Determination of critical low light limit and adaptive physiological and biochemical traits regulating growth and yield of mustard (*Brassica juncea* Coss.)

Badre Alam¹ · Rashmi Singh¹ · Mayank Chaturvedi¹ · Ram Newaj¹ · O. P. Chaturvedi¹

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Abstract Growth and physio-biochemical traits under different incident solar light intensities (100, 67, 50 and 25%) were studied in mustard in a semi-arid agroclimate region of Central India. Our comprehensive studies revealed that incident solar light intensities below about 67% were highly detrimental in mustard for its growth and grain yield. Major factors that contributed to the differential responses under varying light intensities were identified which holds importance for better understanding of low light adaptability in an important oilseed crop like mustard. Biomass index (ratio of dry biomass to height) has been established and evaluated for the differential growth performance of the crop under different light intensities. Biomass index progressively declined from 0.48 (open sunlight) to 0.11 (25% sunlight). Physio-biochemical factors were identified that were playing major role in manifestation of the differential growth and grain yield. Mustard exhibited its low light adaptive trends through differential down-regulation in the rates of net CO₂ assimilation (P_N), stomatal conductance, transpiration, thylakoid electron transport rate (ETR) and leaf wax level. For example, P_N decreased from 35.88 (open light) to 11.64 μmol m⁻² s⁻¹ (25% sunlight). Photochemical events showed critical impact as evidenced by decreased PSII quantum yield, photochemical quenching (qP) and higher non-photochemical quenching (qN) that were clearly associated with physiological efficiency of the plants under varying light intensities. Leaf wax level decreased from 1.69 mg g⁻¹ fresh weight (open light) to 0.96 mg g⁻¹ fresh weight

(25% sunlight). Our results indicated that limited ETR supply across photosystem II (PSII) decreased the photochemical efficiency and carbon gain under low light which resulted in reduction of biomass index and grain yield. Besides, it was found that overexpression of protein band around ~ 26 kDa in low light could be another adaptive feature for mustard related to light harvesting complex. Our findings would augment selection of traits for optimizing growth and grain yield of mustard for low light or light limiting agro-ecosystem.

Keywords Anthocyanin · CO₂ assimilation rate · Chlorophyll · Epicuticular wax · Mustard · Photochemistry · Thylakoid electron transport

Abbreviations

Antho.	Anthocyanin
Chl	Chlorophyll
ETR	Thylakoid electron transport rate
E	Transpiration rate
Gs	Stomatal conductance
LT	Leaf temperature
P _N	Net CO ₂ assimilation rate
PPFD	Photosynthetic photon flux density
qP	Photochemical quenching
qN	Non-photochemical quenching
RH	Relative humidity
Rubisco	Ribulose biphosphate carboxylase-oxygenase
ST	Soil temperature at surface
SST	Sub soil temperature
Ta	Air temperature
Φ _{PSII}	Effective PSII quantum yield

✉ Badre Alam
badrealam@gmail.com

¹ ICAR-Central Agroforestry Research Institute, Gwalior
Road, Jhansi, Uttar Pradesh 284003, India

Introduction

Availability of optimum light is one of the major environmental resources determining the plant's growth, productivity and survival. Variation in light intensities lead to develop acclimation strategies in plants in given environment (Zhang et al. 2007). Mechanisms of adapting to light-limitation in crops are complex phenomenon and many of these are not still clearly understood including the phenotypic plasticity with reference to morpho-physiological traits (Valladares et al. 2007). Most of the plant species develop adaptive mechanisms in response to light conditions even in crop phenology (Singh and Alam 2010). Thus, to cope with such light limiting challenges, crops have to adopt various physiological and biochemical changes. Adaptation of plants to low light environments allow coordinated resources distribution not only to achieve and maintain growth and development, but also to function efficiently under light limiting conditions (Zhang et al. 2007). This limitation of light is a constraint to crop productivity and the plants need to adjust its whole mechanism including photosynthesis, pigments biosynthesis, growth and physiological traits according to the available light (Singh and Alam 2010; Singh et al. 2012). To overcome the constraints of low light conditions, plants put efforts to increase light harvesting and its better utilisation in photosynthetic processes and photochemical events (Alam et al. 2011). However, the capability of adaptation and acclimation under different light environment is species specific. Many natural conditions creates light as limiting factor in atmosphere namely cloud overcast, aerosol deposition, fog and smog etc. or due to agroforestry and mixed cropping practices that pose major constraint to crop production. Low incident sunlight is inevitable in agroforestry practices where crops are grown under tall trees and it creates challenging situation for understory crops. Therefore, understanding the various adaptive strategies of crops for different light condition is important in the context of further crop improvement and productivity.

