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MORPHOPHYSIOLOGY AND GROWTH ANALYSIS OF ONION (*ALLIUM CEPA* L.) CROP GROWN IN AGRIPHOTOVOLTAIC SYSTEMS

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ABSTRACT

Agriphotovoltaics combine solar energy generation and agricultural cultivation on same land A field experiment conducted at Agriphotovoltaic Research Project, Manwat, Parbhani. (M.S.) analysed the effect of agriphotovoltaic system environment on onion morphology and analysed plant growth across the vegetative phase. The experiment was conducted in Randomised Block Design with four replications. Plant height, number of leaves, leaf length, leaf width, leaf thickness, pseudostem diameter, and collar diameter were studied at 75 DAT and SCMR Index at 60 DAT using SPAD-502. Plant Growth Analysis parameters such as AGR, CGR, RGR, NAR and LAR were determined in the 20-40 DAT and 40-60 DAT period and LAI, SLW and SLA was determined at 20, 40 and 60 DAT. Onion morphology below 3.75 m bifacial panel height with 5.65 m pitch distance (T_5) showed significantly better performance compared to other treatments in morphophysiological and growth analysis parameters such as plant height (68.62), number of leaves (13.00), leaf length (53.03) collar diameter (20.46) and growth analysis parameters such as AGR (75.2) and CGR (1.18). Onion plants below 1.75 m monofacial panel with 7.5 m pitch distance (T_1) recorded maximum leaf length (53.95), SCMR Index (67.00), LAR and SLA while maximum leaf width (17.33) and pseudostem diameter (11.91) were recorded in between 3.75 m bifacial panel with 5.65 m pitch distance (T_6). Highest RGR (0.115) and NAR (0.79) values were obtained in open field control conditions.

***Keywords* :** Agriphotovoltaics, Onion, Morphophysiology, Plant Growth Analysis

Introduction

Onion (*Allium cepa* L.) belongs to the Amaryllidaceae family, having originated from Central Asia. It is a bulb crop cultivated extensively worldwide for being a major food ingredient, immense profitability and constant demand in the market. India produced 311.29 lakh metric tonnes (Anonymous, 2022) from 19.14 lakh hectare area in 2022. Morphophysiological traits of onion such as plant height and leaf dimensions are significantly influenced by environmental conditions such as shading or low light availability and significantly impact the photosynthetic efficiency, the assimilation of sugars.

Food and energy demands are increasing proportionally to the human population. Climate change is reducing available arable land, marking the importance of meeting SDG2 and SDG7 with haste. Agriphotovoltaics merges electricity generation and crop cultivation on the same piece of land thus increasing land productivity in less land area. (Goetszberger and Zastrow, 1982) Photovoltaic panels are installed at height from ground level and crops are grown below or in between of panel space. Photovoltaic panels raised off ground allows crops to receive sunlight and also generate solar energy. (Dupraz *et al.,* 2011) Panel-induced shading induces morphological changes such as increase in plant height and leaf area and thinner leaves, typical of shade-avoidant species maximising light capture in decreased light availability. (Amaducci *et al*., 2018) Crop morphology deviation from normal in agriphotovoltaics does not necessarily translate to reduction in yield performance, as benefits from a modified growing condition also are reported. Diffusion of light in below panel treatments improved yields in lettuce. (Tani *et al.*, 2014)

Onion is a light sensitive crop requiring moderate light conditions for adequate development to aid bulb growth. Morphological plasticity in leaves and pseudostem under reduced light availability are reported. (Mondal *et al*., 1986) No significant reduction in onion biomass (Kadowaki *et al.*, 2012) or bulb yield (Jo *et al.*, 2022; Kim *et al.*, 2023) have been reported, suggesting feasibility of onion bulb production under agriphotovoltaics. However, it is important to further elucidate the influence agriphotovoltaic microclimates have on onion growth and development, and provide insight of onion plant adaptability to reduced light in tropical conditions. Analysis of growth will identify the panel height and distance between panels that onion plant growth can tolerate. Hence the present investigation is carried out to study the morphology and growth analysis of onion crop grown in various agriphotovoltaic systems.

