RESEARCH ARTICLE Indian Journal of Agricultural Research, Volume 60 Issue 3: 375-382 (March 2026)

Effect of Varying Light Intensity on Physiological and Yield Characteristics of Wheat

Anshul Gupta[1], Renu Dhupper[1], Harshita Jain[1], Bhupinder Singh[2]

10.18805/IJARe.A-6428

ABSTRACT

Background: Light intensity is a fundamental environmental determinant of plant growth, influencing physiological processes such as photosynthesis, transpiration and assimilate partitioning. In northern India, elevated air pollution levels significantly reduce photosynthetically active radiation (PAR), adversely affecting wheat productivity. This study investigates the impact of varying light intensities, simulated through 50% and 75% shading, on physiological and yield attributes of two widely cultivated wheat genotypes, HD-2967 and HD-3086. Given the increasing threat of atmospheric dimming due to pollution, understanding crop responses to reduced light is vital for ensuring sustainable agricultural output in vulnerable regions.

Methods: A field experiment was conducted over two consecutive *rabi* seasons (2022-23 and 2023-24) at the research farms of ICAR-IARI, New Delhi. Treatments included full sunlight (control), 50% and 75% shading applied for six weeks after six weeks of normal growth. Physiological parameters-plant biomass, root-shoot ratio, chlorophyll content, photosynthetic rate, stomatal conductance and transpiration rate-were monitored at 0, 7 and 14 days after shade removal. Yield attributes such as ear-bearing tillers, 1000-grain weight and final grain yield were recorded at harvest.

Result: Results revealed that shading significantly reduced biomass accumulation, Pn, Gs, E and grain yield, while increasing chlorophyll content and root-shoot ratio. HD-2967 showed higher baseline productivity under optimal light but experienced greater yield reduction under stress. HD-3086 demonstrated comparatively greater resilience, particularly under 50% shade. These findings emphasize the need for breeding light-efficient wheat cultivars to enhance crop stability under pollution-induced light limitation.

Key words: Light intensity, Physiological effects, Productivity, Shading, Wheat.

INTRODUCTION

Light is a fundamental environmental factor influencing plant growth, acting both as an energy source for photosynthesis and a signal that regulates various physiological processes. In recent decades, increasing levels of air pollution-particularly from particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOCs)-have led to the formation of smog and haze. These pollutants reduce the transmission of solar radiation, especially photosynthetically active radiation (PAR), a phenomenon referred to as “global dimming”. This effect is particularly pronounced in urban and peri-urban regions such as Delhi-NCR, where high pollution levels coincide with intensive wheat cultivation. Wheat (*Triticum aestivum* L.), a staple food crop in North India, is highly sensitive to light intensity, which directly influences its photosynthetic efficiency, growth and yield. Declining PAR due to atmospheric pollution compromises the plant’s ability to perform photosynthesis, thereby reducing productivity. This poses a significant threat to food security in the region. Numerous studies have documented the adverse impacts of air pollution on crop performance. Airborne pollutants impair key physiological and biochemical functions in plants, with severity depending on pollutant type, concentration, exposure duration and varietal tolerance (Devrajani *et al.,* 2020; Dong and Wang, 2023). Agathokleous *et al.* (2023) highlighted that deteriorating air quality not only endangers human health but also undermines agricultural productivity.

[1]Amity Institute of Environmental Science, Amity University, Noida-201 313, Uttar Pradesh, India.

[2]Division of Environmental Science, ICAR-Indian Agricultural Research Institute, New Delhi-110 012, India.

Corresponding Author: Renu Dhupper, Amity Institute of Environmental Science, Amity University, Noida-201 313, Uttar Pradesh, India. Email: rdhupper@amity.edu

How to cite this article: Gupta, A., Dhupper, R., Jain, H. and Singh, B. (2026). Effect of Varying Light Intensity on Physiological and Yield Characteristics of Wheat. *Indian Journal of Agricultural Research*. **60(3):** 375-382. doi: 10.18805/IJARe.A-6428.

Submitted: 02-06-2025 **Accepted:** 01-07-2025 **Online:** 13-08-2025

In India, air pollution is estimated to reduce crop yields by as much as 50% (Pandya *et al.,* 2022). Globally, solar radiation has declined by 1.4-2.7% per decade due to rising air pollution (Ramanathan and Feng, 2009). In highly affected regions like China’s Yangtze River basin, reductions exceeding 6% per decade have been associated with reduced photosynthesis and stunted crop growth (Qian *et al.,* 2007). Similar outcomes have been observed in wheat, where shading and light stress impair chloroplast development and reduce yield (Acreche *et al.,* 2009). Dutta *et al.* (2017) reported grain yield decrease upto 55% in rice under low light conditions.

