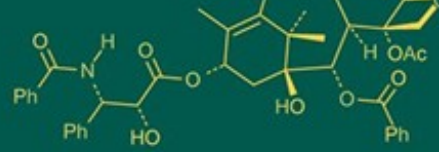
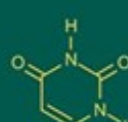


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Morphophysiological changes of rice genotypes in agriphotovoltaic system

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ABSTRACT

Agriphotovoltaic (APV) systems integrate crop production with solar energy generation but modify the radiation and microclimatic environment of crops. The present study evaluated the morphological, phenological, microclimatic and photosynthetic responses. The experiment design was a factorial randomized block design with three rice genotypes, CR Dhan 103, CR Dhan 214 and CR Dhan 415, under different APV conditions during kharif 2025. Leaf thickness, number of leaves per plant, days to 50% flowering, days to maturity, plant height, flag leaf area, canopy temperature, soil temperature, photosynthetically active radiation (PAR) and chlorophyll content were evaluated. APV treatments significantly influenced the studied parameters. Leaf thickness at 90 DAS ranged from 0.213 to 0.317 mm, while the number of leaves per plant varied from 18.56 to 33.33. Days to 50% flowering ranged from 74.33 to 87.11 days and days to maturity from 110.00 to 139.67 days. Plant height ranged from 61.77 to 99.81 cm, while flag leaf area varied from 23.62 to 37.07 cm². Canopy temperature ranged from 22.03 to 26.20 °C and soil temperature from 26.10 to 30.49 °C. PAR declined markedly from 1975.00 to 156.56 $\mu\text{mol m}^{-2} \text{s}^{-1}$, whereas chlorophyll content increased from 1.21 to 3.49 mg g⁻¹ under the open-field and strongly shaded conditions, respectively. The results demonstrate that panel height and crop position substantially modified the growing environment and consequently influenced rice morphology and development under APV conditions.

Keywords: Agriphotovoltaic, Rice, Genotypes, Morphological traits, Temperature, Chlorophyll

1. Introduction

Rice (*Oryza sativa* L.) is a primary cereal crop for nearly half of the global population. Rice is a staple food for a large portion of the global population, particularly in less developed countries. India is the world's second-largest producer of rice and the largest exporter of rice in the world. In India rice is grown on an area of 478.28 lakh hectares with production of 1378.25 lakh tons with productivity of 2882 kg/ha for year 2023-24 (Annual Report, Ministry of Agriculture, Government of India 2024-25) [1]. Agriphotovoltaic (APV) systems integrate agricultural production with photovoltaic electricity generation on the same land area. This approach provides an opportunity to produce renewable energy while continuing crop cultivation.

However, photovoltaic panels modify the quantity and spatial distribution of solar radiation reaching the crop and consequently alter the microclimatic conditions experienced by plants. Yun *et al.* (2025) [2] reported that rice grown under APV conditions showed changes in growth and development associated with the modified radiation environment. Solar radiation is a major factor regulating crop growth because it provides the energy required for photosynthesis and influences leaf development, plant architecture and crop phenology. Under APV systems, radiation received by the crop varies according to panel height, panel arrangement and the distance of plants from the photovoltaic panels. Barron-Gafford *et al.* (2019) [3] reported that photovoltaic panels reduced incoming solar radiation beneath the array and modified the crop microclimate, while Adeh *et al.* (2019) [4] demonstrated that partial shading under agrivoltaic systems altered light availability and crop growing conditions.

Changes in radiation can influence important morphological characteristics of rice, including leaf thickness, number of leaves, plant height and flag leaf area. The response depends on the intensity of shading and the genetic characteristics of the crop. Yun *et al.* (2025) [2] reported changes in rice plant height and leaf morphology under APV conditions and demonstrated that rice plants respond morphologically to the modified light environment. APV systems also modify canopy and soil temperature by reducing the amount of solar radiation reaching the crop and soil surface. These changes in the thermal environment can influence crop development and phenological processes such as flowering and maturity. In addition, altered radiation availability affects photosynthetic pigments. Increased chlorophyll concentration under shaded conditions has been reported in agrivoltaic systems by Gonocruz *et al.* (2021) [5], while Yun *et al.* (2025) [2] reported changes in chlorophyll a and chlorophyll b under reduced radiation.

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Therefore, the present investigation was conducted to evaluate the morph-physiological changes of rice genotypes in agriphotovoltaic system, with particular emphasis on leaf thickness, number of leaves per plant, days to 50% flowering, days to maturity, plant height, flag leaf area, canopy temperature, soil temperature, photosynthetically active radiation and chlorophyll content.

