Khulna University Studies Volume 19(2): 87-96 : 2022

ORIGINAL ARTICLE **LIFE SCIENCE**

DRY MATTER ALLOCATION AND GRAIN YIELD OF WHEAT AS INFLUENCED BY SOLAR RADIATION LEVEL AND PLANT DENSITY

Md. Imran Hossain, Khalid Hasan, Md. Yasin Ali and Md. Yamin Kabir*

Agrotechnology Discipline, Khulna University, Khulna-9208, Bangladesh

KUS: 22/39: 22092022

Manuscript submitted: September 22, 2022 Accepted: November 22, 2022

Abstract

An experiment was conducted from November 2018 to March 2019 to identify the effect of radiation levels and plant population on dry matter allocation and yield of wheat with the variety 'BARI Gom 25'. The study was set out in the Randomized Complete Block Design with four radiation levels (full sunlight, 75% light, 55% light and 25% light) and three plant densities (160 plants m^{-2}, 200 plants m^{-2}, 230 plants m^{-2}) that replicated thrice. Full sunlight or 75% light in combination with optimal plant density (200 plants m^{-2}) resulted maximum culm dry weight, leaf dry weight, spike dry weight and total dry matter weight $plant^{-1}$. The numbers of filled grain and unfilled grain $plant^{-1}$ and yields of grain and straw m^{-2} were the highest from the above-mentioned combination. The lowest dry weights for culm, leaf, spike, and total dry matter and minimum grain yield and straw yield were obtained from 25% light either alone or in combination with any plant densities indicating the profound influence of light on dry matter production and grain yield of wheat. Therefore, reduced light (up to 25%) and optimal plant density can ensure wheat production without significant yield loss. This finding suggests possibility of wheat cultivation in agroforestry system and light limiting areas in Bangladesh and other parts of the world.

Keywords: Wheat, radiation level, plant density, dry matter partitioning, grain yield

Introduction

Wheat, the top cereal crop in the world, ranks second just after rice in Bangladesh. For developing countries, wheat serves as the main source of protein and second most important source of calories (Braun et al., 2010). Production of wheat in Bangladesh is highly variable due to different agro-climatic conditions and average yield is much lower compared to rest of the world. Wheat production needs to increase in the country as the area under wheat is decreasing day by day. Moreover, demand of wheat is increasing due to population pressure. It is expected that yield of wheat may reduce by 15% - 30% just for increase of global temperature by 2 °C within 2040 (Moore and Lobell, 2014; Zhao et al., 2017). Thus, shortage of food is a likely phenomenon in Bangladesh. Therefore, Bangladesh including other developing countries of the world need to make an attempt to grow grain crops on land that remain fallow due to environmental issues.

Wheat is a cool-season crop; requires cool weather for vegetative growth and warm weather for maturity. Solar radiation is an important climatic factor directly influenced the growth and yield of crops including wheat. Solar radiation i.e. light determines photomorphogenesis of plant along with rate of photosynthesis (Albayrak et al., 2011). In fact, light intensity and quality controls plant growth and development through triggering plant physiological reactions (Bozorgi et al., 2011). Received light increases plant biomass that contributes to the crop growth, dry matter production and yield (Poorter and Nagel, 2000; Asseng et al., 2004). Low light reduces plant growth, development, dry matter production and yield (Strain and Cure, 1986) and excess light reduces crop yield through photoinhibition and burning crop canopy (Hasanuzzaman et al., 2012). At optimal light, plant growth is maximum through maximal photosynthesis (Lichtenthaler, 1996). However, low light intensity due to presence of aerosols and air pollutants in the atmosphere appears as a challenge for producing crop in various parts of the world (Mu et al., 2010). Low cloud reduced the light by 25% - 60% in the southern Appalachian Mountains of USA (Reinhardt et al., 2010) and the reduction was 30% - 44% in an apricot-based agroforestry system (Zhang et al.,

*Corresponding author: <yaminkabir@at.ku.ac.bd>
DOI: https://doi.org/10.53808/KUS.2022.19.02.2239-ls

2018). Steady cloudy days or rainfall at critical crop growth stages (e.g. panicle differentiation, grain-filling) make poor quality grains along with loss of grain yield (Janardhan et al., 1980).

Plant density expresses the number of plant population in a unit area, a determinant of allowable space for a single plant. Plant density can affect growth, development and yield of a crop through modulating crop's microenvironment. Increase of plant density beyond optimal limit decreases crop growth and yield (Cakmak et al., 1994). Plant can intercept majority of the photosynthetically active radiation (≥95%) at optimal density resulting highest yield (Dong et al., 2014) and beyond this yield decreases due to decrease of radiation use efficiency (Pommel and Bonhomme, 1998). However, dense planting of wheat can increases the leaf area index, rate of photosynthesis, filled spikelets (%), 1000-grain weight, and grain yield (Nakano et al., 2012). Though there are some studies that evaluated the response of plant population density on growth and yield of wheat; limited information is available on effects of light intensity alone or in combination with plant population density on dry matter partitioning and yield of wheat. Therefore, the objective of this study is to elucidate the effect of light intensity and plant density on the dry matter allocation and grain yield of wheat.

