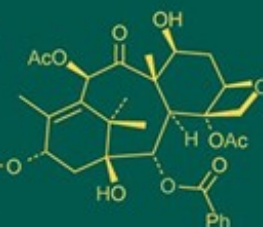
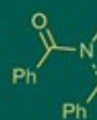


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Effect of different Agriphotovoltaics system on yield and yield attributes of soybean

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ABSTRACT

Background- Agriphotovoltaic, the co-existence of land for farming and photovoltaic (PV), is a creative and progressively emerging way to deal with solar development. Within the framework of agriphotovoltaic systems, a clear understanding of the functional differences among monofacial and bifacial solar cells, panel height, tilt angle and crop spacing strongly influence yield and yield attributes. This experimental study aimed to examine yield responses of soybean crop under varying photovoltaic architectures.

Methods- The field experiment was carried out at Agriphotovoltaics research field, Manwat (Parbhani, Maharashtra) under collaborative research project between GIZ, Germany and Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani during kharif season of 2025. The experimental field has different APV setup having distinct panel height (1.75 m monofacial, 1.75 m bifacial, 3.75 m bifacial and 1.25 m bifacial) with tilt angle. of 110 with below, partially below and in between space for crop cultivation (0.5 m, 1.5 m, 3 m, 4.5 m sowing distance away from centre of panel is used) for study effect of different panel height. Statistical design for experiment was Randomized block design (RBD) having seventeen treatments with three replication.

Result- The result concluded that soybean grown at 3 m distance away from 3.75 m panel height having 5.65 m pitch distance shows significantly higher Higher index. This treatment showed superiority in yield parameters like two seeded and three seeded pods per plant, total pods per plant, number of clusters per plant, seed yield per plant, test weight and seed germination percentage.

Keywords: Agriphotovoltaics, Monofacial, Bifacial, Harvest Index, Soybean

Introduction

Soybean [*Glycine max* (L.) Merrill] is the most important seed legume of family Leguminosae and subfamily Papilionoidea and it contributes nearly 25% of the world's edible oil production. Soybean was introduced into India from China. In several countries, soybean is popularly referred to as the "cow of the field" or "gold from the soil" due to its high economic and nutritional value. Soybean contributes to soil fertility and agricultural productivity by fixing atmospheric nitrogen through symbiotic association with *Rhizobium* bacteria present in root nodules (Mahbub *et al.*, 2016).

The rapid growth of the population coupled with a continuous decline in cultivable land poses a significant challenge to the sustainable cultivation of soybean in the region. According to the Third Advance Estimates for the year 2025-26 released by the Government of India, soybean production is estimated at 125.96 lakh tonnes, reflecting a decline compared to 152.68 lakh tonnes recorded during year 2024-25. Area declined from 129.52 lakh ha. in year 2024-25 to 123.86 lakh ha. in year 2025-26. The growing global demand for both food and energy poses significant challenges to agricultural productivity and energy sustainability, specially in regions constrained by limited arable land. In this context, agriphotovoltaic systems have emerged as a viable and innovative approach, enabling the concurrent production of agricultural crops and renewable energy on the same land area. Goetzberger and Zastrow (1982) introduced the concept of APV but recently the increased environmental concerns and the economic frameworks have stimulated a growing interest in this technology.

Agriphotovoltaic (APV) systems, integrate crop cultivation with solar photovoltaic installations on the same land area. APV systems can modify the crop microclimate through partial shading, resulting in reduced evapotranspiration, improved soil moisture conservation and moderated temperature fluctuations. Such effects may help crops better withstand climate related stresses while contributing to renewable energy production. The success of APV systems depends largely on identifying crops that can adapt to the altered environmental conditions created beneath solar panels. This investigation carried out with objective: To measure and evaluate soybean for yield analysis under Photovoltaic system.

