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Effects of radiation and plant population on growth and yield attributes of wheat

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ABSTRACT

Radiation plays a crucial role for growth and yield of wheat. A field experiment was conducted at the Field Laboratory of Agrotechnology Discipline of Khulna University in Bangladesh during November 2018 to March 2019 to study the effect of radiation levels and plant population on growth and yield attributes of wheat. The study was set out in the randomized complete block design with four radiation levels (full sunlight, 75% light, 55% light, 25% light) and three plant population densities (160 plant/m^2, 200 plant/m^2, 230 plant/m^2) that replicated thrice. Growth and yield attributes of wheat were generally similar between two light levels (full sunlight, 75% light) and two plant densities (200 plant/m^2, 230 plant/m^2). However, the attributes were usually minimum at 25% light. The interaction effect of full sunlight or 75% light with optimal (200 plant/m^2) or maximal (230 plant/m^2) plant densities produced statistically similar plant height, leaf number, tiller number, total dry matter, grain yield, straw yield, and biological yield. Therefore, combination of 75% light with 230 plant/m^2 is suggested for growing wheat in light limited areas and in agroforestry system with acceptable yield.

Keywords: light intensity, plant density, 55% light, harvest index, agroforestry

INTRODUCTION

Wheat is the most important and extensively cultivated cereal that supplies majority of protein and calories for the developing countries and can provide 20% food resources for the people worldwide (Braun et al., 2010; Farzi and Bigloo, 2010). In Bangladesh, wheat ranks second just after rice in terms of area and production. Bangladeshi farmers grow wheat fitting it in their intensive rice-based cropping system.

However, the production of wheat is highly variable due to agro-climatic variations within the country. Though the demand of wheat (cereal grain) is increasing due to rapid population growth, area under the crop is decreasing every year in the country. Moreover, Bangladesh is one of the most sufferers of climate change due to its geographical location and low socioeconomic status (Chowdhury et al., 2021) that makes it vulnerable to food security. Yield of wheat is highly vulnerable due to climate change particularly rise of temperature. An increase of 2 °C temperature may cause 15%-30% yield reduction of wheat by 2040 worldwide (Moore and Lobell, 2014; Zhao et al., 2017). Thus, shortage of food in such a highly climate-vulnerable developing country like Bangladesh is a likely phenomenon. Therefore, Bangladesh as well as other developing, under-developing, and even developed countries of the world need to take steps for producing more food in the land that remains fallow due to climate issues.

Solar radiation i.e. light is the crucial climatic factor directly influences the growth and yield of wheat — a cool season crop that prefers cool weather during vegetative growth and warm weather at maturity. Light determines photo-morphogenesis, growth and yield of crop through photosynthesis (Avercheva et al., 2009; Bozorgi et al., 2011). Morphological and physiological adaptations of plants towards light aim to maintain maximal rate of photosynthesis. Deficient light intensities tend to reduce plant growth and yield (Strain and Cure, 1985) through reduction of photosynthesis. Likewise, excessive light reduces crop yield through light stress (Hasanuzzaman et al., 2012). The light level at which the process of photosynthesis is maximized and plant growth is greatest termed as optimum light for the crop (Lichtenthaler, 1996). Light level can be reduced by 30% - 44% in an apricot-based agroforestry system (Zhang et al., 2018) and by 25% - 60% due to presence of low cloud (Reinhardt et al., 2010). Limited light availability due to presence of aerosols, air pollutants, or continuous cloud during critical growth stages such as panicle differentiation or grain-filling appears as a challenge of crop production and often induce great loss of grain yield and quality in many parts of the world (Mu et al., 2010; Janardhan et al., 1980).

Plant density is another important agronomic factor that manipulates crop microclimate and affects growth, development, and yield of crops. Plant density influences microclimate including interception of radiation (Sangoi, 2001). Crop yield is generally highest at optimal plant density that ensures equal distribution of resources including light (Dong et al., 2014) and beyond optimal density, yield decreases due to increase of competition for radiation (Duncan, 1986; Pommel and Bonhomme, 1998; Purcell et al., 2002). However, dense planting can increase leaf area index, photosynthesis, and grain yield (Nakano et al., 2012). Thus, it is imperative to determine what extent of light reduction and at what plant density a wheat plant can acclimatize without significant yield loss that directs the objective of the present study, which is to evaluate the effect of light intensity and plant density on growth and yield of wheat.