In India, wheat is cultivated on approximately 34.81 million hectares, with an average productivity of 3,521 kg/ha.

Among the widely grown varieties in the North-Western Plains are HD-2967 and HD-3086, developed by the Indian Agricultural Research Institute (IARI), New Delhi.

Considering the increasing threat of air pollution-induced light stress, this study aims to investigate how variations in light intensity-especially reductions in PAR-affect the physiological performance and yield components of wheat varieties grown in North India. This will help elucidate varietal responses to changing light regimes and guide adaptive agronomic strategies for sustaining wheat productivity under polluted atmospheric conditions.

MATERIALS AND METHODS

Experimental setup and planting material

An experiment was conducted during the winters of 2022-23 and 2023-24 at the IARI research farms, New Delhi (28°38′23″N, 77°09′27″E, 228.61 m MSL), under sub-temperate and sub-arid climatic conditions. Two popular hybrid bread wheat (*Triticum aestivum* L.) varieties-HD-2967 and HD-3086-were sown in 9 m^2 field plots with three replicates. Some of the properties of the two varieties are tabulated below:

Property	HD-2967	HD-3086
Parentage	ALD/COC/URES/ HD2160M/HD2278	DBW 14/ HD 2733/ HUW 468
Released	2011	2014
Developer	IARI, New Delhi	
Plant height (cm)	~98	
Days to maturity	~143	
Grain yield (q/ha)	54.8	53.5
Features	Resistant to yellow and brown rust. Rich in zinc, copper and iron.	Resistant to yellow and brown rust. Has higher yield.
Coverage	Alone contributes approximately 50% of the total wheat production in India.	Licensed to about 204 private seed companies for fast spread.

The soil had the following pre-experiment characteristics: pH 7.9, EC 0.5 dS/m, 0.4% organic carbon, available nitrogen 260 kg/ha, phosphorus 37.5 kg/ha, potassium 290 kg/ha, sulphur 15 mg/kg, zinc 2.5 mg/kg, iron 60 mg/kg, manganese 18 mg/kg and copper 0.8 mg/kg. The seed rate was 100 kg ha^{-1} and the row spacing was kept at 0.3 m. Recommended agronomic practices on fertilization and irrigation were followed.

The three sun exposure levels used in the treatments were full sunlight as the control and 50% and 25% of full sunlight as shade treatments during both the seasons of the experiment. Plants grew under natural conditions for six weeks; from the sixth week onward, shade nets of 50% and 75% opacity were used for six weeks to simulate reduced PAR due to fog in north-western India. Initially, a gap of approximately 30 cms was kept between the shade nets and the ground level to allow proper air circulation. The height of the shade net was increased every week to accommodate the increased shoot. The data on harvest and yield attributes were taken five months after the date of plantation.

Shoot, root and leaf characteristics

Plant biomass, root-shoot mass ratio and leaf chlorophyll were measured on 0, 7 and 14 days following the removal of the shade net. Root and shoot biomass were obtained by drying separated shoot and root tissues at 80°C until complete dryness and their total was taken as plant biomass. These values were measured using a high-precision digital weighing balance and expressed as grams dry weight per plant.

Three flag leaves were chosen at random, cut at the base and brought to the lab in test tubes with the cut end soaked in water to maintain freshness. The chlorophyll was measured using the dimethyl sulphoxide (DMSO) method of Hiscox and Israelstam (1979). The absorbance was measured at 645 and 663 nm and total chlorophyll was calculated using the formula given by Arnon (1949) and expressed as (mg g^{-1} fw).

$$\text{Total chlorophyll} = \frac{20.2\,(A_{645}) + 8.02(A_{663})^{*}\,V}{W}$$

Where,
V = Final extract volume.
W = Weight of tissue extracted.

Gas exchange attributes

At 0,7 and 14 days following the removal of the shade net, photosynthesis rate, stomatal conductance and transpiration rate were recorded between 11:00-11:30 AM from the flag leaf using LI-COR LI-6400/XT Portable Photosynthesis System present in the EVS Division of IARI, New Delhi. When the measurement was taken, the temperature was between 25 and 30°C and the PAR levels were 1,700-1,800 μmol/m^2/s. Three leaves from each plot were the subject of independent observations and the mean value is shown.

Yield characteristics

After 150 days of sowing, wheat was harvested and yield parameters were recorded. These included number of ear bearing tillers per plant and per unit of ground area, 1000-grain weight and grain yield, all assessed for both control and treated groups.

Statistical analysis

All data were recorded in triplicate, averaged and analyzed statistically using one-way ANOVA.