Materials and Methods

Experimental site, treatment and design

The experiment was conducted at the Field Laboratory of Agrotechnology Discipline of Khulna University, Khulna with the wheat variety 'BARI Gom 25' during the *Rabi* season (November 2018 to March 2019) having low temperature, low rainfall, low relative humidity and plenty of sunshine. The experimental area is under the Agro-ecological Zone (AEZ) 13 (Ganges Tidal Floodplain) having sub-tropical climate and the soil was clay loam having a pH of 7.6. The variety 'BARI Gom 25' is a semi-dwarf, early maturing, low to medium salt tolerant (8-10 dsm^{-1}), high yielding wheat variety released by Bangladesh Agricultural Research Institute (BARI) of Gazipur (BARI, 2012) particularly for southern region (e.g. Khulna) of the country. The field was prepared to good tilt through ploughing, cross ploughing and laddering and divided into 36 experimental unit each accounting an area of 6 m^2 (3.0 m x 2.0 m) and maintaining 1 m distance between plots and 1.5 m distance between replications and then fertilized with 220, 160, 45 and 115 $kgha^{-1}$, respectively for urea, TSP, MoP and gypsum along with 7 t ha^{-1} cow dung. During final land preparation, one-third of urea and full dose of other fertilizers were applied, and remaining urea was applied in two equal halves at 20 and 40 days after sowing (DAS). The experiment was set out in randomized complete block design with four levels of radiation (full sunlight, 75% light, 55% light, 25% light) and three plant densities [160 plants m^{-2}, 200 plants m^{-2} (optimal), 230 plants m^{-2}] that has been replicated thrice. The seed rate was calculated following plant density treatments and sown directly in line maintaining 20 cm between lines on 16 November 2018. The screens [one layer white net, two layer white net, and two layer markin cloth] were placed over the plot at 35 DAS. Intercultural operations (gap filling, irrigation, weed and insect-pest control) were done as per requirement.

Light measurement

Two-type screens (white net and white markin cloth) were bought from the market and light level under one layer and two layers of white net and two layers of markin cloth were measured several times using Digital Lux Meter (LX1010BS, Taiwan) and compared with that of open field. It revealed that light levels under one layer and two layer of white net were 75% and 55% of full sunlight, respectively and light under two layers of markin cloth was 25% of full sunlight; therefore, the light levels (75%, 55%, 25%) under nets along with full sun (open field) were considered as the treatments. Light intensity at upper canopy and lower canopy from the open field and under the screens (at different levels of solar radiation) was measured at 45, 60, 75, and 90 DAS using the lux meter.

Growth and yield parameters

Five plants from each plot were selected randomly to collect data on culm dry weight (g), leaf dry weight (g), spike dry weight (g), and total dry weight (g) for individual plant starting at 45 DAS and continue up to 90 DAS. The collected plant parts were placed in a labelled brown paper bag and dried in an oven (60 °C temperature for 48 hours. Just before final harvest, five plants were randomly harvested for collecting yield-contributing data. During final harvest, an area of one m^2 was harvested with sickles and sun dried for 2-3 days; threshed, winnowed, separated the clean grains and was weighed to calculate grain yield and straw yield.

Statistical analysis
The collected data on various dry matter and yield parameters were analyzed following ANOVA and F-test using Statistix 10 statistical program. Data means were separated by Duncan's Multiple Range Test at $P \leq 0.05$.

Results and Discussion
Radiation levels at upper and lower canopy of wheat
Radiation levels at upper canopy of wheat plant varied among the radiation levels under cloths at all DAS (45, 60, 75, 90). The highest radiation was measured at full sun, which decreased as the layer of shade net and markin cloth increased, and the lowest radiation from markin cloth (two-layer). Shade net decreased light level under net proportionately to shade level (Kittas et al., 2008; Kabir et al., 2019). At the lower canopy of wheat plant, the highest radiation was measured from the open field at all DAS and the lowest from 25% light (Table 1). Radiation levels varied at the lower canopy but not at the upper canopy of wheat due to plant population density (Table 2) as high density (230 plant m^{-2}) hinders the penetration of light at the lower canopy of wheat but not at the higher canopy. The highest radiation was measured at the lower canopy of wheat plant at the lowest plant population (160 plant m^{-2}) which was statistically similar with optimum plant population (200 plant m^{-2}) and lowest at highest plant density (230 plant m^{-2}) at all DAS (Table 2).

Table 1. Radiation at upper and lower canopy of wheat plants as affected by solar radiation level at different days after sowing (DAS) [z].