2. Materials and methods

The field experiment was conducted at Agriphotovoltaics Research Project at Manwath, Parbhani under collaborative research project between GIZ, Germany and Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani (MS) during *Kharif* season of 2025. The Research site includes various agrivoltaic setup with different APV design *viz.* Elevated structure 1.75 m and 1.25 m bifacial panels with observation recorded at 0.5 m, 1.5 m and 2 m away from center of panels, with fixed tilt of 11° were erected to face southward direction. Morpho-physiological changes of rice genotypes in agriphotovoltaic system was tested in factorial randomized block design with three replications. The treatment have been designed as follows based on location of the plot with respect to panel types, panel height and distance between panel row: Control (P_0), 0.5 m away from center of 1.75 m panel height (P_1), 1.5 m away from center of 1.75 m panel height (P_2) 2 m away from center of 1.75 m panel height (P_3), 0.5 m away from center of 1.25 m panel height (P_4), 1.5 m away from center of 1.25 m panel height (P_5), 2 m away from center of 1.25 m panel

height (P_6). Rice genotypes, CR Dhan 103 (G_1), CR Dhan 214 (G_2) and CR Dhan 415 (G_3) from CRURRS (ICAR- CRRRI), Hazaribag. The location of experimental plots within the photovoltaic systems are schematically represented in Fig-1.

Leaf thickness was calculated from three tagged plants per replication from each genotype, and from each panel including control condition was determined by using a vernier measurement. leaf was segmented in base, middle and top of leaf mean was calculated in mm, at 30, 60 and 90 DAS. Total numbers of leaves were determined by counting the leaves from the top to bottom of all the tillers on a hill and the mean values of the three hills were taken from each genotype and was expressed per hill basis (at flowering). Count number of days required, from sowing to bear 50% flowering on spike. Number of days required for complete maturity, when percentage of milky grain was less than 1 percent, Moisture content of grain less than 20 percent. Plant height (at flowering) was measured in centimeters from ground level to the tip of flag leaf and average values were used for analysis. Three plant samples were taken from the experimental plot at 50% flowering stage. The maximum length and width of flag leaves were measured, for leaf area, a factor 0.75 (at flowering) was used. Canopy temperature was measured using infrared thermometer 0.5–2 m above the canopy. Soil temperature record using thermometer. Chlorophyll extraction through dimethyl sulfoxide (DMSO) (Kumari *et al.*, 2018) [6]. The statistical analysis of data was carried out by the standard method (Panse *et al.*, 1985) [7].

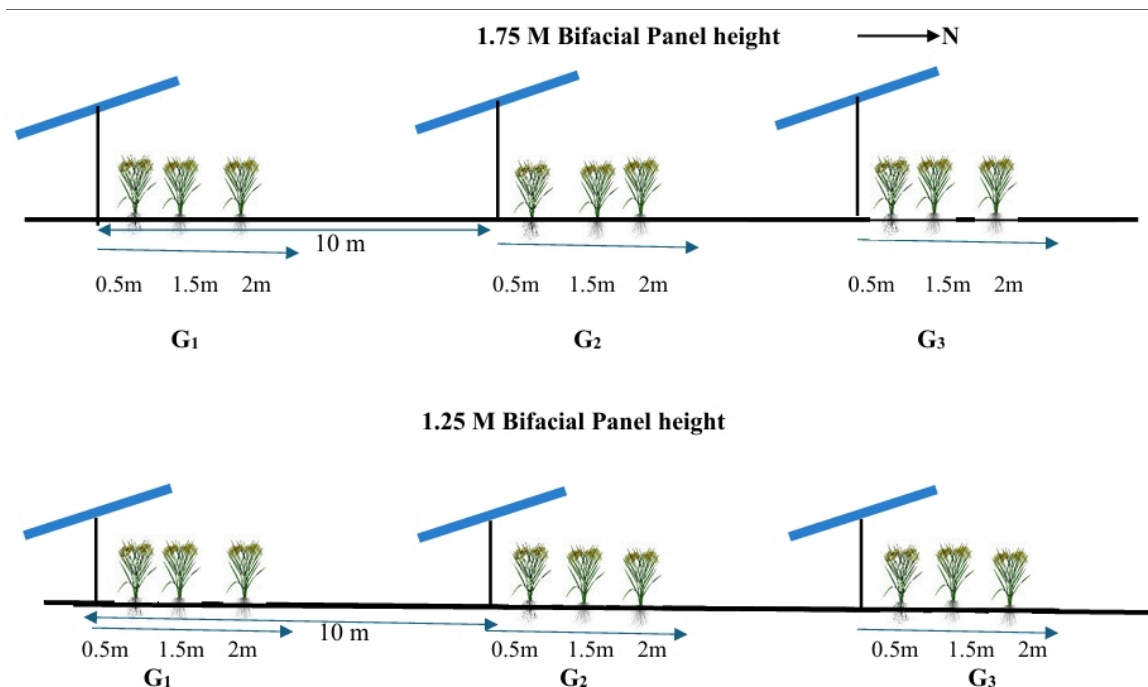


Figure 1. Schematic representation of the treatments within different photovoltaic system