RESULTS AND DISCUSSION

Effect of varying light intensity (PAR) on growth characteristics of wheat

Low light intensity delays phenological events like heading, anthesis and grain filling. Dong *et al.* (2014) observed delayed maturity and reduced plant height in wheat grown

under shaded conditions. Zhang *et al.* (2023) reported that low light increases chlorophyll *b* and decreases the chlorophyll *a/b* ratio, possibly as a light absorption adaptation. Setyaningrum *et al.* (2020) reported biomass reduction of nearly 50% in Indigo when covered with 75% light-reducing shade net. Gupta *et al.* (2025) also reported reduced biomass in tomato when the light intensity was reduced.

Plant biomass

Shading treatments (50% and 75%) reduce plant biomass (g dry weight) in wheat genotypes HD-2967 and HD-3086 as noticed 0, 7 and 14 days after shade removal and depicted in Table 1. Increased shading intensity generally results in a greater reduction in plant biomass. At 0 days after shade

Table 1: Effect of 50% and 75% shading effect on plant biomass and leaf chlorophyll of wheat genotypes HD-2967 and HD-3086 on 0, 7 and 14 days after removal of shade nets (used for six weeks).

Days after shading	Crop year	Plant mass (g dw)				Leaf chlorophyll (mg/g fw)			
		Control	50% shade	75% shade	Mean effect	Control	50% shade	75% shade	Mean effect
Wheat genotype: HD 2967									
0 DAS	2022-23	9.17	6.35	4.87	5.61	1.41	1.59	1.68	1.64
			-(44.41)	-(88.30)	-(63.46)		(11.32)	(16.07)	(13.76)
	2023-24	9.32	6.84	5.12	5.98	1.43	1.62	1.74	1.68
			-(36.26)	-(82.03)	-(55.85)		(11.73)	(17.82)	(14.88)
	Mean	9.25	6.595	4.995	5.80	1.42	1.61	1.71	1.66
			-(40.18)	-(85.09)	-(59.53)		(11.53)	(16.96)	(14.33)
7 DAS	2022-23	10.52	9.01	8.16	8.59	1.46	1.63	1.69	1.66
			-(16.76)	-(28.92)	-(22.54)		(10.43)	(13.61)	(12.05)
	2023-24	10.93	9.65	8.02	8.84	1.47	1.65	1.71	1.68
			-(13.26)	-(36.28)	-(23.71)		(10.91)	(14.04)	(12.50)
	Mean	10.73	9.33	8.09	8.71	1.47	1.64	1.70	1.67
			-(14.95)	-(32.57)	-(23.13)		(10.67)	(13.82)	(12.28)
14 DAS	2022-23	13.91	12.54	9.62	11.08	1.48	1.62	1.73	1.68
			-(10.93)	-(44.59)	-(25.54)		(8.64)	(14.45)	(11.64)
	2023-24	14.02	12.96	10.21	11.59	1.49	1.65	1.72	1.69
			-(8.18)	-(37.32)	-(21.02)		(9.70)	(13.37)	(11.57)
	Mean	13.97	12.75	9.915	11.33	1.49	1.64	1.73	1.68
			-(9.53)	-(40.85)	-(23.23)		(9.17)	(13.91)	(11.61)
CD (0.05)			0.296				0.032		
Wheat genotype: HD 3086									
0 DAS	2022-23	8.58	6.3	4.74	5.52	1.43	1.54	1.62	1.58
			-(36.19)	-(81.01)	-(55.43)		(7.14)	(11.73)	(9.49)
	2023-24	8.87	6.73	5.04	5.89	1.44	1.53	1.59	1.56
			-(31.80)	-(75.99)	-(50.72)		(5.88)	(9.43)	(7.69)
	Mean	8.73	6.52	4.89	5.70	1.44	1.54	1.61	1.57
			-(33.92)	-(78.43)	-(53.00)		(6.51)	(10.59)	(8.60)
7 DAS	2022-23	10.23	8.67	8.14	8.41	1.47	1.57	1.68	1.63
			-(17.99)	-(25.68)	-(21.71)		(6.37)	(12.50)	(9.54)
	2023-24	10.51	8.54	7.91	8.23	1.48	1.60	1.69	1.65
			-(23.07)	-(32.87)	-(27.78)		(7.50)	(12.43)	(10.03)
	Mean	10.37	8.61	8.03	8.32	1.48	1.59	1.69	1.64
			-(20.51)	-(29.22)	-(24.71)		(6.94)	(12.46)	(9.79)
14 DAS	2022-23	12.68	11.36	9.57	10.47	1.51	1.61	1.72	1.67
			-(11.62)	-(32.50)	-(21.17)		(6.21)	(12.21)	(9.31)
	2023-24	13.14	11.87	10.17	11.02	1.52	1.65	1.75	1.70
			-(10.70)	-(29.20)	-(19.24)		(7.88)	(13.14)	(10.59)
	Mean	12.91	11.615	9.87	10.74	1.52	1.63	1.74	1.68
			-(11.15)	-(30.80)	-(20.18)		(7.06)	(12.68)	(9.96)
CD (0.05)			0.266				0.025		