Solar radiation level	Radiation (× 100 Lux) at upper and lower canopy of wheat							
	45 DAS		60 DAS		75 DAS		90 DAS	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Full sunlight	589 a	196 a	599 a	157 a	598 a	177 a	609 a	172 a
75% sunlight	464 b	151 ab	379 b	135 ab	381 b	132 ab	397 b	138 ab
55% sunlight	360 c	113 ab	298 c	94 b	309 c	98 b	311 c	103 b
25% sunlight	175 d	95 b	163 d	88 b	124 d	87 b	139 d	88 b
Level of significance	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01

[z] *Means in a column having the same letters are not statistically different according to Duncan's Multiple Range Test ($P \leq 0.05$).*

Effect of radiation levels and plant density on culm and leaf dry weight of wheat
Culm dry weight plant^{-1} varied among the radiation levels at all DAS except 60 (Table 3). The highest culm dry weight (1.93 g) was resulted from full sunlight, which was statistically similar with 75% light and the lowest dry weight (1.49 g) from 25% light at 90 DAS (Table 3). The culm weight plant^{-1} also varied among the plant population density at 75 DAS only (Table 4). The culm dry weight varied at 45 DAS and 75 DAS due to combined effect of radiation level and plant population (Table 5). The highest culm weight (2.27 g) was recorded from interaction of full sun with optimum (200 plant m^{-2}) plant density. The highest culm dry weight was also obtained from optimal plant density (200 plant m^{-2}) through minimizing internal and external plant competition (Ferreira and Abreu, 2001). Culm dry weight was the lowest at lower (160 plant m^{-2}) and higher (230 plant m^{-2}) plant density because of suboptimal and overcrowded plant population, respectively. Low light decreased tiller number, number of functional chloroplast, activity of photosystem II, net photosynthesis and thus dry matter production (Demotes-Mainard and Jeuffroy, 2004; Mu et al., 2010).

The leaf dry weight plant^{-1} varied due to solar radiation level (Table 3), plant population (Table 4) and interactions between radiation and plant population (Table 5) at all DAS except 90. The highest leaf dry weight was recorded usually from full sunlight (Table 3), 160 and 200 plant m^{-2} plant densities (Table 4) and interactions between them (Table 5). The highest leaf area index (LAI) and consequently a maximum light absorption resulted higher leaf dry weight at optimal plant density (Agele et al., 2007). Sometimes, the leaf dry weight at 90 DAS was lower than 75 DAS, which might due to increased competition among the plants at 90 DAS.

Table 2. Radiation at upper and lower canopy of wheat plants as affected by plant population at different days after sowing (DAS) ^{z}.

Plant Population	Radiation (× 100 Lux) at upper and lower canopy of wheat							
	45 DAS		60 DAS		75 DAS		90 DAS	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
160 plant m^{-2}	329	179 a	350	146 a	360	155 a	327	152 a
200 plant m^{-2}	399	137 ab	328	117 ab	346	123 ab	304	131 ab
230 plant m^{-2}	373	101 b	309	89 b	353	91 b	332	93 b
Level of significance	NS	0.05	NS	0.05	NS	0.05	NS	0.05

^{z}*Means in a column with the same letter do not differ following Duncan's Multiple Range Test (P ≤ 0.05). NS = Non-significant.*

Table 3. Effect of radiation levels on dry weights of wheat culm and leaf at different days after sowing (DAS) ^{z}.

Solar radiation level	Culm dry weight (g) $plant^{-1}$				Leaf dry weight (g) $plant^{-1}$			
	45 DAS	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
Full sunlight	0.62 a	1.53	2.00 a	1.93 a	0.75 a	0.96 b	1.20 a	1.34
75% sunlight	0.42 b	1.19	1.43 b	1.66 ab	0.61 b	0.99 b	1.06 b	1.22
55% sunlight	0.47 b	1.32	1.30 b	1.61 b	0.43 c	1.18 a	1.07 ab	1.15
25% sunlight	0.47 b	1.31	1.30 b	1.49 b	0.43 c	0.97 b	1.14 ab	0.94
Level of significance	0.05	NS	0.05	0.05	0.05	0.05	0.05	NS
CV (%)	19.44	26.05	5.16	13.85	14.26	6.92	9.50	19.00

^{z}*Means in a column with the same letter do not differ following Duncan's Multiple Range Test at P ≤ 0.05.*
NS = Non-significant; CV = Coefficient of variation.

Table 4. Effect of plant population on wheat culm and leaf dry weights at different days after sowing (DAS) ^{z}.

Plant Population	Culm dry weight (g) $plant^{-1}$				Leaf dry weight (g) $plant^{-1}$			
	45 DAS	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
160 plant m^{-2}	0.53	1.29	1.43 b	1.65	0.56 ab	0.98 b	1.29 a	1.13
200 plant m^{-2}	0.52	1.30	1.58 a	1.71	0.50 b	1.00 b	1.12 b	1.19
230 plant m^{-2}	0.44	1.43	1.44 b	1.65	0.59 a	1.10 a	0.95 c	1.17
Level of	NS	NS	0.05	NS	0.05	0.05	0.05	NS
CV (%)	19.44	26.05	5.16	13.85	14.26	6.92	9.50	19.00

^{z}*Means in a column with the same letter do not differ following Duncan's Multiple Range Test at P ≤ 0.05. NS = Non-significant; CV = Coefficient of variation.*

Effect of radiation levels and plant population on spike and total dry weight of wheat

The spike dry weight $plant^{-1}$ varied with the radiation levels at 75 DAS and 90 DAS (Table 6). At 75 DAS, the highest spike dry weight (1.2 g) was recorded at full sunlight and the lowest from 25% light (0.68 g). Similar trend was observed at 90 DAS. Spike dry weight did not vary due to plant population density (Table 7). However, the spike dry weight varied at 75 DAS due to combined effect of radiation level and plant population. The highest spike dry weight (1.37 g) was resulted from full sunlight with optimum plant population (200 plant m^{-2}) and lowest from 25% light with highest plant population (230 plant m^{-2}) (Table 8). Low radiation under shade decreased spike dry weight through reduction of grain number in spring wheat (Willey and Holliday, 1971; Fischer, 1975).