3. Results and discussion

3.1 Morpho-physiological parameter

3.1.1 Leaf thickness (mm)

Leaf thickness was significantly influenced by the agriphotovoltaic (APV) treatments at 30, 60 and 90 DAS, whereas genotype and genotype $\times$ APV interaction effects were non-significant at all three stages. At 30 DAS, the maximum leaf thickness was recorded under P_0 (0.250 mm), followed by P_3 (0.241 mm), while the minimum was recorded under P_4 (0.184 mm). At 60 DAS, P_0 again recorded the maximum value (0.272 mm), followed by P_6 (0.254 mm) and P_3 (0.253 mm), whereas P_4 recorded the minimum (0.201 mm). At 90 DAS, the maximum leaf thickness was recorded under P_0 (0.317 mm) and the minimum under P_4 (0.213 mm). Genotype and genotype $\times$

APV interaction remained non-significant at each stage detailed in table -1.

The consistent reduction in leaf thickness under P_4 was associated with the stronger shading at this position. P_4 received the lowest mean PAR ($156.56 \mu\text{mol m}^{-2} \text{s}^{-1}$), whereas P_0 received $1975.00 \mu\text{mol m}^{-2} \text{s}^{-1}$. Reduced radiation under shaded conditions decreases mesophyll development and produces thinner leaves (Tani *et al.*, 2014; Marrou *et al.*, 2013) [9, 8].

3.1.2 Number of leaves per plant (Nos)

The number of leaves per plant at flowering was significantly influenced by APV treatments, whereas genotype and genotype $\times$ APV interaction effects were non-significant. The maximum number of leaves was recorded under P_0 (33.33), which was statistically at par with P_3 (32.44). The minimum number was recorded under P_1 (15.78 l), which was statistically at par with P_4 (18.56) (Table -1).

Reductions in leaf number under shaded agrivoltaic conditions have also been reported in French bean (Cossu *et al.*, 2021) [10], lettuce (Marrou *et al.*, 2013) [8] and pak choi (Hsiao *et al.*, 2023) [11].

3.1.3 Days to 50% flowering (Nos)

Days to 50% flowering were significantly influenced by genotype and APV treatment, whereas genotype $\times$ APV interaction was non-significant. G₃ recorded the maximum mean duration to 50% flowering (85.24), followed by G₂ (83.95), while G₁ recorded the minimum (70.90). Among APV treatments, flowering occurred earliest under P₀ (74.33), followed by P₃ (76.22) and P₆ (79.11). The maximum duration was recorded under P₄ (87.11 days), followed by P₅ (83.89) and P₁ (81.3) (Table -1). Similar delays in flowering under modified light environments were reported in chilli pepper (Hassanien *et al.*, 2022) [12], tomato (Scarano *et al.*, 2024) [13] and mung bean (Ukwu *et al.*, 2025) [14].

3.1.4 Days to maturity (Nos)

Days to maturity were significantly influenced by genotype and APV treatment, while genotype $\times$ APV interaction was non-significant. G₃ recorded the maximum mean duration to maturity (134.05), followed by G₂ (123.5) and G₁ (115.48). Among the APV treatments, the earliest maturity was recorded under P₀ (110.00), followed by P₃ (112.22) and P₆ (115.56). The maximum duration was recorded under P₄ (139.67), followed by P₁ (136.44) and P₅ (130.89) (Table -1). Delayed maturity under shaded conditions has also been reported in lettuce (Elamri *et al.*, 2018) [15] and wheat (Marrou *et al.*, 2013b) [16], while Thum *et al.* (2025) [17] reported a 10–11 day delay in rice maturity under APV conditions.