Value in parentheses under the treatment values indicates per cent change over the unshaded control.

removal, HD-2967 shows a more substantial percentage reduction in biomass, indicating higher initial sensitivity to shading stress. Conversely, at 14 days after shade removal, HD-3086 tends to show marginally greater percentage reductions in biomass, suggesting slower recovery.

Both genotypes, demonstrate an overall significant reduction in biomass under shading, highlighting the negative impact of reduced light availability on plant growth and its agronomic implications for grain yield.

Leaf chlorophyll

Table 1 shows elevated leaf chlorophyll content in both wheat genotypes under shading compared to the control across all time points, indicating a physiological acclimation to reduced light. Chlorophyll biosynthesis increases to maximize light capture, with higher shading intensity (75%) generally causing greater chlorophyll accumulation than 50% shading. Elevated chlorophyll concentrations persist post-shading, suggesting a delayed down-regulation of biosynthesis. HD-2967 tends to accumulate slightly higher chlorophyll concentrations than HD-3086, particularly at 0 DAS (*e.g.*, 1.66 mg/g fw in HD-2967 vs. 1.57 mg/g fw in HD-3086).

This may indicate a more pronounced acclimation in HD-2967, but the overall chlorophyll increase under shading is similar for both genotypes.

Root-shoot mass ratio (RSR)

Data, in Table 2, indicate that shading treatments elevate the root-shoot mass ratio in both genotypes, especially at 0 days after shade removal (DAS), suggesting a shift towards root development under reduced light to enhance resource uptake. This ratio decreases over time post-shading, implying biomass reallocation during recovery. A gradient effect shows higher ratios under 75% than 50% shading, indicating increased root allocation with more light restriction. At 0 DAS, HD-3086 exhibits a greater increase in the root-shoot mass ratio than HD-2967 (41.66% vs 32.49%), suggesting a stronger initial root development response in HD-3086. However, these genotypic differences lessen at later time points.

In conclusion, shading alters biomass allocation in both genotypes, favouring root growth, with HD-3086 showing a more pronounced initial shift.

Effect of varying light intensity (PAR) on gas exchange attributes of wheat

Kumar *et al.* (2013) demonstrated that reduced light intensity in wheat plants leads to lower net photosynthetic rate, stomatal conductance and transpiration rate, with an increase in intercellular CO_2 concentration, indicating limited carbon fixation. Low light induces oxidative stress, prompting wheat plants to upregulate antioxidant enzymes like

Table 2: Effect of 50% and 75% shading effect on root shoot mass ratio of wheat genotypes HD-2967 and HD-3086 on 0, 7 and 14 days after removal of shade nets (used for six weeks).

Days after shading	Crop year	Root shoot mass ratio			
		Control	50%	75%	Mean effect
		Wheat genotype: HD-2967			
0 DAS	2022-23	0.192	0.251	0.283	0.267
	2023-24	0.190	0.292	0.306	0.299
	Mean	0.191	0.272	0.294	0.283
7 DAS	2022-23	0.294	0.308	0.323	0.315
	2023-24	0.284	0.320	0.343	0.332
	Mean	0.289	0.314	0.333	0.323
14 DAS	2022-23	0.267	0.265	0.288	0.277
	2023-24	0.251	0.262	0.286	0.274
	Mean	0.259	0.263	0.287	0.275
CD (0.05)			0.053		
		Wheat Genotype: HD-3086			
0 DAS	2022-23	0.162	0.267	0.307	0.287
	2023-24	0.180	0.290	0.307	0.298
	Mean	0.171	0.278	0.307	0.293
7 DAS	2022-23	0.288	0.286	0.339	0.313
	2023-24	0.268	0.332	0.343	0.338
	Mean	0.278	0.309	0.341	0.325
14 DAS	2022-23	0.231	0.273	0.299	0.286
	2023-24	0.251	0.258	0.302	0.280
	Mean	0.241	0.265	0.300	0.283
CD (0.05)			0.061		

Table 3: Effect of 50% and 75% shading effect on photosynthetic rate, transpiration rate and stomatal conductance of wheat genotypes hd-2967 and hd-3086 on 0,7 and 14 days after removal of shade nets (used for six weeks).