MATERIALS AND METHODS

Experimental site, treatment and design

The field experiment was conducted with four levels of radiation (full sunlight, 75% light, 55% light, 25% light) and three wheats ‘BARI Gom 25’ plant populations [160 plant/m^2, 200 plant/m^2 (recommended), 230 plant/m^2] during November 2018 to March 2019 at the Field Laboratory of Agrotechnology Discipline of Khulna University, Bangladesh. ‘BARI Gom 25’ — a wheat variety developed by Bangladesh Agricultural Research Institute (BARI) in 2010 — is a semi-dwarf (95-100 cm), awn less, synthetic spring wheat variety having deep green broad-leaf and erect flag leaf. The plant is also deep green having medium wax coating in the panicle, stem, and leaf sheath. Spike is long that contains large, white, and glossy grains. This variety is resistant to leaf rust and leaf blight, and tolerant up to medium salt (8-10 ds/m) that makes it suitable for southern coastal region (e.g. Khulna) of Bangladesh. The experimental field is under Tidal Ganges Floodplain having clay loam soil that contains 2.03% organic matter, 0.125% total nitrogen, 10.20 ppm available phosphorus, 5.2 ppm available potassium, 1.57 ppm zinc, and 0.75 ppm boron (Saha et al., 2019) and a pH of 7.5. It has humid, wet, and hot summer and dry, mild winter with an average annual temperature 26.3 °C, rainfall 187.8 cm, and relative humidity 87.4%. The field was prepared through ploughing and cross ploughing followed by laddering to obtain the desirable tilt. The field was labeled after removing weeds and stubbles; divided into 36 experimental unit each measuring 3.0 m x 2.0 m maintaining 1 m distance between plots and fertilized with recommended dose of urea (220 kg/ha), triple superphosphate (160 kg/ha), muriate of potash (45 kg/ha), gypsum (115 kg/ha), and cow dung (7 t/ha). One-third of urea and full dose of other fertilizers were applied during final land preparation, and remaining urea was applied in two equal splits at 20 and 40 days after sowing (DAS). The number of seeds were calculated following plant density and sowed directly in line maintaining 20 cm distance between seeds on 16 November 2018. As the crop stand established, weedy species such as Bermuda grass (*Cynodon dactylon*), Java grass (*Cyperus rotundus*), and goosefoot (*Chenopodium album*) were grown. Weeding and other intercultural operations (gap filling, irrigation, and insect-pest control) were done as per requirement. The two-factor experiment (radiation level and plant density) was set out following randomized complete block design (RCBD) to identify the effects of radiation and plant density with three replications (Woldekiros, 2020).

Measurement of light

Two type of screens that consists of white net and white markin cloth were collected from the market and placed over the plot on 21 December at 35 DAS. Light under screens such as one layer of white net or two layer of white net and two layer of markin cloth were measured several times using Digital Lux Meter (LX1010BS, Taiwan). The light measurements showed that light under one layer and two layer of white nets were 75% and 55% of full sunlight, respectively and it was just 25% under two layers of markin cloth.

Therefore, our treatment consists of four light levels [full sunlight (open field), 75% light (light under one layer of white net), 55% light (light under two layer of white net), and 25% light (light measured under two layer of markin cloth)]. Light intensity at upper canopy and lower canopy from the open field and under the screens were measured at 45, 60, 75, and 90 DAS using the lux meter. Light level at upper canopy ranged from 57 795 lux (open field) to 15 026 lux (under two layer of markin cloth i.e. 25% light) during the experimental period.

Growth and yield parameters

Five plants from each plot were selected randomly to measure plant growth parameters such as plant height (cm), number of leaves per plant, number of tillers per plant, total dry matter per plant (g), spike length (cm), number of spikelet per spike at 45, 60, 75, and 90 DAS (Woldekiros, 2020; Gezahegn et al., 2022). Collected plants were placed in a labelled brown paper bag and dried in an oven (60 °C temperature for 48 hours) to get the total dry matter. Before harvesting, five plants were collected randomly from each plot leaving the central one m^2 area to determine the yield attributes such as number of spike, length of spike (cm), and number of grains per spike. Wheat was harvested from central one m^2 area (to avoid the border effect of light) of each plot with sickles and sun dried for 2-3 days; threshed, winnowed, separated the clean grains, and sundried to calculate the grain yield (weight of grain/m^2), straw yield (biomass except grain), biological yield (grain yield + straw yield) and finally expressed these parameters as t/ha (Woldekiros, 2020; Gezahegn et al., 2022). A sample of thousand grain from each plot weighed to measure the 1000-grain weight. The harvest index was calculated with the ratio of grain yield and biological yield and expressed as percentage.

Statistical analyses

The variances of the collected data were analyzed as per the experimental design (Woldekiros, 2020) using Statistix 10 statistical program (2105 Miller Landing Rd, Tallahassee, FL 32312, USA). Duncan's Multiple Range Test at $P \leq 0.05$ separated the treatment means. The error bar in the graph represents mean±standard error (SE).

RESULTS

Radiation at wheat canopy

Average daily radiation at upper and lower canopy of wheat varied due to screens during the growing period; measuring highest radiation at full sunlight that decreased as the layer of screens increased (Figure 1A). However, the radiation at full sunlight and 75% light were similar at lower canopy of wheat. Similarly, lower canopy radiation at 55% light and 25% light did not differ (Figure 1A). Radiation at upper canopy remained unaltered but varied at lower canopy due to plant density (Figure 1B). During the entire growing period of 114 days (16 November 2018 to 9 March 2019), the daily rainfall ranges from 0 mm – 75.8 mm, daily maximal air temperature ranges from 19.4 °C – 33.5 °C, daily minimal air temperature from 8 °C – 22 °C, and daily relative humidity (RH) (900, UTC+6) from 37% - 95% (Figure 2).

Effects of radiation levels and plant population on wheat plant height

The highest plant height was recorded from the wheat grown in full sunlight and the lowest from 25% light at different DAS (45, 60, 75, and 90).