3.1.5 Plant height (cm)

Plant height was significantly influenced by genotype, APV treatment and genotype $\times$ APV interaction. Among the genotypes, G₁ recorded the maximum overall mean plant height (93.74), followed by G₃ (86.84) and G₂ (75.50). Among APV treatments, P₀ recorded the maximum mean plant height (99.81), followed by P₃ (95.24) and P₆ (94.74), whereas P₄ recorded the minimum (61.77) (Table -1). The significant genotype $\times$ APV interaction demonstrated that plant height responded differently according to the combination of genotype and panel position. The tallest plants were recorded in G₁P₀ (115.57), followed by G₁P₆ (108.40) and G₁P₃ (106.73). The shortest plants were recorded in G₃P₄ (59.00), followed by G₂P₄ (61.40) and G₁P₄ (64.90). The reduction in plant height under the strongly shaded treatments was related to the lower availability of PAR. Reduced light interception restricts photosynthesis and carbohydrate production, limiting the assimilates available for cell division and internode elongation. Reduced light availability also alters gibberellin metabolism and decreases the accumulation of bioactive gibberellins involved in internode elongation, resulting in reduced stem elongation (Lestari *et al.*, 2020) [18].

Nos- Numbers, PH- Plant Height, LA- Leaf area, CT- Canopy Temperature, ST- Soil Temperature, PAR- Photosynthetically Active Radiation, NS- Non Significant

3.1.6 Flag leaf area (cm²)

Flag leaf area at flowering was significantly influenced by APV treatment, whereas genotype and genotype $\times$ APV interaction effects were non-significant. P₀ recorded the maximum mean flag leaf area (37.07), followed by P₃ (36.57) and P₆ (34.97). P₄ recorded the minimum value (23.62), followed by P₅ (26.23) and P₁ (26.35). The maximum flag leaf area under P₀ corresponded with the maximum radiation availability, while the minimum under P₄ corresponded with the lowest PAR. P₀ received 1975.00 $\mu\text{mol m}^{-2} \text{s}^{-1}$ PAR, whereas P₄ received 156.56 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Reduced radiation restricted leaf expansion and resulted in a smaller flag leaf area at the strongly shaded position. The reduction was particularly pronounced between P₀ (37.07) and P₄ (23.62) (Table -1).

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3.2 Microclimatic and radiation parameters

3.2.1 Canopy temperature (°C)

Canopy temperature was significantly influenced by the agrivoltaic (APV) treatments, whereas genotype and genotype $\times$ APV interaction effects were non-significant. The maximum mean canopy temperature was recorded under the open-field treatment P₀ (26.20), followed by P₆ (24.5) and P₃ (23.9). The lowest canopy temperature was recorded under P₄ (22.03°), followed by P₁ (22.47) and P₅ (22.81) (Table -1). Similar reductions in rice canopy temperature under shaded conditions have been reported where reduced radiation lowered daytime canopy temperature relative to the control (Wang *et al.*, 2015) [19].

3.2.2 Soil temperature (°C)

Soil temperature was significantly influenced by the APV treatments, whereas genotype and genotype $\times$ APV interaction effects were non-significant. The maximum mean soil temperature was recorded under P₀ (30.4), followed by P₃ and P₆ (29.37 °C each). The lowest soil temperature was recorded under P₄ (26.10), followed by P₁ (26.56) and P₅ (27.08) (Table -1). The reduction in soil temperature under the APV treatments resulted from the lower amount of direct solar radiation reaching the soil surface. P₄, which recorded the lowest soil temperature, also received the lowest PAR.

3.2.3 Photosynthetically active radiation ($\mu\text{mol m}^{-2} \text{s}^{-1}$)

Photosynthetically active radiation (PAR) was significantly influenced by genotype, APV treatment and genotype $\times$ APV interaction. Among the APV treatments, P₀ recorded the maximum mean PAR (1975.00), followed by P₃ (1333.67) and P₆ (1105.11) (Table -1). The lowest PAR was recorded under P₄ (156.56), followed by P₁ (189.00) and P₅ (268.56). Among the genotypes, G₂ recorded the maximum mean PAR (837.43), followed by G₁ (772.48) and G₃ (663.6).

The significant genotype $\times$ APV interaction demonstrated variation in the radiation environment among genotype $\times$ panel-position combinations. The maximum PAR was recorded in G₂P₀ (2081.00), whereas the lowest was recorded in G₃P₄ (151.67). The pronounced reduction in PAR at positions close to the panels resulted from interception of incoming solar radiation by the photovoltaic modules. Agrivoltaic systems create spatially variable light environments because the crop receives alternating periods and locations of direct and shaded radiation.

3.3 Photosynthetic parameter

3.3.1 Chlorophyll content

Chlorophyll content at flowering was significantly influenced by the APV treatments, whereas genotype and genotype $\times$ APV interaction effects were non-significant. Among the APV treatments, P₄ recorded the maximum mean chlorophyll content (3.49), which was statistically at par with P₁ (3.42) (Table -1). The minimum value was recorded under P₀ (1.21), followed by P₆ (1.22). Maximum leaf chlorophyll under agrivoltaic conditions compared with open-field conditions was also reported by Gonocruz *et al.* (2021) [5].