Days after shading	Crop year	Photosynthetic rate (Pn) (μmol CO_2 m^{-2} s^{-1})				Transpiration rate (E) (mmol H_2O m^{-2} s^{-1})				Stomatal conductance (Gs) (mmol CO_2 m^{-2} s^{-1})			
		Control	50% shade	75% shade	Mean effect	Control	50% shade	75% shade	Mean effect	Control	50% shade	75% shade	Mean effect
Wheat genotype: HD 2967													
0 DAS	2022-23	16.8	11.7	9.5	10.60	3.83	2.87	2.45	2.66	0.457	0.353	0.287	0.32
			-(43.59)	-(76.84)	-(58.49)		-(33.45)	-(56.33)	-(43.98)		-(29.46)	-(59.23)	-(42.81)
	2023-24	17.1	12	10.1	11.05	3.86	2.82	2.39	2.61	0.475	0.366	0.299	0.33
			-(42.50)	-(69.31)	-(54.75)		-(36.88)	-(61.51)	-(48.18)		-(29.78)	-(58.86)	-(42.86)
	Mean	16.95	11.85	9.8	10.83	3.85	2.845	2.42	2.63	0.466	0.360	0.293	0.33
			-(43.04)	-(72.96)	-(56.58)		-(35.15)	-(58.88)	-(46.06)		-(29.62)	-(59.04)	-(42.84)
7 DAS	2022-23	16.9	11.8	9.6	10.70	3.85	2.92	2.53	2.73	0.461	0.367	0.298	0.33
			-(43.22)	-(76.04)	-(57.94)		-(31.85)	-(52.17)	-(41.28)		-(25.61)	-(54.70)	-(38.65)
	2023-24	17.3	11.8	9.9	10.85	3.89	2.9	2.48	2.69	0.481	0.383	0.311	0.35
			-(46.61)	-(74.75)	-(59.45)		-(34.14)	-(56.85)	-(44.61)		-(25.59)	-(54.66)	-(38.62)
	Mean	17.10	11.8	9.75	10.78	3.87	2.91	2.505	2.71	0.471	0.375	0.305	0.34
			-(44.92)	-(75.38)	-(58.70)		-(32.99)	-(54.49)	-(42.94)		-(25.60)	-(54.68)	-(38.63)
14 DAS	2022-23	17.1	11.9	9.7	10.80	3.88	2.78	2.56	2.67	0.463	0.371	0.302	0.34
			-(43.70)	-(76.29)	-(58.33)		-(39.57)	-(51.56)	-(45.32)		-(24.80)	-(53.31)	-(37.59)
	2023-24	17.5	11.9	9.8	10.85	3.91	2.81	2.36	2.59	0.486	0.386	0.315	0.35
			-(47.06)	-(78.57)	-(61.29)		-(39.15)	-(65.68)	-(51.26)		-(25.91)	-(54.29)	-(38.66)
	Mean	17.30	11.9	9.75	10.83	3.90	2.80	2.46	2.63	0.475	0.379	0.309	0.34
			-(45.38)	-(77.44)	-(59.82)		-(39.36)	-(58.33)	-(48.24)		-(25.36)	-(53.81)	-(38.14)
CD (0.05)			0.83				0.38					0.031	
Wheat genotype: HD 3086													
0 DAS	2022-23	16.9	11.8	9.6	10.70	3.86	2.76	2.31	2.54	0.458	0.344	0.288	0.32
			-(43.22)	-(76.04)	-(57.94)		-(39.86)	-(67.10)	-(52.27)		-(33.14)	-(59.03)	-(44.94)
	2023-24	17.3	12.2	10.3	11.25	3.84	2.82	2.41	2.62	0.474	0.360	0.296	0.33
			-(41.80)	-(67.96)	-(53.78)		-(36.17)	-(59.34)	-(46.85)		-(31.67)	-(60.14)	-(44.51)
	Mean	17.10	12	9.95	10.98	3.85	2.79	2.36	2.58	0.466	0.352	0.292	0.32
			-(42.50)	-(71.86)	-(55.81)		-(37.99)	-(63.14)	-(49.51)		-(32.39)	-(59.59)	-(44.72)
7 DAS	2022-23	17.1	11.9	9.7	10.80	3.86	2.94	2.58	2.76	0.462	0.351	0.294	0.32
			-(43.70)	-(76.29)	-(58.33)		-(31.29)	-(49.61)	-(39.86)		-(31.62)	-(57.14)	-(43.26)
	2023-24	17.4	12.1	10.4	11.25	3.88	2.9	2.48	2.69	0.482	0.366	0.295	0.33
			-(43.80)	-(67.31)	-(54.67)		-(33.79)	-(56.45)	-(44.24)		-(31.69)	-(63.39)	-(45.84)
	Mean	17.25	12	10.05	11.03	3.87	2.92	2.53	2.73	0.472	0.359	0.295	0.33

Table 3: Continue....