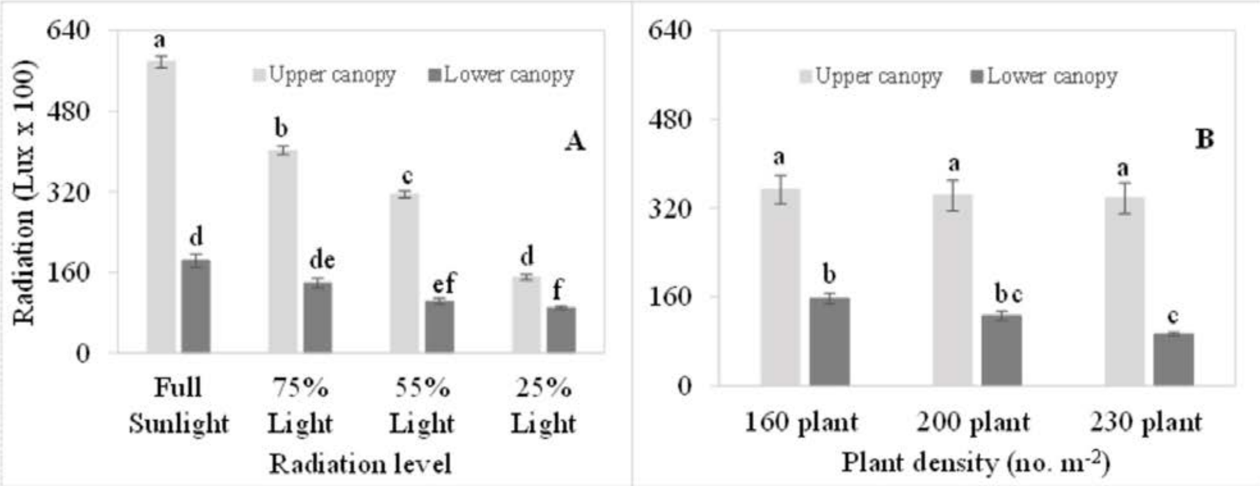

Figure 1. Average daily radiation at upper (light gray bar) and lower (dark gray bar) canopy of wheat as influenced by the light level (A), and plant density (B) during the growing period at Khulna, Bangladesh (means within a treatment (radiation level or plant density) having similar letter (s) did not differ at 5% level of significance according to Duncan's Multiple Range Test. The error bars represent mean ± SE)