Oil seed crops being next to food crops cover gross cropped area in India. Mustard (*Brassica juncea* Coss.) is an important oil seed plant. Cultivation of mustard is done in winter season and thus, it also experiences natural light limitation due to cloudy weather, fog and snow precipitation. In mixed cropping with trees as in agroforestry system, tree shade poses constraint to sufficient incident light resulting in low yield in comparison to monocrop. Low availability of incident sunlight due to tree canopy affected mustard yield in agroforestry field which also highlighted the necessity of better understanding about the impact of different light intensities on mustard crop for better

production (Newaj et al. 2005). Therefore, it is essential and important to determine the critical limit (tolerance limit) and acclimation strategies of mustard crop under different limiting light conditions and effect on major adaptive traits of the crop. Thus, improved understanding of microclimatic conditions and their influences on growth and physiology of crop is needed to help towards selecting critical low light limit of crop under light limiting environment. The aim of this study was to evaluate the critical limit of light on mustard under different limiting light conditions and to decipher the regulatory mechanisms through assessing growth, physiological, biochemical traits and their impact on yield of the crop.

Materials and methods

Plant material and location of experiment

The experiment was conducted at ICAR-Central Agroforestry Research Institute, Jhansi (25°27'N latitude and 78°35'E longitude, 271 m above MSL) in the semi-arid tract of central plateau of India. The experiment was conducted under varying light intensities or full sunlight (open field) during rabi seasons (sowing in November and harvesting in April) in the years 2007–2008 and 2008–2009 with mustard (*Brassica juncea* Coss. variety Varuna). There were three net houses (25 × 8 × 3 m) providing about 67, 50 and 25% of incident sunlight respectively. The basis of choosing the three category of shade net houses was to simulate three different light intensities which would provide moderate shade (67% light), deep shade (50% light) and extreme shade (25% light) as it is normally observed in wide range of agroforestry system. Different intensity of sunlight was obtained in each of three separate net houses as different category (porosity) of shade-net namely 33% shade (67% light), 50% shade (50% light) and 75% shade net (25% light) was used to cover the respective net house to allow the respective incident sunlight intensities. The crop (mustard) was also grown in adjacent open field (full sun light). There were three replications in each light environment prepared in RBD (randomized block design) having plot size of 5.8 × 3.4 m. Soil in the experiment field was black having a mean pH 7.02. The study was conducted taking all the standard agronomic practices including irrigation and plant protection measures. Microclimatic data of the experimental sites were observed in the morning between 09:30 A.M. and 10:00 A.M. (local time) during the experimental period in both the years (Table 1).

Table 1 Microclimatic data and soil temperature of the experimental sites during the experimental period of two consecutive years as recorded

Light environments	PPFD	RH (%)	Ta	ST	SST
Full sun light	1029.9 ± 94.2	45.38 ± 6.4	23.1 ± 1.3	27.4 ± 1.5	25.3 ± 1.5
67% sun light	659.8 ± 63.4	49.38 ± 6.6	22.6 ± 1.5	25.8 ± 1.4	24.7 ± 1.3
50% sun light	480.7 ± 38.9	55.21 ± 7.3	21.2 ± 1.0	24.6 ± 1.3	21.7 ± 1.3
25% sun light	252.5 ± 22.6	56.63 ± 7.5	20.6 ± 1.0	21.6 ± 0.9	19.4 ± 0.9

PPFD = photosynthetic photon flux density ($\mu\text{mol m}^{-2} \text{s}^{-1}$), RH = relative humidity (%), Ta = air temperature ($^{\circ}\text{C}$), ST = Soil temperature at surface ($^{\circ}\text{C}$), SST = sub soil temperature ($^{\circ}\text{C}$) (0–15 cm depth). Mean with $\pm$ standard error

Determination of biomass index and grain yield

Biomass index was obtained by the ratio of dry mass and height of the crop. For dry biomass estimation, fifteen plants from each light environment were collected at 45 DAS (days after sowing) by reaping the plants at ground level. Then the plant parts were separated and dried in a hot air oven at 70°C for 48 to 72 h to a constant weight. Dried samples were taken for biomass estimation. For grain yield estimation, whole plants were harvested. Pods and seeds were separated per plant basis. Following the aforesaid procedures, biomass and grain yield of crop were estimated from each category of light environments i.e. three intensities of low light and full sun light grown crop.