Table 5. Interaction effect of solar radiation level and plant population on culm and leaf dry weight of wheat at different days after sowing (DAS) [z].

Solar radiation level × Plant population [y]	Culm dry weight (g) plant^{-1}				Leaf dry weight (g) plant^{-1}			
	45 DAS	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
P_1S_1	0.65 a	1.47	1.87 b	1.90	0.92 a	0.84 de	1.47 a	1.39
P_2S_1	0.64 a	1.63	2.27 a	1.97	0.63 bcd	1.23 b	1.16 a-e	1.31
P_3S_1	0.58 abc	1.5	1.87 b	1.93	0.67 abc	0.81 df	0.97 def	1.33
P_1S_2	0.29 d	1.23	1.27 c	1.57	0.55 cde	0.69 e	0.99 def	1.07
P_2S_2	0.47 a-d	1.10	1.47 c	1.77	0.44 def	1.12 bc	1.04 c-f	1.49
P_3S_2	0.51 a-d	1.23	1.30 c	1.63	0.83 ab	1.17 bc	1.15 b-e	1.09
P_1S_3	0.59 ab	1.56	1.30 c	1.67	0.52 cde	1.70 a	1.43 ab	1.20
P_2S_3	0.49 a-d	1.3	1.30 c	1.47	0.44 def	0.70 e	0.96 def	0.88
P_3S_3	0.30 cd	1.10	1.30 c	1.70	0.34 ef	1.15 bc	0.82 f	1.39
P_1S_4	0.57 a-d	0.90	1.30 c	1.47	0.27 f	0.68 e	1.26 a-d	0.86
P_2S_4	0.48 a-d	1.18	1.30 c	1.63	0.50 c-f	0.97 cd	1.31 abc	1.08
P_3S_4	0.35 bcd	1.87	1.30 c	1.37	0.52 cde	1.27 b	0.85 ef	0.87
Level of significance	0.05	NS	0.05	NS	0.05	0.05	0.05	NS
CV (%)	19.44	26.05	5.16	13.85	14.26	6.92	9.50	19.00

[y] 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% sunlight, S_3 = 55% sunlight, S_4 = 25% sunlight. [z] Means in a column followed by the dissimilar letters differ significantly according to Duncan's Multiple Range Test (P ≤ 0.05); NS = Non-significant, CV = Coefficient of variation.

Table 6. Effect of radiation levels on spike dry weight and total dry weight of wheat at different days after sowing (DAS) [z].

Radiation level	Spike dry weight (g) plant^{-1}			Total dry weight (g) plant^{-1}			
	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
Full sunlight	0.62	1.2 a	2.30 a	0.82	2.62	3.46 a	4.47 a
75% sunlight	0.66	0.80 b	1.65 ab	0.61	2.13	2.41 b	3.52 b
55% sunlight	0.61	0.93 ab	1.73 ab	0.87	2.24	2.49 b	3.57 b
25% sunlight	0.43	0.68 b	1.33 b	0.72	2.37	2.42 b	3.03 b
Level of significance	NS	0.05	0.05	NS	NS	0.05	0.05
CV (%)	15.75	24.33	28.51	18.75	26.30	9.49	17.56

[z] Means in a column having similar letters are not statistically different at P ≤ 0.05 (Duncan's Multiple Range Test); NS = Non-significant; CV = Coefficient of variation.

The total dry matter of wheat plant did not vary at early stages (45 DAS and 60 DAS) of growth but at later stages (75 DAS and 90 DAS) (Table 6). The highest dry matter was recorded from full sun and lowest one from 25% light at 75 DAS and 90 DAS. The maximum total dry matter (2.82 g) was obtained from optimal plant population and minimum from highest plant population (230 plant m^{-2}) at 75 DAS (Table 7). The highest total dry matter was recorded from full sunlight with optimum plant population (200 plant m^{-2}) and the lowest from 25% light with highest plant population (230 plant m^{-2}) (Table 8). A little accumulation of dry matter at low light resulted lowest dry matter at 25% light either separately or in combination with plant densities (Staver et al., 2001).