Material and Methods

The field experiment was conducted in *Kharif* 2024 at Agriphotovoltaics Research Peoject at Manwat, Parbhani District by Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, Maharashtra. The research site is divided into four sections consisting of three photovoltaic (PV) systems and one Non-PV i.e. control conditions. Six experimental plots were located below of and in between of panels in each of the three systems and one experimental plot was located in the open field condition without PV systems. Three types of panels with 20% efficiency and 11° panel tilt were erected to face southward direction and details are detailed in Table-1.

Onion production (var. Bhima Super) under seven photovoltaic systems was tested in a randomised block design with four replications. The treatments have been designed as follows based on location of the plot with respect to panel type, panel height and distance between panel rows: (T_1) below 1.75 m monofacial panel with 7.5 m pitch distance, (T_2) in between 1.75 m monofacial with 7.5 m pitch distance, (T_3) below 1.75 m bifacial panel with 10 m pitch distance, (T_4) in between 1.75 m bifacial panel with 10 m pitch distance, (T_5) below 3.75 m bifacial panel with 5.65 m pitch distance, (T_6) in between 3.75 m bifacial panel with 5.65 m pitch distance and (T_7) is non-PV *i.e.* open field. The location of experimental plots within the photovoltaic systems are schematically represented in Fig-1.

45-day old onion seedlings var. Bhima Super (DOGR, Pune) were transplanted at a spacing 15 cm between rows 10 cm within rows in all treatments. Recommended dose of fertiliser was applied as: 100:50:50 kg NPK per hectare. Half dose of Nitrogen and full dose of Phosphorous and Potassium was added at land preparation and the remaining half dose of nitrogen was applied in split doses at 30 and 45 days after transplanting (DAT). The crop was maintained by recommended plant protection measures and irrigated at regular intervals.

Number of leaves were counted at 75 DAT. Plant height, leaf length and leaf width at 75 DAT were determined with a meter scale, leaf thickness, pseudostem diameter, collar diameter at 75 DAT were determined with vernier callipers while SCMR Index was recorded with Chlorophyll Meter SPAD-502 Plus (Konika Minolta Optics, Japan) at 60 DAT. Absolute Growth Rate (AGR) (Radford 1967), Crop Growth Rate (CGR) (Watson 1952), Relative Growth Rate (RGR) (Blackman 1919), Net Assimilation Rate (NAR) (Radford 1967), Leaf Area Index (LAI) (Watson, 1952), Leaf Area Ratio (LAR) (Whitehead and Mycersough, 1962), Specific Leaf Area (SLA) (Radford 1967) and Specific Leaf Weight (SLW) (Radford 1967) were determined from five whole plant samples per replication per treatment collected at 20, 40, 60 DAT. Leaf area for the above calculation was determined by Leaf Area Meter (Li-3100C, LI-COR Inc. USA N.E.) Plant samples were dried at 65°C till constant weight was obtained and total dry weight of plants for the above calculations were measured with electrical single pan balance.

The data collected was analysed by one-way ANOVA and the mean performance of parameters are represented. The results are considered statistically significant at $P < 0.05$ level.

Results and Discussion

Experimental data related to morpho-physiological parameters *viz.* plant height, number of leaves, leaf length, leaf width, leaf thickness, pseudostem diameter, collar diameter, SCMR Index, and growth analytical parameters such as AGR, CGR, RGR, NAR, LAI, LAR, SLA, SLW were measured at 20 days interval from date of transplanting at 20, 40 and 60 DAT under different photovoltaic systems are critically interpreted and the results are presented below.

Significant variation were noted in morphophysiological parameters as caused by different agriphotovoltaic systems. The mean performance of morphophysiological parameters are presented with appropriate figures.

Morpho-physiology

The maximum plant height (68.62) was observed in T_5 - below 3.75 m bifacial panel with a pitch distance of 5.65 m, statistically in line with T_3 (64.77) as is illustrated in Fig. 1. T_1 (58.59) followed thereafter. Minimum plant height were observed in T_6 (40.56). Photovoltaic panel-induced shading increased the height of onion plants located below the panel as a shade avoidant mechanism. Increase in plant height in crops grown under PV panels conditions has been reported in lettuce (Marrou *et al.*, 2013). The maximum leaf length (53.95) was seen in T_1 - below 1.75 m monofacial panel with pitch distance of 7.5 m which was statistically at par with T_5 (53.03) and followed by T_3 (48.10) The minimum leaf length was attained in T_4 (32.98).