Estimation of pigments, epicuticular wax level and soluble protein of leaf

Fully matured (top most) healthy leaves of nine uniform plants (visual appearance on the basis of uniform height of the plants) were tagged and selected from each category of light intensity at 45–50 DAS (days after sowing) for all the measurements. Chlorophyll (Chl) was extracted from the leaves with acetone and DMSO (Dimethyl sulphoxide) (1:1) solvents and estimated according to Arnon (1949). Anthocyanin in leaf was extracted in methanol and HCl solvents (9:1) and estimated as per the technique of Kho et al. (1977). Epicuticular wax level of leaf was estimated as per the gravimetric technique of Silva Fernandes et al. (1964) using chloroform solvent extraction. The amount of wax was calculated against fresh weight. Soluble protein in leaf was estimated as per the method of Bradford (1976).

Simultaneous measurements of gas exchange and chlorophyll fluorescence

A portable photosynthesis system (LI-6400XT, Licor, U.S.A.) attached with a leaf chamber fluorometer (LCF-6400-40) was used for simultaneous measurements of gas exchange and chlorophyll fluorescence. Measurement of photosynthetic traits and chlorophyll fluorescence parameters were simultaneously conducted on intact mature

leaves (top most) attached to the plants during 40–50 DAS (days after sowing). To achieve similar microclimatic conditions, the measurements were conducted in the morning between 9:30 and 10:30 A.M. (local time). Each leaf was dark adapted for about 25 min. in the sample chamber and at this point CO_2 efflux from the leaf was taken as rate of dark respiration. Following the dark measurements, photosynthetic light response curves were made at different levels of photosynthetic photon flux densities (PPFD) using a LED source attached to the leaf chamber fluorometer at constant CO_2 concentration of $385 \mu\text{mol mol}^{-1}$. During the measurement, leaf temperature was maintained at ambient temperature and leaf-air VPD was 1.0 to 1.2 kPa. CO_2 assimilation, stomatal conductance and fluorescence were constantly monitored to ensure that they reached at steady-state before a reading was taken.

Various chlorophyll fluorescence parameters namely maximal fluorescence under dark (F_m) and under light exposure (F_m'), steady state fluorescence at any given time (F_s) and minimal fluorescence immediately under dark (F_o) and after light exposure (F_o') which were required for estimation of different components of photochemical events and electron transport rate across PSII (ETR) of the leaf were recorded following the standard techniques (Krause and Weis 1991; Schreiber et al. 1998; Van Kooten and Snel 1990) as given below.

$F_v = F_m - F_o$, where F_v denotes variable chlorophyll fluorescence and F_v/F_m is the maximum potential quantum yield of PSII in dark adapted state.

Estimation of effective PS II quantum yield (Φ_{PSII}) was assessed as

$$\Phi_{\text{PSII}} = (F_m' - F_s)/F_m'$$

The rate of non-cyclic electron flow across PS II (ETR) was calculated from the chlorophyll fluorescence data as

$$\text{ETR} = \Phi_{\text{PSII}} \times \text{PPFD} \times 0.84 \times 0.5$$

where 0.84 is the leaf fractional absorptance of incident PPFD and 0.5 is the fraction of absorbed PPFD which is absorbed by the light harvesting complex of PS II as widely

accepted for C_3 species (Genty et al. 1989; Schreiber et al. 1998).

Photochemical quenching qP of fluorescence was computed from

$$qP = (Fm' - Fs)/(Fm' - Fo')$$

Non photochemical quenching qN of fluorescence includes mechanisms such as heat dissipation and calculated as

$$qN = (Fm - Fm')/(Fm - Fo').$$

All the measurements were conducted in six plants grown under varying light intensities and in full sunlight and thus each data point is the mean of six replications.