Table 3: Continue...

			-(43.75)	-(71.64)	-(56.46)		-(32.53)	-(52.96)	-(42.02)		-(31.66)	-(60.27)	-(44.56)
14 DAS	2022-23	17.2	11.8	9.8	10.80	3.91	2.81	2.36	2.59	0.471	0.356	0.292	0.32
			-(45.76)	-(75.51)	-(59.26)		-(39.15)	-(65.68)	-(51.26)		-(32.30)	-(61.30)	-(45.37)
	2023-24	17.60	11.7	10.1	10.90	3.87	2.91	2.56	2.74	0.484	0.391	0.303	0.35
			-(50.43)	-(74.26)	-(61.47)		-(32.99)	-(51.17)	-(41.50)		-(23.79)	-(59.74)	-(39.48)
	Mean	17.40	11.75	9.95	10.85	3.89	2.86	2.46	2.66	0.478	0.374	0.298	0.34
			-(48.09)	-(74.87)	-(60.37)		-(36.01)	-(58.13)	-(46.24)		-(27.84)	-(60.50)	-(42.32)
CD (0.05)			0.60				0.28				0.032		

Value in parentheses under the treatment values indicates percent change over the unshaded control.

superoxide dismutase, peroxidase and catalase to mitigate oxidative damage (Zhang *et al.,* 2023).

Photosynthesis rate

Table 3 shows a significant reduction in the photosynthetic rate (Pn) in both genotypes under 50% and 75% shading, indicating that shading stress inhibits photosynthetic activity. Increasing shading intensity from 50% to 75% further decreases Pn, suggesting a dose-dependent response.

Both genotypes show a similar pattern of reduced Pn under shading, with minor quantitative differences. At 0 days after shade removal (DAS), HD-2967 shows a slightly greater percentage reduction in Pn under 75% shade (-72.96%) compared to HD-3086 (-71.86%), suggesting a higher initial sensitivity to severe shading in HD-2967. However, at 14 DAS, HD-3086 exhibits a larger percentage reduction in Pn under 50% shade (-48.09%) compared to HD-2967 (-45.38%), potentially indicating slower photosynthetic recovery in HD-3086. Overall, genotypic differences are small.

Stomatal conductance

Table 3 data shows reduced stomatal conductance (Gs) in both genotypes under 50% and 75% shading compared to the control. This indicates that shading decreases stomatal aperture, potentially limiting CO_2 uptake and photosynthetic efficiency. Increasing shading from 50% to 75% further reduces Gs, suggesting a dose-dependent stomatal closure response.

Both genotypes show a similar pattern of reduced Gs under shading, but with quantitative differences. At 0 days after shading (DAS), HD-3086 has a slightly greater percentage reduction in Gs than HD-2967, implying a stronger initial stomatal closure response in HD-3086. At 14 DAS, HD-3086's Gs remains more affected by 75% shading. However, the overall genotypic differences in Gs are relatively small.

Transpiration rate

Table 3 shows a reduction in transpiration rate (E) in both wheat genotypes under 50% and 75% shading compared to the control, indicating decreased water loss, likely through stomatal regulation. Transpiration rate generally decreases as shading intensity increases, with 75% shading causing a more significant reduction than 50% shading. Shaded plants maintain lower transpiration rates than the control throughout the 14-day observation period.

Both genotypes exhibit a similar pattern of reduced transpiration, but with some quantitative differences. At 0 days after shading (DAS), HD-3086 shows a slightly greater percentage reduction in E (mean of -63.14% under 75% shade) than HD-2967 (mean of -58.88% under 75% shade). At 7 DAS, reductions are comparable and by 14 DAS, HD-2967 has a marginally greater reduction in E under 75% shade (-58.33%) compared to HD-3086 (-58.13%). These findings indicate that while both genotypes reduce transpiration under shading, there are subtle differences in the extent of this response.

Effect of varying light intensity (PAR) on yield attributes of wheat

Light intensity significantly affects several yield components of wheat, including the number of ear-bearing tillers (EBT) per unit area, number of EBT per plant and 1000-grain weight. Dong *et al.* (2014) found that shading during grain filling can reduce wheat yield by up to 30%, linked to reduced photosynthetic rate and starch synthesis. This effect is similar to that of any other major pollutant like SO_2 (Dhupper *et al.,* 2019).