Table 7. Effect of plant population on spike dry weight and total dry weight of wheat at different days after sowing (DAS) [z]

Plant Population	Spike dry weight (g) $plant^{-1}$			Total dry weight (g) $plant^{-1}$			
	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
160 plant m^{-2}	0.52	0.87	1.70	0.86	2.28	2.70 ab	3.58
200 plant m^{-2}	0.56	0.98	1.90	0.76	2.16	2.82 a	3.83
230 plant m^{-2}	0.65	0.86	1.66	0.65	2.57	2.56 b	3.54
Level of significance	NS	NS	NS	NS	NS	0.05	NS
CV (%)	15.75	24.33	28.51	18.75	26.30	9.49	17.56

[z] Means in a column having similar letters are not statistically different at P ≤ 0.05 (Duncan's Multiple Range Test); NS = Non-significant; CV = Coefficient of variation.

Table 8. Interaction effect of radiation and plant population on spike dry weight and total dry weight of wheat at different days after sowing [z].

Solar radiation level × Plant population [y]	Spike dry weight (g) $plant^{-1}$			Total dry weight (g) $plant^{-1}$			
	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
P_1S_1	0.60	1.10 ab	2.33	0.82 ab	2.76	3.25 ab	4.48 ab
P_2S_1	0.67	1.37 a	2.50	0.85 ab	2.55	3.89 a	4.68 a
P_3S_1	0.59	1.33 ab	2.07	0.80 ab	2.54	3.24 ab	4.25 ab
P_1S_2	0.59	0.59 b	1.42	0.44 b	2.06	2.13 c	3.04 ab
P_2S_2	0.47	0.93 ab	1.77	0.65 ab	1.87	2.64 bc	3.79 ab
P_3S_2	0.92	0.93 ab	1.93	0.74 ab	2.45	2.47 c	3.75 ab
P_1S_3	0.60	1.03 ab	1.83	1.38 a	2.53	2.62 bc	3.73 ab
P_2S_3	0.70	0.94 ab	1.87	0.72 ab	2.24	2.46 c	3.51 ab
P_3S_3	0.53	0.80 ab	1.50	0.51 b	1.95	2.41 c	3.47 ab
P_1S_4	0.30	0.76 ab	1.42	0.81 ab	1.77	2.80 bc	3.07 ab
P_2S_4	0.41	0.68 b	1.46	0.79 ab	1.98	2.33 c	3.32 ab
P_3S_4	0.57	0.60 b	1.12	0.55 ab	3.35	2.12 c	2.70 b
Level of significance	NS	0.05	NS	0.05	NS	0.05	0.05
CV (%)	15.75	24.33	28.51	18.75	26.30	9.49	17.56

[y] 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% sunlight, S_3 = 55% sunlight, S_4 = 25% sunlight. [z] Treatment means in a column followed by the dissimilar letters differ significantly according to Duncan's Multiple Range Test (P ≤ 0.05); NS = Non-significant, CV = Coefficient of variation.

Table 9. Grain yield and straw yield of wheat as affected by solar radiation [z].

Radiation level	Filled grain (no.) $spike^{-1}$	Unfilled grain (no.) $spike^{-1}$	Grain yield (g m^{-2})	Straw yield (g m^{-2})
Full sunlight	43.17 a	2.89 a	382 a	481 a
75% sunlight	43.68 a	3.22 a	317 b	398 b
55% sunlight	35.03 b	2.63 a	294 b	369 b
25% sunlight	29.48 b	1.63 b	188 c	285 c
Level of significance	0.05	0.05	0.05	0.05
CV (%)	11.26	22.34	12.96	12.96

[z] Means in a column having similar letters are not statistically different at P ≤ 0.05 (Duncan's Multiple Range Test); CV = Coefficient of variation.

Effect of solar radiation levels and plant population on yield and yield attributes of wheat

The number of filled grain and unfilled grain in a spike varied among the radiation levels, plant population, and interactions between them (Table 9-11). The maximum number of filled grain and unfilled grain were recorded from 75% light and the minimum from 25% light (Table 9). Similarly, both the filled grain and unfilled grain were maximum at lowest plant density and minimum at highest plant density (Table 10). The highest number of filled grain and unfilled grain in a wheat spike were resulted from combination of full sunlight or 75% light with different plant populations particularly (200 plant m^{-2} and 160 plant m^{-2}) and the lowest from 25% light with highest plant population (230 plant m^{-2}) (Table 11). Similar number of filled and unfilled grains were observed at full sunlight and 75% light as a slight shade (e.g. 20%) did not alter the number of filled grains in wheat (Li et al., 2010). However, low light from transplanting to booting in rice reduces number of grains (Liu et al., 2014). Planting density highly influenced the number of grains per panicle in wheat (Valério et al., 2013). However, below optimal density may decrease yield and net profit (Whaley et al., 2000) and above optimal may increase cost of production (Laghari et al., 2011).

Table 10. Wheat grain yield and straw yield as influenced by plant population [z].

Plant Population	Filled grain (no.) spike^{-1}	Unfilled grain (no.) spike^{-1}	Grain yield (g m^{-2})	Straw yield (g m^{-2})
160 plant m^{-2}	40.80 a	2.84 a	274 b	352 b
200 plant m^{-2}	37.26 b	2.76 ab	296 ab	393 a
230 plant m^{-2}	34.46 b	2.109 b	316 a	404 a
Level of significance	0.05	0.05	0.05	0.05
CV (%)	11.26	22.34	12.96	12.96

[z] *Means in a column having similar letters are not statistically different at P ≤ 0.05 (Duncan's Multiple Range Test); CV = Coefficient of variation.*

Table 11. Interaction effect of radiation levels and plant population on grain yield and straw yield of wheat [z].