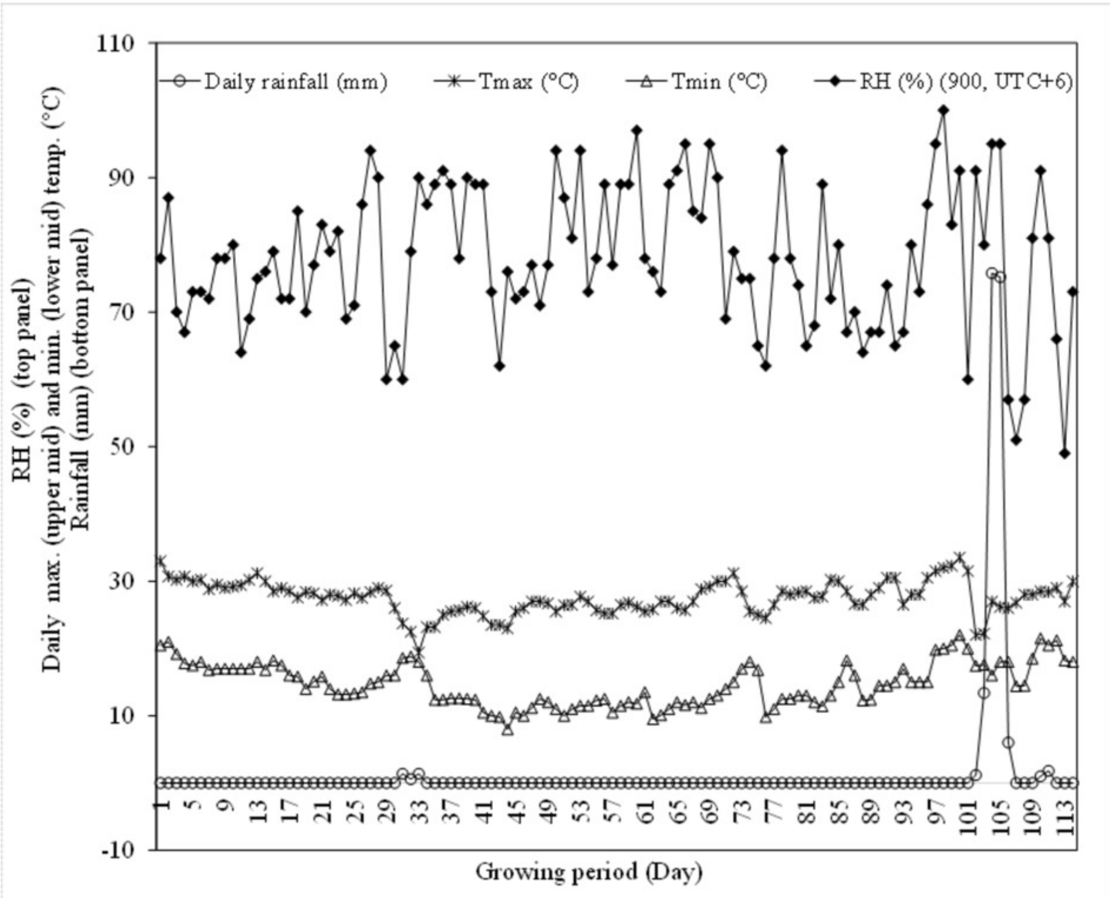

Figure 2. Daily relative humidity (top panel, %) at 9:00 am (UTC+6), daily maximal and minimal air temperatures (°C) (upper and lower middle panels, respectively), and daily rainfall (mm) (bottom panel) during the experimental period (16 November 2018 to 9 March 2019, total growing period 114 days) (Tmax, Tmin and RH (%) are daily maximal, minimal air temperatures (°C), and relative humidity (%), respectively. Weather data obtained from nearby Khulna Meteorological Station (less than 50 m) of the experimental field)

However, almost similar plant height was measured among the light levels at harvest (Figure 3A). The highest plant height was obtained generally from the recommended (200 plant/m^2) or highest (230 plant/m^2) plant density and the lowest from lowest plant density (160 plant/m^2) for almost all DAS (45, 60, 75). However, plant height did not differ among plant pollutions at harvest (Figure 3B). Likewise, plant height generally did not differ between interaction of radiation level and plant population at harvest. However, interaction of lowest plant density (160 plant/m^2) with lowest (25%) light sometimes resulted lowest plant height at early growth stages (e.g. at 45 DAS) (Table 1).

Effects of radiation levels and plant population on leaf and tiller number of wheat

Leaf number/plant differed among the radiation levels at 45 DAS only. Highest leaf number was obtained from full sunlight and lowest from 25% light (Table 2). Tiller number/plant differed among the radiation levels at all DAS (45, 60, 75, and 90); the highest tiller number was generally recorded from 75% light that was statistically similar with full sunlight and the lowest from 25% light (Table 2). Leaf number/plant differed due to plant population at 45 and 75 DAS; the lowest plant population (160 plant/m^2) usually resulted highest leaf number and vice versa. However, plant population had no effect on tiller number/plant (Table 3). Likewise, similar leaf number and tiller number were recorded due to interactions of radiation and plant population. However, differences were recorded at growth stages if lowest light (25%) is included in the interactions (Table 4).

Table 1. Interaction effect of radiation levels and plant population on plant height of wheat at different days after sowing (DAS)

Treatment Combination ^{a}	Plant height (cm) ^{b}				
	45 DAS	60 DAS	75 DAS	90 DAS	At Harvest
P_1S_1	62.33^{a}	82.67^{abc}	92.13^{ab}	95.33^{a}	91.27^{ab}
P_2S_1	65.33^{a}	91.40^{a}	93.33^{ab}	94.60^{ab}	91.30^{ab}
P_3S_1	67.40^{a}	89.07^{ab}	92.67^{ab}	95.20^{a}	92.40^{ab}
P_1S_2	58.40^{abc}	76.53^{cd}	84.77^{cd}	92.20^{ab}	89.72^{ab}
P_2S_2	59.65^{ab}	81.67^{bc}	90.87^{abc}	95.67^{a}	90.50^{ab}
P_3S_2	62.19^{a}	87.93^{ab}	91.62^{abc}	93.50^{ab}	92.47^{ab}
P_1S_3	48.27^{cd}	76.20^{cd}	87.87^{bcd}	92.70^{ab}	92.17^{ab}
P_2S_3	61.67^{a}	82.07^{abc}	91.32^{abc}	93.73^{a}	93.08^{ab}
P_3S_3	68.67^{a}	90.07^{ab}	95.27^{a}	96.90^{a}	96.04^{a}
P_1S_4	49.33^{bcd}	65.20^{e}	82.59^{d}	84.70^{c}	84.07^{b}
P_2S_4	65.13^{a}	77.20^{c}	88.37^{a-d}	89.36^{bc}	90.87^{ab}
P_3S_4	44.73^{d}	69.73^{de}	86.67^{bcd}	90.51^{abc}	88.57^{ab}
Level of significance	0.01	0.01	0.05	0.05	0.05
CV (%)	6.02	3.97	2.70	2.52	3.36

^{a} P_1 = 160 plant/m^2, P_2 = 200 plant/m^2, P_3 = 230 plant/m^2; S_1 = Full sunlight, S_2 = 75% light, S_3 = 55% light, S_4 = 25% light. ^{b} Means in a column followed by the similar letters are not statistically different according to Duncan's Multiple Range Test ($P \le 0.05$). CV = Coefficient of variation.

Table 2. Effect of radiation levels on leaf and tiller number of wheat at different days after sowing (DAS) [a]

Radiation level	Leaf number/plant				Tiller number/plant			
	45 DAS	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
Full sunlight	8.02[a]	11.54	15.07	14.49	3.35[a]	4.05[ab]	5.24[a]	5.68[a]
75% light	6.73[ab]	12.13	15.58	15.52	3.83[a]	4.38[a]	4.90[ab]	5.81[a]
55% light	5.22[b]	11.78	14.86	14.30	2.70[b]	3.67[b]	4.44[b]	4.95[ab]
25% light	4.48[c]	12.70	13.94	13.14	2.26[b]	3.76[ab]	4.21[b]	4.70[b]
Level of significance	0.01	NS	NS	NS	0.01	0.05	0.01	0.05
CV (%)	21.19	16.51	13.34	15.77	15.74	12.25	12.94	13.79

[a] Means in a column followed by the similar letters are not statistically different according to Duncan's Multiple Range Test (*P*≤0.05). CV = Coefficient of variation.