Ear bearing tillers (per plant and per unit of ground area)

Shading reduces EBT per plant and per square meter in both genotypes compared to the control, indicating a negative impact on productive tillers in wheat. Increasing shading intensity from 50% to 75% further reduces EBT, suggesting a dose-dependent effect where more severe shading decreases productive tillers (Table 4).

Both genotypes show a reduction in EBT under shading, but with quantitative differences. HD-3086 has a less drastic reduction in tillers per plant under 50% shading compared to HD-2967 (17.29% vs 23.95%), suggesting that HD-3086 maintains more tillers per plant under moderate shading. However, under 75% shading, HD-2967 shows a greater reduction in tillers per plant (73.93%) than HD-3086 (50.22%).

Consistent with the trend for tillers per plant, HD-3086 exhibits a less severe reduction in tillers per square meter under 50% shading (25.74% vs 31.74% for HD-2967). Under 75% shading, both genotypes show substantial reductions, but the reduction is more pronounced in HD-2967 (66.18%) compared to HD-3086 (52.25%).

Thousand grain weight

Shading negatively affects 1000-grain weight in both wheat genotypes. Increasing shading intensity from 50% to 75% further reduces these yield components, indicating a greater yield reduction with higher shading stress.

Both genotypes show a decrease in 1000-grain weight under shading. Under 50% shading, HD-2967 shows a 12.37% reduction, while HD-3086 shows an 11.83% reduction.

Table 4: Effect of 50% and 75% shading on ear bearing tillers per plant and ear bearing tillers per m^2 of ground area of wheat genotypes HD-2967 and HD-3086 upon final harvest.

Parameter/Shading	EBT/Plant				EBT/m^2			
Crop year	2022-23	2023-24	Mean	Diff (%)	2022-23	2023-24	Mean	Diff (%)
Wheat genotype: HD-2967								
Control	9.71	9.37	9.54	NA	476	487	481.5	NA
50%	7.50	7.89	7.70	19.32	360	371	365.5	24.09
75%	5.39	5.58	5.48	42.51	205	223	214	55.56
Mean effect	6.45	6.73	6.59	30.91	282.5	297.0	289.8	39.82
CD (0.05)		0.36				2.41		
Wheat genotype: HD-3086								
Control	9.61	9.28	9.45	NA	490	492	491	NA
50%	7.88	8.23	8.05	14.74	386	395	390.5	20.47
75%	6.38	6.19	6.29	33.43	249	260	254.5	48.17
Mean effect	7.13	7.21	7.17	24.09	317.5	327.5	322.5	34.32
CD (0.05)		0.39				2.95		

Table 5: Effect of 50% and 75% shading on 1000-grain weight and grain yield of wheat genotypes HD-2967 and HD-3086 upon final harvest.

Parameter/Shading	1000-Grain weight				Grain yield (in grams)			
Crop year	2022-23	2023-24	Mean	Diff (%)	2022-23	2023-24	Mean	Diff (%)
Wheat genotype: HD-2967								
Control	49.7	48.1	48.9	NA	1064	1081	1072.5	NA
50%	43.4	42.3	42.9	12.37	728	719	723.5	32.54
75%	39.7	40.5	40.1	18.00	561	548	554.5	48.30
Mean effect	41.6	41.4	41.5	15.18	645	634	639	40.42
CD (0.05)		0.678				3.97		
Wheat genotype: HD- 3086								
Control	48.5	47.9	48.2	NA	951	964	957.5	NA
50%	43.1	41.9	42.5	11.83	687	676	681.5	28.83
75%	39.2	37.4	38.3	20.54	499	486	492.5	48.56
Mean effect	41.2	39.7	40.4	16.18	593	581	587	38.69
CD (0.05)		0.748				3.51		

Under 75% shading, the reduction is more pronounced, with HD-3086 showing a larger reduction (20.54%) compared to HD-2967 (18.00%).

While HD-2967 has higher yield potential under optimal light, HD-3086 shows relatively greater stability under moderate shading. However, both are significantly impacted by severe shade stress.

Grain yield

Analysis of grain yield data in Table 5 shows that shading negatively impacts wheat genotypes HD-2967 and HD-3086. Under control conditions, HD-2967 had a higher mean grain yield (1072.5 g) than HD-3086 (957.5 g). However, grain yield significantly decreased in both genotypes as shading intensity increased to 50% and 75%.

At 50% shading, HD-2967's yield decreased by 32.54% (to 723.5 g) and at 75% shading, it decreased by 48.30% (to 554.5 g). HD-3086's yield decreased by 28.83% (to 681.5 g) at 50% shading and by 48.56% (to 492.5 g) at 75% shading.