Solar radiation level × Plant population [y]	Filled grain (no.) spike^{-1}	Unfilled grain (no.) spike^{-1}	Grain yield (g m^{-2})	Straw yield (g m^{-2})
P_1S_1	50.94 a	3.00 ab	366 abc	431 ab
P_2S_1	36.98 bcd	2.98 ab	386 ab	500 a
P_3S_1	41.59 abc	2.70 abc	394 a	513 a
P_1S_2	44.46 ab	2.90 ab	272 b-f	370 cd
P_2S_2	50.99 a	4.35 a	323 a-d	411 a-d
P_3S_2	35.59 bcd	2.40 bc	355 abc	412 a-d
P_1S_3	38.98 abc	2.61 abc	295 a-e	368 cd
P_2S_3	30.12 cd	2.66 abc	256 c-f	354 cde
P_3S_3	36.10 bcd	2.60 bc	329 a-d	385 bcd
P_1S_4	32.84 bcd	2.77 abc	162 f	239 e
P_2S_4	31.05 cd	1.06 c	219 def	308 de
P_3S_4	24.56 d	1.06 c	184 ef	307 de
Level of significance	0.05	0.05	0.05	0.05
CV (%)	11.26	22.34	12.96	12.96

[y] *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% sunlight, S_3 = 55% sunlight, S_4 = 25% sunlight.* [z] *Treatment means in a column followed by the dissimilar letters differ significantly according to Duncan's Multiple Range Test (P ≤ 0.05); CV = Coefficient of variation.*

The highest grain yield (382 g m^{-2}) and straw yield (481 g m^{-2}) were obtained from full sunlight and the lowest grain yield (188 g m^{-2}) and straw yield (285 g m^{-2}) were obtained from 25% light. The highest grain yield (316 g m^{-2}) and straw yield (404 g m^{-2}) were obtained from maximal plant population density which were statistically similar with optimal plant density and the lowest yields from lowest plant population density. The highest grain yield

(394 g m^{-2}) and straw yield (513 g m^{-2}) were estimated from full sunlight with maximal plant population, which was statistically similar with several other combinations and the lowest from the 25% light with 160 plants m^{-2} (Table 11). Yield of crops can be reduced at low light (Islam et al., 1993, Abeledo et al., 2014; Wang et al., 2015; Kabir et al., 2022) and low yield is the result of low carbon-use efficiency at reduced light (Ball et al., 2000). However, grain yield of wheat was lower at 100% irradiance compared to 90% and 50% at Mediterranean environment where annual irradiance is much higher compared to other parts of Europe (Arenas-Corraliza et al., 2019) and a 19% shade resulted highest photosynthesis in bell pepper during summer in Georgia of USA (Kabir et al., 2022). Increase of plant density may result higher yield providing availability of resources along with prevalence of optimal climate for crop production (Bavec and Bavec, 2002). Increase of planting density at a certain threshold level increases the grain yield through increasing total number of grains as reported in the present study. The straw yield increases at full sunlight through higher accumulation dry matter compared to 25% light. The increase of total plant population also increases the total straw yield and vice versa.

Conclusion

Full sunlight or 75% light with optimal plant density (200 plant m^{-2}) resulted maximum dry weights for culm, leaf, spike, and total dry matter for a wheat plant. These combinations also yielded higher number of filled and unfilled grains per plant along with higher grain yield and straw yield in an area of one m^2. Though the high plant density (230 plant m^{-2}) resulted statistically similar grain yield with optimal plant density, it is not recommended due to higher seed requirement. Therefore, 75% light with optimal plant density is sufficient for good yield of wheat. This information could be useful for growing wheat in an agroforestry system and light limiting areas in Bangladesh as well as in other parts of the world.

Acknowledgement

The authors express their sincere gratitude to the Farm Authority of Agrotechnology Discipline of Khulna University for their supports during the experimental period.

Conflict of Interests

The author declares no conflict of interest.

References

Abeledo, L. G., Savin, R., & Slafer, G. A. (2014). Leaf photosynthesis during grain filling under mediterranean environments: are barley or traditional wheat more efficient than modern wheats? *Journal of agronomy and crop science*, *200*(3), 172-182. https://doi.org/10.1111/jac.12054

Agele, S. O., Maraiyesa, I. O., & Adeniji, I. A. (2007). Effects of variety and row spacing on radiation interception, partitioning of dry matter and seed set efficiency in late season sunflower (Helianthus annuus L.) in a humid zone of Nigeria. *African Journal of Crop Science*, *2*(3), 80-88.

Albayrak, S., Mevlüt, T. Ü. R. K., & Yüksel, O. (2011). Effect of row spacing and seeding rate on hungarian vetch yield and quality. *Turkish Journal of Field Crops*, *16*(1), 54-58.