Table 3. Effect of plant population on leaf and tiller number of wheat at different days after sowing (DAS) [a]

Plant Population	Leaf number/plant				Tiller number/plant			
	45 DAS	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
160 plant/m^2	7.41[a]	12.08	16.30[a]	14.16	2.91	3.90	4.79	5.16
200 plant/m^2	5.25[b]	12.45	14.88[ab]	14.46	3.04	4.18	4.75	5.41
230 plant/m^2	5.66[b]	11.58	13.40[b]	14.46	3.16	3.82	4.55	5.30
Level of significance	0.01	NS	0.01	NS	NS	NS	NS	NS
CV (%)	21.19	16.51	13.34	15.77	15.74	12.25	12.94	13.79

[a] Means in a column followed by the similar letters are not statistically different according to Duncan's Multiple Range Test (*P*≤0.05). CV = Coefficient of variation.

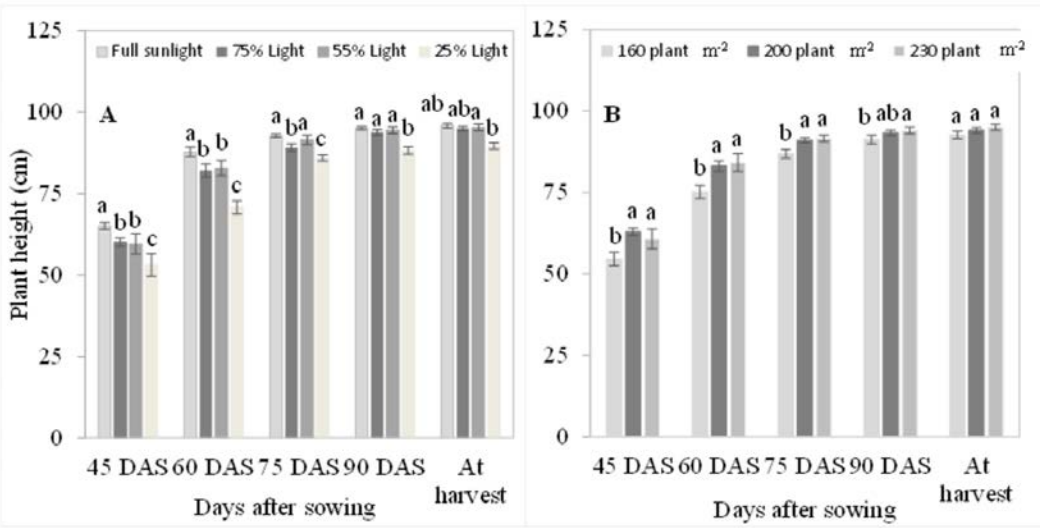

Figure 3. Plant height of wheat as affected by radiation levels (A) and plant population (B) at different days after sowing (means in a same time point (e.g., 45 DAS) followed by the similar letters are not statistically different according to Duncan's Multiple Range Test (*P*≤0.05). The error bars represent mean ± SE)

Table 4. Interaction effect of radiation levels and plant population on leaf number and tiller number of wheat at different days after sowing (DAS) [a]

Treatment Combination [b]	Leaf number/plant				Tiller number/plant			
	45 DAS	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
P_1S_1	10.41^{a}	12.29	17.97^{a}	15.61	3.53^{a}	4.10^{abc}	5.20^{ab}	5.60
P_2S_1	6.88^{abc}	12.53	16.05^{ab}	14.80	3.23^{a}	4.60^{ab}	5.67^{a}	6.07
P_3S_1	6.78^{abc}	9.80	11.20^{b}	13.05	3.30^{a}	3.47^{bc}	4.86^{ab}	5.40
P_1S_2	8.57^{ab}	11.59	15.25^{ab}	12.83	3.86^{a}	4.10^{abc}	4.43^{ab}	5.17
P_2S_2	4.27^{c}	9.77	14.84^{ab}	16.40	3.70^{a}	3.87^{abc}	4.67^{ab}	6.00
P_3S_2	7.34^{abc}	15.03	16.64^{ab}	17.32	3.93^{a}	5.20^{a}	5.60^{a}	6.27
P_1S_3	6.42^{bc}	11.37	16.61^{ab}	14.92	2.71^{ab}	3.53^{bc}	5.00^{ab}	5.07
P_2S_3	4.74^{bc}	12.48	15.23^{ab}	13.12	2.63^{ab}	3.87^{abc}	4.33^{ab}	4.80
P_3S_3	4.49^{c}	11.51	12.73^{ab}	14.87	2.76^{ab}	3.60^{bc}	4.00^{ab}	5.00
P_1S_4	4.24^{c}	13.08	15.37^{ab}	13.29	1.53^{b}	3.86^{abc}	4.53^{ab}	4.80
P_2S_4	5.15^{bc}	15.03	13.43^{ab}	13.54	2.60^{ab}	4.40^{abc}	4.36^{ab}	4.76
P_3S_4	4.05^{c}	10.00	13.03^{ab}	12.58	2.67^{ab}	3.03^{c}	3.73^{b}	4.53
Level of significance	0.05	NS	0.05	NS	0.05	0.01	0.05	NS
CV (%)	21.19	16.51	13.34	15.77	15.74	12.25	12.94	13.79

[a] Means in a column followed by the similar letters are not statistically different according to Duncan's Multiple Range Test ($P \leq 0.05$). [b] P_1 = 160 plant/m^2, P_2 = 200 plant/m^2, P_3 = 230 plant/m^2; S_1 = Full sunlight, S_2 = 75% light, S_3 = 55% light, S_4 = 25% light. CV = Coefficient of variation.