Protein profiles through SDS-PAGE

Leaf protein profile was studied using SDS-PAGE (Sodium dodecyl sulphate Polyacrylamide gel electrophoresis) following the technique of Laemmli (1970), with the gel that consisted of 12% of polyacrylamide containing urea (6 mM). Sample of leaves were ground in a pre-cooled mortar and pestle with liquid nitrogen and grinding buffer. The extract was centrifuged at 4 °C at 10,000 rpm for 45 min. The supernatant was mixed with sample buffer (0.2 M Tris–HCl (pH 6.8), 10 mM 2-mercaptoethanol, 10% (w/v) SDS, 20% (w/v) glycerol, 0.05% (w/v) bromophenol blue and sucrose) as ratio of 500 μ l 1:1 (v:v). Electrophoresis was carried out at 30 mA in air conditioned laboratory (around 18 °C) for 4 h with the help of running buffer (25 mM Tris buffer, 200 mM glycine and 0.1% (w/v) SDS). Gels were stained in the solution of methanol/acetic acid/water (4:1:5, v/v/v) containing 0.1% (w/v) Coomassie brilliant blue R. The gel was de-stained in the solution of methanol/acetic acid/water (4:1:5, v/v/v).

Statistical analysis

The numeric data obtained from the mean of consecutive 2 years (2007–2008 and 2008–2009) of experiments were analyzed through ANOVA (analysis of variance) followed by calculation of mean and CD (critical difference) at $p = 0.05$ to compare the significance of means of plants grown under all the light environments.

Results

Crop growth and grain yield

Varying light environment had significant impact on biomass index and yield of mustard. Biomass index of crop growth was significantly higher in 67% sun light than the other two light environments (50% sunlight and 75%

sunlight), however, it was less as compared to open grown crops (Fig. 1a). Similarly, in 67% sunlight, reduction of yield was comparatively less than in very low sunlight (50 and 25%) as compared to full sunlight grown crop (Fig. 1b). It was noted that comparative reduction of yield in mustard at 67% sunlight was much less indicating its low light tolerance property (Fig. 1b).

Pigments concentration, wax level and soluble protein in leaf

Chl *a*, Chl *b* and total Chl (Chl *a* + *b*) progressively increased with decreasing light intensity in mustard (Table 2). Total Chl was higher in 25% sunlight in comparison with other light environments. In contrast, anthocyanin, wax level and soluble protein of leaf gradually declined with decreasing light intensity in mustard (Table 2). In 67% sunlight, reduction of anthocyanin, wax level and soluble protein was less than the other light environments (50% sunlight and 75% sunlight) when compared with crops grown under open light.

Simultaneously measured gas exchange and chlorophyll fluorescence parameters

The net rate of CO_2 assimilation (P_N) was significantly higher in full sun light grown crop and gradually decreased under low light conditions (Fig. 2a). Maximum reduction in P_N was recorded at very low light intensity (25% sun light); while a moderate reduction was observed in 67%

Fig. 1 Differential biomass index (a) and grain yield (b) of mustard grown under varying light intensities and in full sunlight. Vertical bars represent $\pm$ standard errors. $n = 30$ [*significant at 5% level]

Table 2 Changes in leaf pigments, wax content and soluble protein of mustard leaves grown under varying light intensities and in full sunlight

Light environments	Chl <i>a</i>	Chl <i>b</i>	Chl (<i>a</i> + <i>b</i>)	Anthocyanin	Wax	Soluble protein
Full sun light	1.71	0.37	2.08	1.06	1.69	110.41
67% sun light	2.07	0.50	2.57	0.97	1.19	94.96
50% sun light	2.31	0.59	2.90	0.81	1.07	82.03
25% sun light	2.51	0.68	3.20	0.70	0.96	73.22
CD at 5%	0.25	0.08	0.29	0.09	0.25	9.30

Chl = chlorophyll (mg/g), anthocyanin (absorbance_(530 nm)/g fresh weight), wax level = (mg/g fresh weight), soluble protein = (mg/g fresh weight), CD = critical difference

Fig. 2 Response of PPFD versus net CO₂ assimilation rate (P_N) (a), thylakoid electron transport rate (ETR) (b), quantum yield (Φ_{PSII}) (c), photochemical quenching (qP) (d) and non-photochemical quenching (qN) (e) of mustard plants grown under varying light intensities and in full sunlight. Vertical bars represent $\pm$ standard errors

sun light grown crops (Fig. 1a). Under open field or full sunlight conditions, the rate of P_N was higher in mustard.