Table 1. Morpho-Physiological Responses and Temperature Variation in rice Genotypes under Agri-photovoltaic System

Genotypes	Leaf Thickness (mm)			No. of leaves (Nos)	Day to 50% flowering	Day to Maturity	PH (cm)	LA (cm ²)	CT (°C)	ST (°C)	PAR (umolm ⁻² s ⁻¹)	Chlorophyll content (mg/g)
	30 DAS	60 DAS	90 DAS									
G ₁ (CR Dhan 103)	0.223	0.236	0.272	25.14	70.90	115.48	93.74	32.40	23.77	28.20	772.48	1.74
G ₂ (CR Dhan 214)	0.211	0.230	0.272	25.33	83.95	123.52	75.50	30.17	23.14	28.39	837.43	1.95
G ₃ (CR Dhan 415)	0.221	0.236	0.272	24.86	85.24	134.05	86.84	30.21	24.02	28.33	663.67	2.13
SE (±)	0.005	0.005	0.006	1.147	1.679	2.665	1.803	0.850	0.509	0.613	21.011	0.146
CD@5 %	NS	NS	NS	NS	4.800	7.616	5.153	NS	NS	NS	60.053	NS
Agriphotovoltaic system												
P ₀ (Control)	0.250	0.272	0.313	33.33	74.33	110	99.81	37.07	26.20	30.49	1975.00	1.21
P ₁ (0.5 m +1.75 m)	0.194	0.206	0.228	15.78	81.33	136.44	74.38	26.35	22.11	27.13	225.56	3.42
P ₂ (1.5 m +1.75 m)	0.212	0.230	0.242	27.89	78.22	125.67	87.48	31.69	22.99	28.13	579.89	1.69
P ₃ (2 m +1.75 m)	0.241	0.253	0.311	32.44	76.22	112.22	95.24	36.57	23.96	29.37	1333.67	1.28
P ₄ (0.5 m +1.25 m)	0.184	0.201	0.213	18.56	87.11	139.67	61.77	23.62	22.03	26.10	156.56	3.49
P ₅ (1.5 m +1.25 m)	0.210	0.222	0.294	21.67	83.89	130.89	84.10	26.23	23.71	27.56	355.22	1.26
P ₆ (2 m +1.25 m)	0.237	0.254	0.299	26.11	79.11	115.56	94.74	34.97	24.50	29.37	679.11	1.22
SE (±)	0.008	0.008	0.009	1.752	2.565	4.070	2.754	1.299	0.778	0.937	32.094	0.223
CD@5 %	0.022	0.024	0.027	NS	7.545	11.971	8.099	3.819	2.289	2.755	94.390	0.655
Interaction	0.013	0.014	0.016	3.034	4.443	7.050	4.770	2.249	1.348	1.623	55.589	0.386
SE (±)	NS	NS	NS	NS	NS	NS	13.484	NS	NS	NS	157.148	NS
CD@5 %												

4. Conclusion

Based on the findings of the present investigation, agriphotovoltaic (APV) systems substantially modified the radiation and microclimatic environment and consequently influenced the morpho-physiological and phenological responses of rice genotypes. The magnitude of these responses varied primarily with panel height and the position of the crop relative to the photovoltaic panels. The open-field condition (P_0) generally recorded higher leaf thickness, number of leaves, plant height, flag leaf area, Canopy Temperature, Soil Temperature and PAR, whereas conditions subjected to greater shading, particularly P_4 (0.5 m from the centre of the 1.25 m panel), exhibited pronounced reductions in these parameters. The lowest PAR under P_4 ($156.56 \mu\text{mol m}^{-2} \text{s}^{-1}$) was associated with reduced leaf thickness, leaf number, plant height and flag leaf area, indicating a strong morphological response to restricted radiation availability. APV conditions also altered crop phenology, with delayed 50% flowering and maturity under the more shaded treatments. Among the genotypes, CR Dhan 103 (G_1) exhibited comparatively greater plant height, whereas CR Dhan 415 (G_3) required a longer duration to flowering and maturity. The significant genotype $\times$ APV interaction for plant height and PAR further indicates that rice genotypes differed in their responses to the spatially variable radiation environment created by the photovoltaic panels. APV was characterized by lower canopy and soil temperatures relative to the open-field condition, particularly at positions receiving greater shading. In contrast, chlorophyll content increased markedly under the shaded APV conditions, with the highest value recorded under P_4 (3.49 mg g^{-1}).

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