Effects of radiation levels and plant population on total dry matter production of wheat

The highest total dry matter was produced from full sunlight, which was statistically similar with 75% light at 45, 60, and 90 DAS, and the lowest from 25% light (Figure 4). Plant population had significant effect on dry matter production at 45 DAS only; the highest dry matter was obtained from highest plant population (230 plant/m²) and the lowest from lowest plant population (160 plant/m²) (Table 5). Though the interaction effect of radiation levels and plant population on dry matter varied at all stages except at 60 DAS (Table 6), it was usually lowest when the lowest light level has been included in the interactions (Table 6).

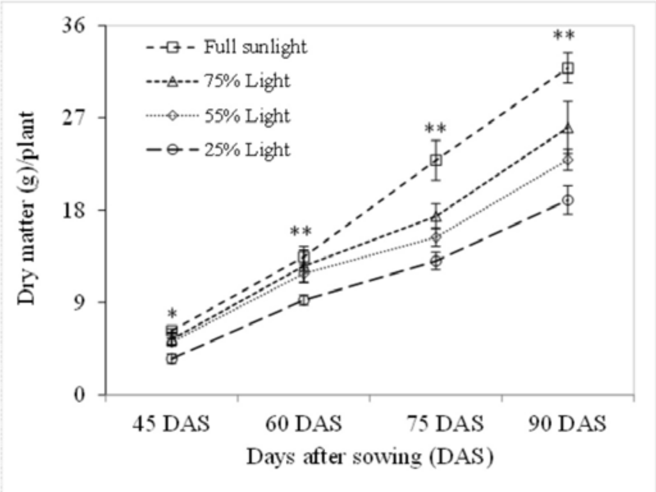

Figure 4. Effect of radiation levels (full sunlight, 75% light, 55% light, 25% light) on dry matter production (g/plant)) of wheat at different days after sowing (DAS) (* = Significant at 5%; ** = Significant at 1% level of significance)

Effects of radiation levels and plant population on yield and yield contributing attributes of wheat

Length of spike (17.73 cm), grain (no.)/spike (50.27), 1000-grain weight (51.88 g), grain yield (3.82 t/ha), straw yield (4.81 t/ha), biological yield (8.63 t/ha), and harvest index (44.25%) were highest in full sunlight and lowest at 25% light. However, length of spike, grain (no.)/spike, and harvest index were statistically similar between full sunlight and 75% light (Table 7). Number of spikelet/spike also varied among the radiation level (data not shown).

Table 5. Effect of plant population on dry matter of wheat at different days after sowing (DAS) [a]

Plant Population	Dry matter (g/plant)			
	45 DAS	60 DAS	75 DAS	90 DAS
160 plant/m²	4.30[b]	10.49	17.38	26.70
200 plant/m²	5.24[ab]	11.92	17.33	25.57
230 plant/m²	5.65[a]	12.84	16.76	23.19
Level of significance	0.01	NS	NS	NS
CV (%)	19.67	25.44	24.14	19.32

[a] Means in a column followed by the similar letters are not statistically different according to Duncan's Multiple Range Test ($P \leq 0.05$). CV = Coefficient of variation.

The highest length of spike (16.78 cm) and grain (no.)/spike (45.46) were found in 160 plant/m² and 200 plant/m², respectively and the highest grain yield (3.16 t/ha), straw yield (4.04 t/ha), biological yield (7.20 t/ha) were recorded from 230 plant/m². However, the lowest length of spike (15.27 cm) and grain (no.)/spike (42.02) were recorded at highest plant population (230 plant/m²) and the lowest grain yield (2.74 t/ha), straw yield (3.52 t/ha), and biological yield (6.25 t/ha) were recorded from the lowest density (160 plant/m²) (Table 8).

The interaction effect of radiations and plant populations revealed that full sunlight or 75% light with optimal or maximal plant population resulted higher grain yield, straw yield, and biological yield compared to interaction of 25% light with any plant populations (Table 9).

DISCUSSION

Radiation at wheat canopy

The screens reduced the radiation levels both at upper and lower canopy of wheat indicating that the screens were effective against light penetration. Shade net reduced the light proportionately to the shade net factor (Kittas et al., 2009; Kabir et al., 2020). However, light level did not vary at upper canopy of wheat but at lower canopy due to plant population suggesting the effect of higher plant density on light penetration at lower part of plant.