Arenas-Corraliza, M. G., Rolo, V., López-Díaz, M. L., & Moreno, G. (2019). Wheat and barley can increase grain yield in shade through acclimation of physiological and morphological traits in Mediterranean conditions. *Scientific reports*, *9*(1), 1-10.

Asseng, S., Jamieson, P. D., Kimball, B., Pinter, P., Sayre, K., Bowden, J. W., & Howden, S. M. (2004). Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO2. *Field Crops Research*, *85*(2-3), 85-102. https://doi.org/10.1016/S0378-4290(03)00154-0

Ball, R. A., Purcell, L. C., & Vories, E. D. (2000). Optimizing soybean plant population for a short-season production system in the southern USA. *Crop Science*, *40*(3), 757-764. https://doi.org/10.2135/cropsci2000.403757x

BARI (Bangladesh Agricultural ResearchInstitute). (2012). Means of profitable wheat cultivation (A booklet in Bangla). Wheat Research Centre. Bangladesh Agricultural Research Institute, Joydebpur, Gazipur.

Bavec, F., & Bavec, M. (2002). Effects of plant population on leaf area index, cob characteristics and grain yield of early maturing maize cultivars (FAO 100–400). *European Journal of Agronomy*, *16*(2), 151-159. https://doi.org/10.1016/S1161-0301(01)00126-5

Bozorgi, H. R., Faraji, A., Danesh, R. K., Keshavarz, A., Azarpour, E., & Tarighi, F. (2011). Effect of plant density on yield and yield components of rice. *World Applied Sciences Journal*, *12*(11), 2053-2057.

Braun, H. J., Atlin, G., & Payne, T. (2010). Multi-location testing as a tool to identify plant response to global climate change. *Climate change and crop production*, *1*, 115-138.

Cakmak, I., Hengeler, C., & Marschner, H. (1994). Partitioning of shoot and root dry matter and carbohydrates in bean plants suffering from phosphorus, potassium and magnesium deficiency. *Journal of Experimental Botany*, *45*(9), 1245-1250. https://doi.org/10.1093/jxb/45.9.1245

Demotes-Mainard, S., & Jeuffroy, M. H. (2004). Effects of nitrogen and radiation on dry matter and nitrogen accumulation in the spike of winter wheat. *Field Crops Research*, *87*(2-3), 221-233. https://doi.org/10.1016/j.fcr.2003.11.014

Dong, C., Fu, Y., Liu, G., & Liu, H. (2014). Low light intensity effects on the growth, photosynthetic characteristics, antioxidant capacity, yield and quality of wheat (Triticum aestivum L.) at different growth stages in BLSS. *Advances in Space Research*, *53*(11), 1557-1566. https://doi.org/10.1016/j.asr.2014.02.004

Ferreira, A. M., & Abreu, F. G. (2001). Description of development, light interception and growth of sunflower at two sowing dates and two densities. *Mathematics and Computers in simulation*, *56*(4-5), 369-384. https://doi.org/10.1016/S0378-4754(01)00308-1

Fischer, R. A. (1975). Yield potential in a dwarf spring wheat and the effect of shading 1. *Crop Science*, *15*(5), 607-613. https://doi.org/10.2135/cropsci1975.0011183X001500050002x

Hasanuzzaman, M., Hossain, M. A., Silva, J. A., & Fujita, M. (2012). Plant response and tolerance to abiotic oxidative stress: antioxidant defense is a key factor. In *Crop stress and its management: perspectives and strategies* (pp. 261-315). Springer, Dordrecht. DOI: 10.1007/978-94-007-2220-0_8

Islam, M. T., Kubota, F., Mollah, F. H., & Agata, W. (1993). Effect of shading on the growth and yield of mungbean (Vigna radiata [L.] Wilczek). *Journal of Agronomy and Crop Science*, *171*(4), 274-278. https://doi.org/10.1111/j.1439-037X.1993.tb00140.x

Janardhan, K. V., Murty, K. S., & Dash, N. B. (1980). Effect of low light during ripening period on grain yield and translocation of assimilates in rice varieties. *Indian Journal of Plant Physiology*, *23*, 163-168.

Kabir, M. Y., Nambeesan, S. U., & Díaz-Pérez, J. C. (2022). Carbon Dioxide and Light Curves and Leaf Gas Exchange Responses to Shade Levels in Bell Pepper (Capsicum annuum L.). *Plant Science*, 111532. https://doi.org/10.1016/j.plantsci.2022.111532

Kabir, M. Y., Nambeesan, S. U., Bautista, J., & Díaz-Pérez, J. C. (2022). Plant water status, plant growth, and fruit yield in bell pepper (Capsicum annum L.) under shade nets. *Scientia Horticulturae*, *303*, 111241. https://doi.org/10.1016/j.scienta.2022.111241

Kabir, M. Y., Díaz-Pérez, J. C., & Nambeesan, S. U. (2019). Effect of shade levels on plant growth, physiology, and fruit yield in bell pepper (Capsicum annuum L.). In *XI International Symposium on Protected Cultivation in Mild Winter Climates and I International Symposium on Nettings,1268,* 311-318. https://doi.org/10.17660/ActaHortic.2020.1268.42

Kittas, C., Rigakis, N., Katsoulas, N., & Bartzanas, T. (2008). Influence of shading screens on microclimate, growth and productivity of tomato. In *International Symposium on Strategies Towards Sustainability of Protected Cultivation in Mild Winter Climate, 807,* 97-102. https://doi.org/10.17660/ActaHortic.2009.807.10.