Maximum leaf width (17.33) was attained in T_6 - In between 3.75 m bifacial panel with 5.65 m pitch distance, followed by T_7 (15.23) as is shown in Fig. 3. The minimum width of leaf was observed in T_4 (11.30). Maximum leaf thickness (1.62) was obtained in T_7 - non-PV open field *i.e.* control which was followed by T_5 (1.36). The least thickness of leaf was observed in T_1 (0.81). Mondal *et al.* (1986) in their research reported that longer leaves help onion plants intercept light better. The width of leaf reduced due to reallocation of photosynthates that increased length of leaf over width and thickness. Redistribution of photosynthates to increase length of the leaves over width or thickness, improved light reception in PV-shaded plants (Wu *et al.*, 2017) However, the same was not observed in T_6 where width and leaf thickness did not decrease significantly. Higher panel clearance height disperses light evenly, resulting in foliar growth of plants less impacted by light stress. (Tani *et al.,* 2014; Amaducci *et al.*, 2018) Maximum pseudostem diameter (11.91) was obtained in T_6 - In between 3.75 m bifacial panel with 5.65 m pitch distance. It was statistically at par with T_7 (11.71) and minimum diameter was recorded in T_4 (6.74) The maximum diameter of collar (20.46) was recorded in T_6 - In between 3.75 m bifacial panel with 5.65 m pitch distance. It was followed by T_7 (15.69). The minimum collar diameter was obtained in T_3 (11.77). Increase in pseudostem and collar diameter has not been reported in any literature related to crop cultivation in agriphotovoltaics so far as reduction of stem diameter is the typical behaviour in shade avoidant plants. The transportation of photo-assimilates into the bulbs is believed to have caused the onion pseudostem and collar to thicken (Mettananda and Fordham, 1999) The bifacial panels and height of PV panels in T_6 created a microclimate and light environment favourable for onion foliar growth, thus improving photosynthetic efficiency (Amaducci *et al.*, 2018)

The variation in number of leaves and SCMR Index observed in each photovoltaic system is illustrated in Fig. 4. The maximum number of leaves (13.00) was achieved in T_5 - below 3.75 m panel height with 5.65 m pitch distance, which was found statistically at par with T_4 (12.00), and followed by T_7 - Non-PV open field (11.50). The number of leaves were the least in T_1 (8.25). Reduction in number of leaves under APV conditions were noticed in green bean (Cossu *et al.*, 2021) due to the limited availability of PAR which caused slow accumulation of sugars, reducing leaf initiation, thus, improving the assimilation capacity of existing leaves (Mondal *et al.*, 1986). The maximum SCMR Index (67.00) was observed in T_1 - Below 1.75 m monofacial panel with 7.5 m pitch distance, that was found statistically at par with T_2 (65.03), T_6 (64.73) and T_3 (63.00). The minimum SCMR Index value was recorded in T_7 (47.23) Shading reduced volume and increased the number of chloroplasts, improving photosynthetic efficiency in reduced light. Similar observations were reported for rice (Thum *et al.*, 2025)

Growth Analysis

AGR (Fig-5A) improved over time in agriphotovoltaic conditions. The maximum AGR (71.05) was obtained in T5 which was followed by T6 (48.38). The minimum AGR was obtained in T_1 (13.96) Between 40-60 DAT he maximum AGR (75.21) was obtained in T5 followed by T6 (56.91) The minimum AGR was obtained in T1 (17.95) CGR (Fig-5B) showed an increasing trend over the vegetative period under photovoltaic conditions. The maximum CGR between 20-40 DAT (1.18) was obtained in T5. which was followed by T7 (0.78). The minimum CGR value in the same time period was obtained in T1 (0.21). The maximum CGR in 40-60 DAT (1.14) was recorded in T5 which was followed by T6 (0.86) while the minimum CGR was obtained in T1 (0.27) AGR and CGR performance observed is attributed to better light availability under panels with taller heights. Availability of light influences crop growth significantly. (Marrou *et al.*, 2013) A 13% decrease in light availability was reported between panel at greater panel heights while 4% increase in below panel light availability was reported (Zhang *et al.*, 2025). This is reflected in the better performance of T_5 over T_6 at 3.75 m panel clearance height. The influence of increase in light availability on the photosynthetic assimilation was reflected in the AGR and CGR values obtained in the experiment.