Table 6. Interaction effect of radiation levels and plant population on dry matter of wheat at different days after sowing (DAS)

Treatment Combination [a]	Dry matter (g/plant) [b]			
	45 DAS	60 DAS	75 DAS	90 DAS
P_1S_1	6.46[ab]	12.22	20.99[ab]	30.23[ab]
P_2S_1	6.11[ab]	15.24	25.46[a]	33.21[a]
P_3S_1	6.14[ab]	12.82	22.12[ab]	32.15[a]
P_1S_2	3.72[bc]	9.833	15.02[ab]	19.49[ab]
P_2S_2	5.77[ab]	10.93	16.77[ab]	27.72[ab]
P_3S_2	6.69[a]	16.86	20.40[ab]	30.93[ab]
P_1S_3	4.85[abc]	11.51	17.95[ab]	23.94[ab]
P_2S_3	5.06[abc]	11.51	14.44[ab]	22.75[ab]
P_3S_3	5.43[ab]	12.44	13.65[ab]	22.02[ab]
P_1S_4	2.18[c]	8.39	13.09[b]	19.11[ab]
P_2S_4	4.02[abc]	10.01	12.84[b]	20.61[ab]
P_3S_4	4.33[abc]	9.25	13.16[b]	17.19[b]
Level of significance	0.05	NS	0.05	0.05
CV (%)	19.67	25.44	24.14	19.32

[a] P_1 = 160 plant/m^2, P_2 = 200 plant/m^2, P_3 = 230 plant/m^2; S_1 = Full sunlight, S_2 = 75% light, S_3 = 55% light, S_4 = 25% light. [b] Means in a column followed by the similar letters are not statistically different according to Duncan's Multiple Range Test ($P \leq 0.05$). CV = Coefficient of variation.

Table 7. Effect of radiation levels on yield and yield contributing characters of wheat at harvest [a]

Radiation level	Length of spike (cm)	Grain (no.) / spike	1000 grain weight (g)	Grain Yield (t/ha)	Straw Yield (t/ha)	Biological Yield (t/ha)	HI (%)
Full sunlight	17.73[a]	50.27[a]	51.88[a]	3.82[a]	4.81[a]	8.63[a]	44.24[a]
75% light	16.38[ab]	47.30[a]	49.34[a]	3.17[b]	3.98[b]	7.14[b]	44.25[a]
55% light	15.73[b]	41.99[b]	47.97[a]	2.94[b]	3.69[b]	6.63[b]	44.14[a]
25% light	14.83[b]	36.04[c]	42.81[b]	1.88[c]	2.85[c]	4.73[c]	39.81[b]
Level of significance	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CV (%)	7.59	7.34	6.90	12.96	12.96	12.21	4.42

[a] Means in a column followed by the similar letters are not statistically different according to Duncan's Multiple Range Test ($P \leq 0.05$). CV = Coefficient of variation.

Table 8. Effect of plant populations on yield and yield contributing characters of wheat at harvest [a]

Plant Population	Length of spike (cm)	Grain (no.) / spike	1000 grain weight (g)	Grain Yield (t/ha)	Straw Yield (t/ha)	Biological Yield (t/ha)	HI (%)
160 plant/m^2	16.78^a	44.28^{ab}	49.03	2.74^b	3.52^b	6.25^b	43.27
200 plant/m^2	16.45^{ab}	45.46^a	48.67	2.96^{ab}	3.93^a	6.89^{ab}	42.73
230 plant/m^2	15.27^b	42.02^b	46.29	3.16^a	4.04^a	7.20^a	43.34
Level of significance	0.05	0.05	NS	0.05	0.05	0.05	NS
CV (%)	7.59	7.34	6.90	12.96	12.96	12.21	4.42

[a] Means in a column followed by the similar letters are not statistically different according to Duncan's Multiple Range Test ($P \leq 0.05$). CV = Coefficient of variation.

The weather data show the typical characteristics of Bangladeshi winter, which extends December to February. The winter was mild (lowest temperature, 8 °C), and dry [rainfall occurs only nine days (three in December, four in February, and two in March), lowest RH, 37%].

Effects of radiation levels and plant population on wheat plant height

Light is an intrinsic component of photosynthesis to produce carbohydrate for plant growth, development and yield. At low radiation (e.g. 25% light), wheat plant height decreased irrespective of plant population density due to deficiency of adequate light for photosynthesis. However, plants grown at low light (55% light) started to increase their height at the later stage of plant growth e.g. at harvest and reached at maximum. Even plants grown at 25% light at harvest had the similar height of full sunlight and 75% light indicating that the exclusion of light with a menace (screens) increases plant height. Similar findings were observed for other plants (Yang et al., 2008; Wang et al., 2009). Plant height in bell pepper also increased under low light (Kabir et al., 2020; Kabir et al., 2022). Highest plant height at highest plant population might be due to competition of plant for light as was recorded for maize (Sharma and Adamu, 1984, Yaday and Warsi, 1986).

Effects of radiation levels and plant population on leaf and tiller number of wheat

As the plant density decreased, the leaf number increased at full sunlight and increasing the plant density decreased the number of leaves especially when plants were grown at low light regime. At an early stage of growth e.g. 45 DAS, full sunlight and low plant population (160 plant/m^2) produced higher number of leaf due to low competition for light and other resources. Leaf number/plant decreased with low light (high shade) in bell pepper (Kabir et al., 2022). Curtail of light and increase of plant population decreased tiller number due to insufficient light availability and increased competition among the plants for resources. Light environment can modify tiller appearance in cereal crops, mainly if canopy of plants competes for light (Abeledo et al., 2014).