Laghari, G. M., Oad, F. C., Tunio, S., Chachar, Q., Ghandahi, A. W., Siddiqui, M. H., ... & Ali, A. (2011). Growth and yield attributes of wheat at different seed rates. *Sarhad Journal of Agriculture*, *27*(2), 177-183.

Li, H., Jiang, D., Wollenweber, B., Dai, T., & Cao, W. (2010). Effects of shading on morphology, physiology and grain yield of winter wheat. *European Journal of Agronomy*, *33*(4), 267-275. https://doi.org/10.1016/j.eja.2010.07.002

Lichtenthaler, H. K. (1996). Vegetation stress: an introduction to the stress concept in plants. *Journal of plant physiology*, *148*(1-2), 4-14. https://doi.org/10.1016/S0176-1617(96)80287-2

Liu, Q. H., Xiu, W. U., Chen, B. C., & Jie, G. A. O. (2014). Effects of low light on agronomic and physiological characteristics of rice including grain yield and quality. *Rice science*, *21*(5), 243-251. https://doi.org/10.1016/S1672-6308(13)60192-4

Moore, F. C., & Lobell, D. B. (2014). Adaptation potential of European agriculture in response to climate change. *Nature Climate Change*, *4*(7), 610-614. https://doi.org/10.1038/nclimate2228

Mu, H., Jiang, D., Wollenweber, B., Dai, T., Jing, Q., & Cao, W. (2010). Long‐term low radiation decreases leaf photosynthesis, photochemical efficiency and grain yield in winter wheat. *Journal of Agronomy and Crop Science*, *196*(1), 38-47. https://doi.org/10.1111/j.1439-037X.2009.00394.x

Nakano, H., Morita, S., Kitagawa, H., Wada, H., & Takahashi, M. (2012). Grain yield response to planting density in forage rice with a large number of spikelets. *Crop science*, *52*(1), 345-350. https://doi.org/10.2135/cropsci2011.02.0071

Pommel, B., & Bonhomme, R. (1998). Variations in the vegetative and reproductive systems in individual plants of an heterogeneous maize crop. *European Journal of Agronomy*, *8*(1-2), 39-49. https://doi.org/10.1016/S1161-0301(97)00012-9

Poorter, H., & Nagel, O. (2000). The role of biomass allocation in the growth response of plants to different levels of light, CO2, nutrients and water: a quantitative review. *Functional Plant Biology*, *27*(12), 1191-1191. https://doi.org/10.1071/PP99173_CO

Reinhardt, K., Smith, W. K., & Carter, G. A. (2010). Clouds and cloud immersion alter photosynthetic light quality in a temperate mountain cloud forest. *Botany*, *88*(5), 462-470. https://doi.org/10.1139/B10-008

Staver, C., Guharay, F., Monterroso, D., & Muschler, R. G. (2001). Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. *Agroforestry systems*, *53*(2), 151-170. https://doi.org/10.1023/A:1013372403359

Strain, B. R., & Cure, J. D. (Eds.). (1986). *Direct effects of increasing carbon dioxide on vegetation*. US Department of Energy, Office of Energy Research, Office of Basic Energy Sciences, Carbon Dioxide Research Division.

Valério, I. P., Carvalho, F. I. F. D., Benin, G., Silveira, G. D., Silva, J. A. G. D., Nornberg, R., ... & Oliveira, A. C. D. (2013). Seeding density in wheat: the more, the merrier?. *Scientia Agricola*, *70*, 176-184. https://doi.org/10.1590/S0103-90162013000300006

Wang, L., Deng, F., & Ren, W. J. (2015). Shading tolerance in rice is related to better light harvesting and use efficiency and grain filling rate during grain filling period. *Field Crops Research*, *180*, 54-62. https://doi.org/10.1016/j.fcr.2015.05.010

Whaley, J. M., Sparkes, D. L., Foulkes, M. J., Spink, J. H., Semere, T., & Scott, R. K. (2000). The physiological response of winter wheat to reductions in plant density. *Annals of Applied Biology*, *137*(2), 165-177. https://doi.org/10.1111/j.1744-7348.2000.tb00048.x

Willey, R. W., & Holliday, R. (1971). Plant population, shading and thinning studies in wheat. *The Journal of Agricultural Science*, *77*(3), 453-461. https://doi.org/10.1017/S0021859600064522

Zhang, D., Du, G., Sun, Z., Bai, W., Wang, Q., Feng, L., ... & Zhang, L. (2018). Agroforestry enables high efficiency of light capture, photosynthesis and dry matter production in a semi-arid climate. *European Journal of Agronomy*, *94*, 1-11. https://doi.org/10.1016/j.eja.2018.01.001

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., ... & Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, *114*(35), 9326-9331. https://doi.org/10.1073/pnas.1701762114