ×25 cm and 20 cm ×20 cm spacing which suppose Bara variety performed better in wider than narrower spacing. Comparing the results of the two planting distances (25 cm ×25 cm and 20 cm × 20 cm), it can be seen that spacing of 25×25 cm performed the best for most of the agro-morphological characters evaluated (Anwari *et al.,* 2019).The wider spacing (30 cm × 10 cm) recorded higher biological yield (138.75 q/ha) followed by 20 cm × 15 cm spacing (134.62 q/ha) and 25 cm × 12 cm spacing (127.10 q/ha) and were statistically different from each other. The reason for higher yield and yield contributing characters was mainly because higher PAR interception was observed under wider spacing as compared to closer spacing which led to better photosynthetic activity and higher yield contributing characteristics. Thus, higher yield contributing characteristics led to higher biological, straw and grain yield under wider spacing as compared to closer spacing (Sharma *et al*., 2011). Closer spacing hinders intercultural operations, increases competition among the plants for nutrients, air, light, which results in weaker plants, mutual shading thus favours more straw yield than grain yield. Optimum plant spacing ensures plant to grow properly with their aerial and underground parts by utilizing more solar radiation and nutrients (Sultana *et al.,* 2012).Similar results were observed in case of straw yield. These results are also supported by Oteng *et al.* (2013). Wider spacing produced better yield due to proper availability of nutrients. But on other hand in closer spacing the nutrient competition is there in between plants as reported by Hasan *et al.* (2015).

Conclusion

The findings underscore the pivotal role of optimal plant spacing in maximizing rice yield and enhancing yield-contributing characters. Wider spacing configurations, exemplified by the 30 cm × 10 cm arrangement, not only facilitated superior photosynthetically active radiation interception but also mitigated competition for crucial resources such as nutrients and light. This reduction in intraplant competition fostered robust plant growth, bolstering both yield and quality parameters. Moreover, the observed limitations associated with closer spacing configurations, including hindered intercultural operations and competition among plants, underscore the importance of adopting spacing strategies that prioritize plant vitality and resource utilization efficiency. By strategically modifying plant and row spacing, farmers can harness the full potential of solar radiation and soil nutrients, thereby optimizing rice yield without incurring additional costs. In essence, these findings advocate for a paradigm shift towards precision spacing practices in rice cultivation, emphasizing the imperative of balancing plant density with resource availability to achieve sustainable, high-yielding cropping systems. This research underscores the transformative potential of spacing optimization as a cost-effective approach to bolstering agricultural productivity and resilience in rice farming landscapes.

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