Effects of radiation levels and plant population on total dry matter production of wheat

Light plays a crucial role in photosynthesis; at full sunlight, higher rate of photosynthesis occur that leads to higher dry matter production. When plants grown at low light (e.g. 25%), the dry matter production reduced drastically due to low plant growth (Staver et al., 2001). Higher plant density (200 or 230 plant/m^2) increased dry matter production due to more number of plants per unit area in the present study. Dry matter accumulation increased in maize and sunflower with higher plant density (Ferreira and Abreu, 2001; Sedghi et al., 2008). However, at reduced light (e.g. 25%); dry matter did not increase whatever the plant populations were.

Table 9. Interaction effect of radiation levels and plant population on yield and yield contributing characters of wheat at harvest [a]

Treatment Combination [b]	Length of spike (cm)	Grain (no.) / spike	1000 grain weight (g)	Grain Yield (t/ha)	Straw Yield (t/ha)	Biological Yield (t/ha)	HI (%)
P_1S_1	18.42[a]	50.28[ab]	52.25[ab]	3.66[abc]	4.31[ab]	7.96[ab]	45.76[a]
P_2S_1	17.67[ab]	52.40[a]	53.53[a]	3.86[ab]	5.00[a]	8.86[a]	43.44[ab]
P_3S_1	17.10[abc]	48.12[abc]	49.86[ab]	3.94[a]	5.13[a]	9.07[a]	43.53[ab]
P_1S_2	16.85[abc]	48.60[abc]	47.83[abc]	2.72[b-f]	3.70[cd]	6.44[bcd]	42.36[ab]
P_2S_2	16.12[abc]	49.13[abc]	50.33[ab]	3.23[a-d]	4.11[a-d]	7.33[abc]	44.11[ab]
P_3S_2	16.19[abc]	44.43[a-d]	49.85[ab]	3.55[abc]	4.12[a-d]	7.67[ab]	46.26[a]
P_1S_3	16.59[abc]	42.12[bcd]	50.36[ab]	2.95[a-e]	3.68[a-d]	6.63[bcd]	44.51[a]
P_2S_3	16.37[abc]	43.27[a-d]	47.21[abc]	2.56[c-f]	3.54[cde]	6.11[b-e]	41.85[ab]
P_3S_3	14.23[bc]	40.58[cd]	46.33[abc]	3.29[a-d]	3.85[bcd]	7.15[abc]	46.05[a]
P_1S_4	15.27[ab]	36.13[d]	45.70[abc]	1.62[f]	2.39[e]	4.00[e]	40.44[ab]
P_2S_4	15.67[ab]	37.05[d]	43.62[bc]	2.19[def]	3.08[de]	5.27[cde]	41.49[ab]
P_3S_4	13.55[b]	34.9[d]	39.11[c]	1.84[ef]	3.07[de]	4.92[de]	37.52[b]
Level of significance	0.05	0.05	0.05	0.05	0.05	0.05	0.05
CV (%)	7.59	7.34	6.90	12.96	12.96	12.21	4.42

[a] Means in a column followed by the similar letters are not statistically different according to Duncan's Multiple Range Test ($P \le 0.05$). [b] P_1 = 160 plant/m^2, P_2 = 200 plant/m^2, P_3 = 230 plant/m^2; S_1 = Full sunlight, S_2 = 75% light, S_3 = 55% light, S_4 = 25% light. CV = Coefficient of variation.

Effects of radiation levels and plant population on yield and yield contributing attributes of wheat

Yield is the ultimate results of combined effect of yield contributing characters. As yield-contributing characters affected by variations of radiation and plant population, the final grain yield was also affected. Changes in radiation influence both photosynthetic light and carbon-use efficiency, and will ultimately affect total grain yield (Ball et al., 2000). Yield of crops is reduced at low light (Islam et al., 1993; Slafer et al., 2001; Kabir et al., 2022). The grain yield was decreased by 7.43% for lowest plant population (160 plant/m^2) and increased by 6.75% for highest plant population (230 plant/m^2) over the optimum plant population (200 plant/m^2) in the present study. Increased plant population could lead to increased yields providing availability of resources (Bavec and Bavec, 2002). However, interaction of 75% light with optimal plant density resulted statistically similar yield with the interaction of full sunlight and optimal or maximal plant density in the present study suggesting suitability of wheat cultivation under reduced light (e.g. 75%) without significant yield loss. In fact, the yield of wheat and bell pepper increased under shade in Mediterranean and US (Georgia) conditions, respectively (Arenas-Corraliza et al., 2019; Díaz-Pérez et al., 2020).

CONCLUSIONS

The growth parameters were generally similar between full sunlight and 75% light, optimal and maximal plant density and between their interactions. Though the interaction effect of full sunlight or 75% light with optimal or maximal plant density produced statistically similar yield; the highest numerical yield (3.94 t/ha) was obtained from the interaction of full sunlight and highest plant density, and the interaction of 75% light and highest plant density resulted very similar yield (3.55 t/ha). Therefore, the combination of 75% light with the highest plant density (230 plant/m^2) can be suggested for producing wheat in the regions of low light intensity and in agroforestry system. However, similar trials need to be conducted in other parts of the country to verify the results as well as to validate the current suggestion.

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