RGR (Fig-5C) values under photovoltaic conditions decreased over time. The maximum RGR (0.12) between 20 to 40 DAT was obtained in T_7 which was followed by T_4 (0.09) The minimum RGR in 20-40 DAT duration was recorded in T1 (0.04). The RGR decreased further in 40-60 DAT time period with maximum RGR (0.04) obtained in T_5 which was at par with T_4 (0.03). Maximum light is available in the open field conditions when compared to below panel or in between panels. Zhang et al. (2025) reported decrease in light availability by 50% in between panels and by 70% at least below panels. This is reflected in the maximal RGR value in T_7 in between 20 and 40 day interval which reduced steeply in 40-60 DAT due to meeting growth requirements prior to bulb development. NAR (Fig-5D) observations revealed a decreasing trend across the crop duration. The maximum NAR between 20-40 DAT (0.79) was obtained in T7 which was at par with T5 (0.75). The minimum NAR in the same period was obtained in T1 (0.19). NAR values recorded a steep decrease between 40-60 DAT when compared to 20-40 DAT period. Maximum NAR (0.48) in this time interval was obtained in T_5 which was at par with T_7 (0.43) and T_4 (0.42). The minimum NAR value was obtained in panel shaded treatments of T_3 (0.17). The greater light availability in open field conditions revealed a non-significant increase in NAR between 20-40 DAT over T_5. The reversal in this trend in 40-60 DAT is attributed to plants in T_7 meeting the growth requirements for bulb production. The decrease in light availability below panels of 3.75 m height did not significantly hinder the NAR in plants. SLW (Fig-6B) decreased over the vegetative phase. Higher values were obtained in between panels as compared to below the panels. The maximum SLW (5.78) at 20 DAT was obtained in T_5, followed by T_6 (4.83). At 40 DAT, T_7 recorded the highest value (7.86) which was at par with T6 (7.52) and T5 (7.37). T_7 recorded the maximum SLW (12.01) at 60 DAT which followed by T6 (10.64). The minimum SLW was obtained in T_1 at 20 DAT (2.42), 40 DAT (2.91) and 60 DAT (3.38). Improved photosynthetic efficiency and photo-assimilation in the 3.75 m panel height photosystem was reflected in the SLW observations recorded. Reduction in SLW under photovoltaic panels was reported in pak choi and rape plant (Hsiao *et al.*, 2023)

LAI (Fig-6A) revealed an increase trend over time in all treatments from 20 to 60 DAT. The maximum LAI at 20 DAT (0.54) was recorded in T_6 and T_3 which was followed by T_5. The maximum LAI at 40 DAT (1.20) was obtained in T_6 which was followed by T_5 (0.90) and T_3 (0.82) At 60 DAT, maximum LAI recorded in T_6 (1.22) and T_2 recorded minimum LAI (0.17) at 20 DAT. At 40 DAT minimum LAI was recorded in T_7 (0.42) at 60 DAT, it was recorded in T_2

(0.71) The LAR (Fig-5E) values increased across the vegetative period with maximum values recorded in T_1 between 20-40 DAT (0.20) and 40-60 DAT (0.19) which was followed by T_3 in 20-40 DAT (0.17) and 40-60 DAT (0.12). The minimum LAR (0.09) was obtained in T5 and T7 at 20-40 DAT and in T5 (0.06) at 40-60 DAT. SLA (Fig-6C) was found to increase across the duration of vegetative growth. The maximum SLA at 20 DAT (0.42) 40 DAT (0.34) and 60 DAT (0.30) was observed in T_1 which was followed by T_3 at 20 DAT (0.30) 40 DAT (0.28) and 60 DAT (0.24). The minimum SLA values were recorded in T_4 at 20 DAT (0.18), 40 DAT (0.14) and 60 DAT (0.10). LAI increased greatly in the juvenile stages in the 3.75 m photosystem due to ample light availability. The leaf growth rate decreased however an increasing trend in leaf area was still observed. Plants under shade tend to alter their morphology to efficiently utilise the low light availability by increasing leaf area (Hsiao *et al.*, 2023). This was reflected in the increased values of leaf area-dependent traits such LAI, LAR and SLA that were obtained in T_1 and T_3. Plants below 1.75 m panel height experienced higher shading than plants in the 3.75 m photosystem as was also reported in Kiwi tree by Zhang *et al.* (2025) Similar effects of solar panel-induced shading were reported in photovoltaic greenhouse-grown rape plant (Hsiao *et al.*, 2023) and french bean (Cossu et al., 2021) where increment in SLA and LAR respectively were reported.