The overall mean yield reduction across shaded treatments was slightly higher for HD-2967 (40.42%) than for HD-3086 (38.69%). While HD-2967 has a higher yield potential under optimal light, HD-3086 shows marginally better stability under shading stress. Both genotypes, however, suffer significant yield losses under low light.

CONCLUSION

This study highlights the significant effects of reduced light intensity, simulated through 50% and 75% shading, on the physiological and yield parameters of wheat genotypes HD-2967 and HD-3086. Shading led to notable declines in plant biomass, photosynthetic rate, stomatal conductance and transpiration rate, while leaf chlorophyll content and root-to-shoot ratio increased as adaptive responses to low light conditions. Despite these physiological adjustments, substantial yield reductions were observed under both shading treatments. HD-2967 exhibited superior performance under optimal light conditions but experienced a greater decline in yield under shading. In contrast, HD-3086 showed better resilience under moderate shade, maintaining higher tiller counts and grain stability. It also exhibited a stronger initial root development response. Overall, both genotypes were adversely affected by severe light limitation, with HD-3086 showing comparatively better adaptability. These findings highlight the importance of developing and promoting wheat varieties with enhanced tolerance to reduced light environments, especially in pollution-prone regions. Such efforts are essential to sustain wheat productivity and ensure food security under changing environmental conditions.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish or preparation of the manuscript.

REFERENCES

Acreche, M.M., Brice˜no-Félix, G., Sánchez, J.A.M. and Slafer, G.A. (2009). Grain number determination in an old and a modern Mediterranean wheat as affected by pre-anthesis shading. *Crop Pasture Sci.* **60:** 271-279.

Agathokleous, E., Frei, M. and Knopf, O.M. (2023). Adapting crop production to climate change and air pollution at different scales. *Nat Food*. **4:** 854-865.

Devrajani, S.K., Qureshi, M., Imran, U. and Tamat-Ul-Nisa (2020). Impact of gaseous air pollutants on agricultural crops in developing countries: A review. *J. Environ. Sci. Public Health.* **4:** 71-82.

Dhupper, R., Yadav, P. and Singh, B. (2019). Crop adaptation to air pollution I. Effect of particulate and SO_2 pollution on growth, yield attributes and sulphur nutrition of wheat, barley and chickpea. *Indian J. Agri. Res.* **53(3):** 303-308. doi: 10.18805/IJARe.A-5273.

Dong, C., Fu, Y., Liu, G. and Liu, H. (2014). Low light intensity effects on the growth, photosynthetic characteristics, antioxidant capacity, yield and quality of wheat at different growth stages in BLSS. *Adv. Space Research*. **53(11):** 1557-1566.

Dong, D. and Wang, J. (2023). Air pollution as a substantial threat to the improvement of agricultural total factor productivity. *Global Evidence, Environment International.* **173:** 107842.

Dutta, S.S., Tyagi, W. and Mayank, R. (2017). Physiological and molecular response to low light intensity in rice: A review. *Agricultural Reviews.* **38(3):** 209-215. doi: 10.18805/ag.v38i03.8980.

Gupta, A., Dhupper, R. and Singh, B. (2025). Effect of sulphur dioxide enrichment on growth attributes and its biochemical basis in tomato. *J. Applied Horticulture*. **27(1):** 66-71.

Hiscox, J.D. and Israelstam, G.F. (1979). A method for the extraction of chlorophyll from leaf tissue without maceration. *Can. J. Bot.* **57:** 1332-1334.

Kumar, A., Singh, D. and Singh, V. (2013). Physiological basis of yield variability in wheat under varying degree of shades. *Plant Physiology Reports*. **18(2):** 164-168.

Pandya, S., Gadekallu, T.R. and Sharma, R. (2022). A study of the impacts of air pollution on the agricultural community and yield crops. *Sustainability.* **14:** 13098.

Qian, Y., Wang, W. and Kaiser, D.P. (2007). Variability of solar radiation under cloud-free skies in China: The role of aerosols. *Geophys. Res. Lett.* https://doi.org/10.1029/2006GL028800.

Ramanathan, V. and Feng, Y. (2009). Air pollution, greenhouse gases and climate change: global and regional perspectives. *Atmos. Environ.* **43:** 37-50.

Setyaningrum, D., Budiastuti, M.T.S and Supriyono. (2020). Light intensity and biofertilizers effect on natural Indigo production and nutrient uptake of (*Indigofera tinctoria* L.). *Indian J. Agri. Res.* **54(5):** 578-584. doi: 10.18805/IJARe.A-507.

Zhang, Y., Liu, Y. and Wang, Y. (2023). Physiological and molecular responses of wheat to low light intensity. *Agronomy*. **13(1):** 272.