In mustard, the dark adapted values of maximum potential quantum yield of PSII (F_v/F_m) of the leaves were around 0.80 in all the light environments. Thylakoid electron transport rate (ETR) across PSII versus various concentrations of PPFD have shown clear differences among the crops as they were grown at varying intensity of light (Fig. 2b). There was decreasing trend in ETR across PSII with decreasing light intensity in the crop (Fig. 2b). Similar trends were also observed with Φ_{PSII} (PSII quantum yield), and qP (photochemical quenching) (Fig. 2c, d), whereas,

non-photochemical quenching (qN) showed overall increasing trend (Fig. 2e). PPFD required to saturate ETR was much higher in open field as compared with low light grown crop.

Transpiration (E) and stomatal conductance (G_s) gradually decreased with decreasing light intensity (Table 3). A similar trend was also observed with leaf temperature. However, marginal differences were observed in leaf temperature in the crop under varying light environment (Table 3).

Table 3 Modulation in transpiration rate, stomatal conductance and leaf temperature of mustard grown under varying light intensities

Light environments	E	Gs	LT
Full sun light	2.95	357.44	19.0
67% sun light	2.34	313.22	18.0
50% sun light	2.05	237.72	17.1
25% sun light	1.91	201.11	16.1
CD at 5%	0.61	14.94	2.07

E = transpiration rate ($\text{mmol m}^{-2} \text{s}^{-1}$), Gs = stomatal conductance ($\text{mmol m}^{-2} \text{s}^{-1}$), LT = leaf temperature ($^{\circ}\text{C}$), CD = critical difference

SDS-PAGE of leaf proteins

Differential protein bands were noticed in mustard leaf across all the low light intensities and in full sun light. Marginal differences were found in proteins bands around ~ 55 and ~ 15 kDa in all the light intensities (Fig. 3). However, marked differential protein bands were found overexpressed in the molecular weight of ~ 26 kDa in low light intensities (Fig. 3).

Discussion

The results highlighted the ability of mustard to grow under low light as well as in full sunlight through several adaptations at growth, physiological and biochemical levels. With concern to the biomass index, it was lower in 25%

sun light compared with other light intensities (Fig. 1), suggesting that biomass production, under given conditions, is related to the quantity of incident light on the crop. In this context, role of incident light on the crop became more relevant for growth and productivity. As biomass index is the ratio of dry biomass to height of the plant, it indicates the relative strength of the plant. Our results suggested that the low biomass index in very low light environment (below 50% of incident sunlight) is responsible for the weak performance of the plant. However, decline in biomass index and yield can be balanced by other beneficial effects under light limiting conditions like reduction in leaf temperature and increase in humidity. Higher tolerance to low light conditions can help to ameliorate such limitations by the crop by enhanced flexibility of light-harvesting and utilization capacity (Valladares et al. 2002; Li et al. 2010).

The ability to assimilate CO_2 is part of function of the rate of electron transfer occurring in photochemistry in PSII. Light received by the chlorophyll in the leaf is either absorbed, used in photochemistry, lost as heat or as fluorescence. The chlorophyll fluorescence of a leaf can be used as a measure of photosynthetic capability (Schreiber et al. 1998).

In present study, the rate of CO_2 assimilation observed in P_N versus PPFD curve under varying light intensity clearly demonstrated the status of photosynthetic efficiency of mustard crop (Fig. 2a). It has been observed through P_N versus PPFD curve that the reduction in P_N under low light was mainly due to decrease in ETR in low light grown crops. With increasing the supply of light, the plants grown

Fig. 3 Differential protein profiles of mustard leaves grown under varying light intensities and in full sunlight as obtained through SDS-PAGE. Lane 1: molecular weight markers (kDa). Lane 2–4: full sunlight; Lane 5–7: 67% sunlight; Lane 8–10: 50% sunlight, Lane 11, 12: 25% sunlight. (I, II) Black arrow indicate subunits of Rubisco protein around ~ 55 kDa and ~ 15 kDa. (III) Black arrow indicate LHC (Light Harvesting Complex) like protein around ~ 26 kDa