Conclusion

Plants in T_1, T3 and T6 exhibited shade avoidant response to shading by photovoltaic panels Significant variation due to low light availability were reflected as increase in plant height, leaf length, leaf width, SCMR, and decrease in leaf thickness. The significant variation observed in pseudostem diameter and collar diameter are attributed to reduction in photosynthetic assimilation in the below panel treatments. Plant growth analysis conducted echoed the same with photo-assimilation decreasing in the panel-shaded treatments (T_1, T3 and T6) as compared to open field conditions (T_7) or treatments with reduced shade effect (T_2, T_4 and T_5). Of the seven treatments, plants below 3.75 m bifacial panel with 5.65 m pitch distance revealed the most efficient utilisation of resources in photovoltaic conditions, showing significant performance in parameters such as plant height, number of leaves, leaf length, leaf width, leaf thickness, SCMR, pseudostem diameter, collar diameter, AGR, CGR, RGR, NAR, LAI, LAR, SLA and SLW.

Table 1 : Specifications of agriphotovoltaic systems viz. panel type, panel height and pitch distance between panel rows.

Panel Type	Panel Clearance Height (in meters)	Pitch Distance (in meters)
Monofacial	1.75	7.5
Bifacial	1.75	10
Bifacial	3.75	5.65

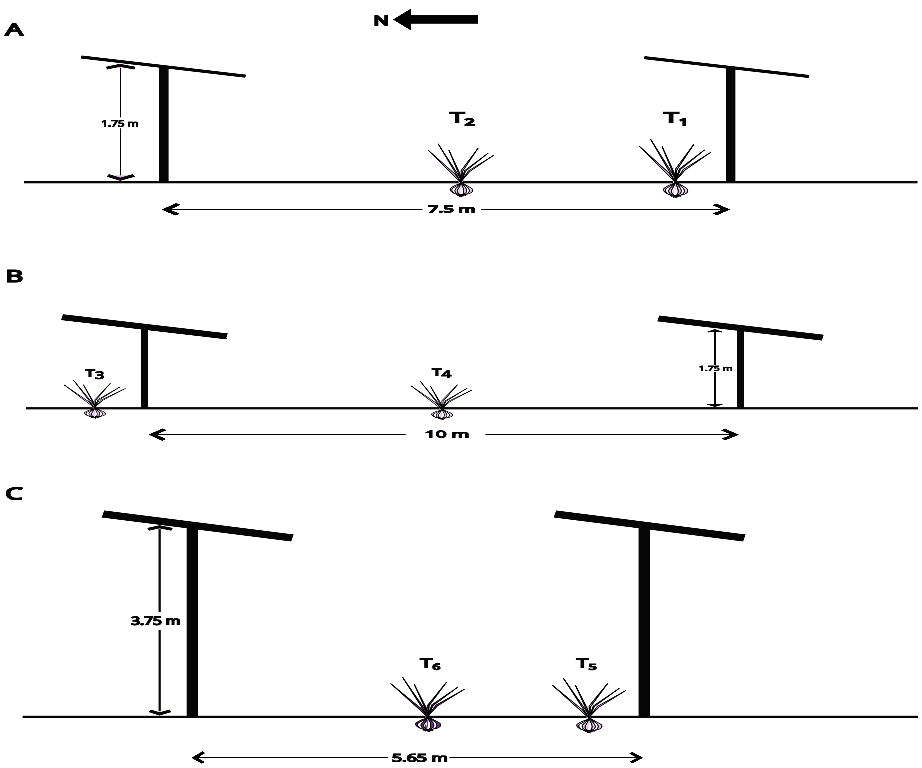

Fig. 1: Schematic representation of the treatments within different photovoltaic systems, (A) monofacial panel of 1.75 m height and 7.5 m pitch distance. (B) bifacial panel of 1.75 m height and 10 m pitch distance. (C) bifacial panel of 3.75 m height and 5.65 m pitch distance. Within each system, plots were positioned either below the photovoltaic panel or in between panel rows (*e.g.*, T_1 located below monofacial panels of 1.75 m height and 7.5 m pitch distance)

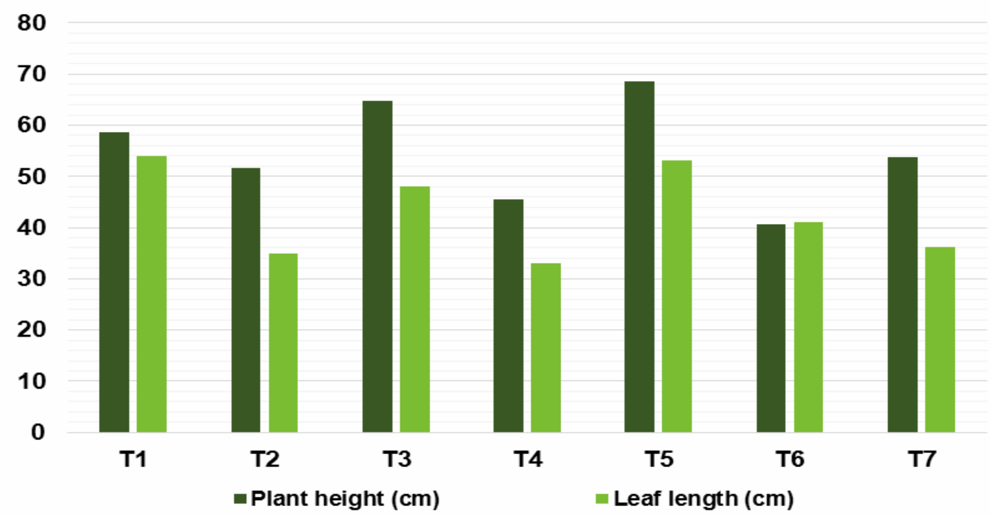

Fig. 2: Plant height and leaf length in centimetres as affected by different agriphotovoltaic systems

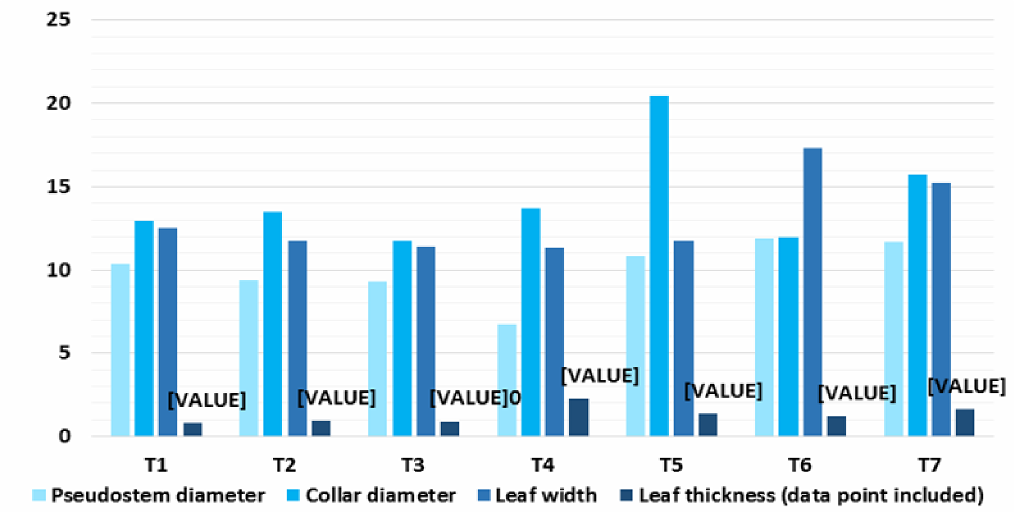

Fig. 3 : Leaf Width, Leaf thickness, Pseudostem diameter and Collar Diameter in millimetres as affected by different agriphotovoltaic systems. The values for leaf thickness are included.