under the low light conditions could not use CO_2 assimilation as efficiently as the plants did in case of full sunlight or moderate sunlight grown crops. This indicated that the low light has conspicuously affected the photosynthetic processes at cellular and functional level and finally affected yield and productivity of crop (Fig. 1b) as it has also been noted in other crops and plants (Hastwell and Facelli 2003; Alam et al. 2011). From our results, it is clear that low light poses a great limitation to ETR. ETR is highly essential for continuing photosynthetic reactions. This ultimately led to reduced photosynthetic process due to lack of sufficient photosynthetic electrons under low light conditions. Photochemical quenching (qP) is related to photosynthetic performance and light use efficiency. Thus, qP holds much importance in light limiting environment. Non photochemical (qN) is highest when light intensities are high, perhaps reflecting a plant protection mechanism to avoid over-energization of the thylakoid membrane. This has been clearly observed in low light grown plants. These facts corroborate with some earlier reports related to low temperature stress also (Alam et al. 2005). At low light intensity of about $200 \mu\text{mol m}^{-2} \text{s}^{-1}$, Φ_{PSII} and qP were similar in low light as well as in full sun light grown plants. Φ_{PSII} and qP decreased with the increase in PPFD as this is inversely related with the potential efficiency of PSII photochemistry (Genty et al. 1989). Reduction in E and Gs with decrease in light intensity in addition to the decrease in PSII activity especially P_N and ETR, evidently affected the entire chloroplast functioning of the plants.

In present study, Chl content progressively increased with decreasing light intensity and was accompanied by relative increase in accessory pigment Chl *b* more than Chl *a* (Table 2). Increase in Chl *b* indicates adaptation of LHCP (Light Harvesting Complex Protein) (Masarovicova and Elias 1981). Relative increase in accessory pigment like Chl *b* is adaptive response of plants to variable PPFD. Chl *b* is associated with distal antennae of LHCP II, the relative changes in this pigment could indicate a change in the distal antenna size (Misra 1995). The increase in the distal antenna size under low light grown leaves probably increases the relative radius of solar energy interception in a chloroplast. Increased chlorophyll *b* content with low chlorophyll *a/b* ratio in plants grown under light limiting conditions suggests adaptation in light-harvesting complexes (Evans and Poorter 2001), thereby increasing the efficiency of light harvesting in low-light environments.

The crop grown in full sun light had higher anthocyanin but it gradually decreased with decreasing light intensity (Table 2). The formation of anthocyanin mainly depends on quantity of light which plays an essential role in light dissipation and as an important antioxidant in plants. The reduction of anthocyanin with decrease in sunlight

indicates its less requirement in low light conditions (Zhou and Singh 2004). Our results indicate that in high light the deposition of wax was higher than in low light (Table 2). As under full sun light, deposition of wax was more, this could be related to thicker leaves in full sun light than low light grown leaves for more reflectance of excess light (Osborn and Taylor 1990). Our findings are consistent with the fact that low light induced reduction in leaf protein (Burkey et al. 1997). The low level of soluble proteins in the plants grown in light limiting conditions could be explained as the possible reduction in Rubisco synthesis which constitutes as a major soluble protein of leaves (Misra 1995).

The crop has adapted its photosynthetic apparatus to maximize light interception through increasing chlorophyll *b* (Chl *b*) contents as it has been clearly reflected in the over-synthesis of leaf proteins bands around ~ 26 kDa corroborating towards enhanced Light Harvesting chlorophyll Complex Proteins (LHCP). This trend was noted in the crop as shown in our results (Fig. 3). This is supported by SDS-PAGE analysis of leaf protein which confirms the reduction of ~ 55 kDa (LSU) and ~ 15 kDa (SSU) in low sunlight grown leaves corresponding to the RUBISCO (Ribulose biphosphate carboxylase-oxygenase) (Bertamini and Nedunchezian 2002; Bertamini et al. 2006).

In the present work, decreasing light intensity markedly affected the net rate of CO_2 assimilation, photochemical efficiency, ETR, E and Gs which has been reflected in reduction of grain yield. Thus, these major physiological traits could be well related to the low light adaptive features of the crops. Reduction of yield in 67% sun light was relatively smaller than very low sun light intensity (50 and 25% sun light) as compared to open or full sun light.

Lack of sufficient ETR across PSII decreased photochemical efficiency of the low light grown crops which ultimately reflected in the loss of crop grain yield under low light condition. Comparatively higher CO_2 assimilation, ETR, photochemical quenching (qP), soluble protein in leaf and grain yield in mustard suggested its low light adaptability with a minimum loss of yield at the moderate sun light (like 67% sun light). This indicates that broadly about 67% of incident sun light could be the critical limit of low light for mustard and below this level, the loss of yield would be highly detrimental. Our findings would augment selection of traits for optimizing growth of mustard and grain yield for low light or light limiting agroecosystem.

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