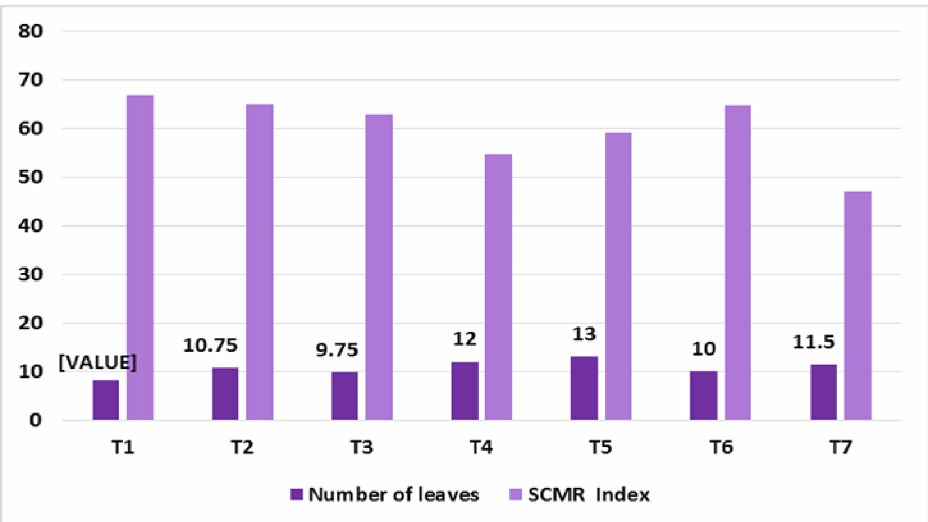

Fig. 4 : Number of leaves and SCMR Index as influenced by different agriphotovoltaic systems. The data points for number of leaves are included.

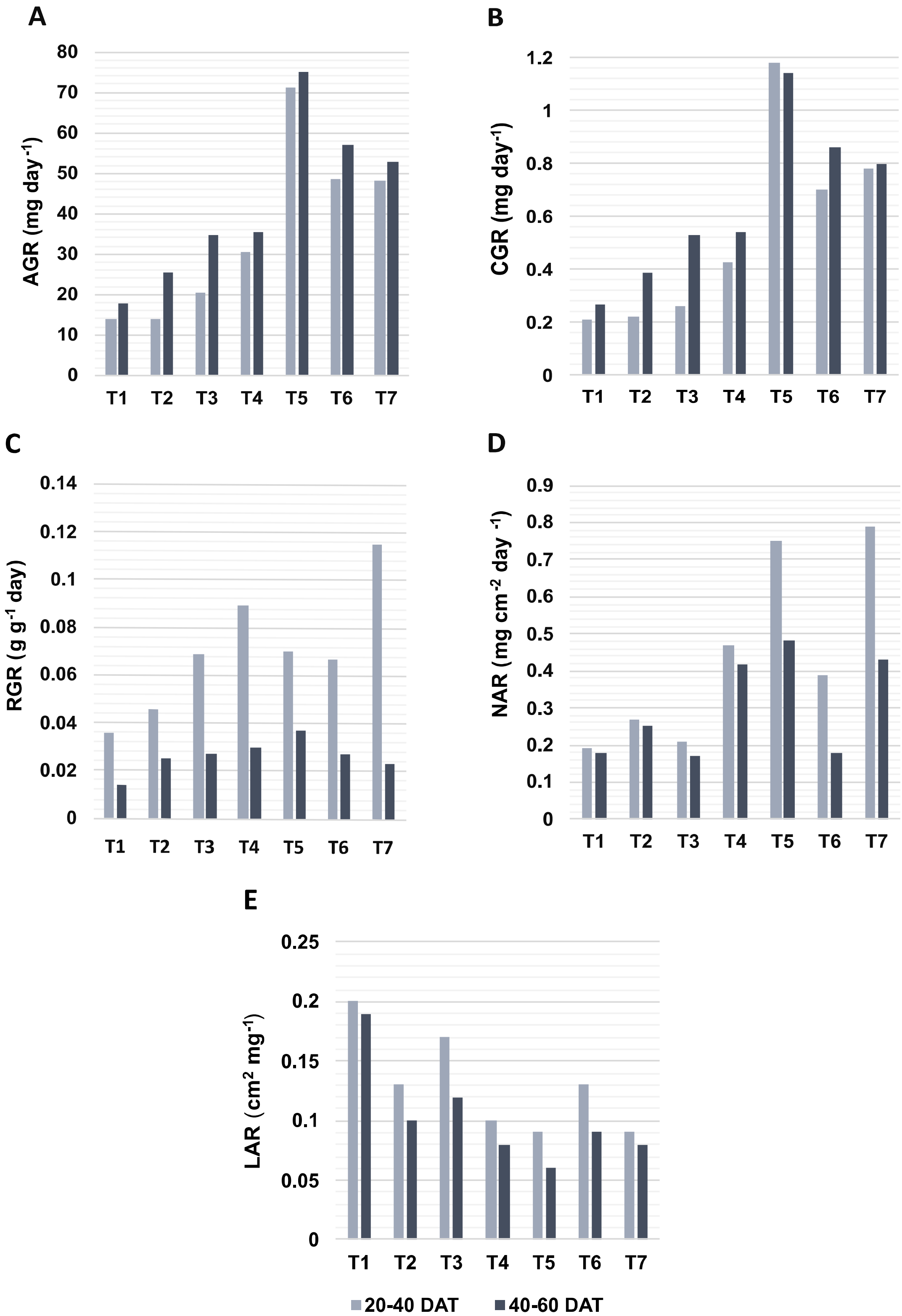

Fig. 5 A : Effect of agrophotovoltaic systems on AGR in 20-40 DAT and 40-60 DAT B. Effect of agrophotovoltaic systems on CGR C. Effect of agrophotovoltaic systems on RGR. D. Effect of agrophotovoltaic systems on NAR. E Effect of agrophotovoltaic systems on LAR. The values were calculated in twenty day intervals from 20-40 DAT and 40-60 DAT. The light coloured columns depict values obtained in 20-40 DAT period while the dark coloured column depict values obtained in 40-60 DAT duration.

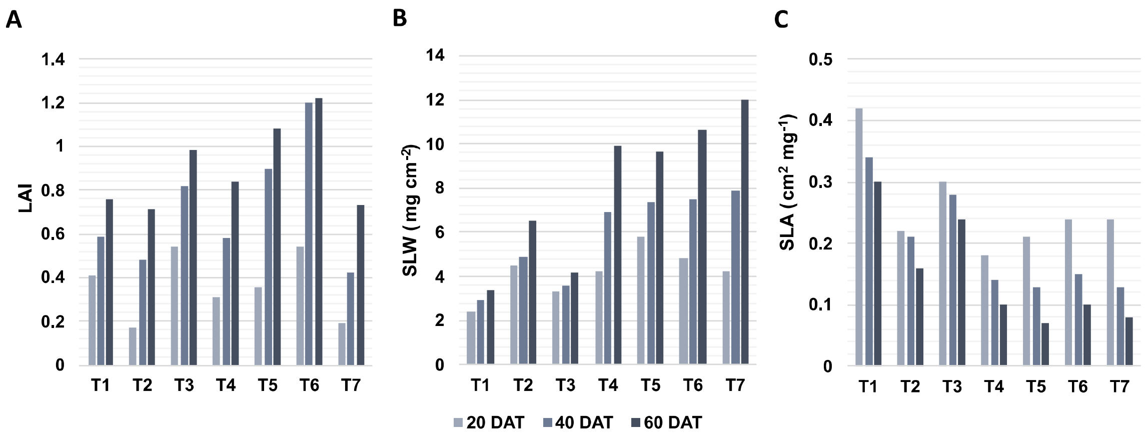

Fig 6 : A. Effect of Agriphotovoltaic Systems on Leaf Area Index ; B. Effect of Agriphotovoltaic Systems on Specific Leaf Weight (mg cm^{-2}). C. Effect of Agriphotovoltaic Systems on Specific Leaf Area (cm^2 mg^{-1}). The observations were taken in 20 day intervals at 20, 40 and 60 DAT. The lightest column depicts observations taken at 20 DAT, the middle column at 40 DAT and followed by the dark coloured column at 60 DAT.

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