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Materials and Methods

The present study carried out at “Agriphotovoltaic Research Project, Manwat, District, Parbhani.” (Maharashtra, India). The agriphotovoltaic system comprises area below solar panels, partially below solar panel, in between solar panels and a control non-photovoltaic field (open plot) outside of the agriphotovoltaic system. The ground mounted photovoltaic panels (PVPs) are installed in south-facing direction. The field is divided into four sections: Three agriphotovoltaic sections and one Non-PV section (control section). The panel specification includes four types of panels, all with 20% efficiency and 11° tilt. The ground clearance of panels varies as 1.75 m (Monofacial panel), 1.75 m (Bifacial panel), 1.25 m (Bifacial panel) and 3.75 m (Bifacial panel) with pitch distance of 7.5 m, 10 m, 10 m and 5.65 m respectively. These elevated panels allow crops to be grown partially under the panels and in the space between panels. To optimize water usage, the project has implemented an advanced water management system by spreading drip irrigation network.

The field experiment was conducted during the *Kharif* season of 2025. The experiment was laid out in a Randomized Block Design (RBD) comprising seventeen treatments viz. 0.5 m sowing distance away from center of 1.75 m monofacial panel height (T₁), 1.5 m sowing distance away from center of 1.75 m monofacial panel height (T₂), 3 m sowing distance away from center of 1.75 m monofacial panel height (T₃), 4.5 m sowing distance away from center of 1.75 m monofacial panel height (T₄), 0.5 m sowing distance away from center of 3.75 m bifacial panel height (T₅), 1.5 m sowing distance away from center of 3.75 m bifacial panel height (T₆), 3 m sowing distance away from center of 3.75 m bifacial panel height (T₇), 4.5 m sowing distance away from center of 3.75 m bifacial panel height (T₈), 0.5 m sowing distance away from center of 1.75 m bifacial panel height (T₉), 1.5 m sowing distance away from center of 1.75 m bifacial panel height (T₁₀), 3 m sowing distance away from center of 1.75 m bifacial panel height (T₁₁), 4.5 m sowing distance away from center of 1.75 m bifacial panel height (T₁₂), 0.5 m sowing distance away from center of 1.25 m bifacial panel height (T₁₃), 1.5 m sowing distance away from center of 1.25 m bifacial panel height (T₁₄), 3 m sowing distance away from center of 1.25 m bifacial panel height (T₁₅), 4.5 m sowing distance away from center of 1.25 m bifacial panel height (T₁₆), Non-PV system (T₁₇) with three replications to ensure the reliability and precision of statistical analysis. The soybean variety MAUS-162, developed by Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani was used for the study. Each experimental plot consisted of rows of 7 m length and the crop was sown at a plant to plant spacing of 5 cm. The experimental setup was designed to evaluate the performance of different treatments under agriphotovoltaic conditions during the period from June 2025 to October 2025.

The performance of yield parameters like number of pods per cluster, number of clusters per plant, two and three seeded pods per plant, total number of pods per plant, seed yield per plant, test weight, seed germination percentage and harvest index, were calculated after harvesting. The collected data was statistically analysed using Analysis of Variance (ANOVA) method.

Result and Discussion

Experimental data of yield parameters like number of pods per cluster, number of clusters per plant, two seeded and three seeded pods per plant, total pods per plant, seed yield per plant, test weight, seed germination percentage and harvest index were calculated.

The result from table 1 showed that maximum number of pods per cluster (3.33) observed in treatments 3 m and 4.5 m sowing distance from center of solar panel. In contrast, minimum number of pods per cluster (range from 1.33 to 2.33) observed in treatment 0.5 m sowing distance from center of solar panel. As shown in fig. 3, maximum number of clusters per plant (11.33) observed in treatment T₇ i.e. 3 m sowing distance from center of 3.75 m bifacial panel height with 5.65 m pitch distance as there is maximum number of branches and nodes on branch which gives maximum number of clusters. Minimum num-

ber of clusters per plant (6.67) observed in treatment T₁ i.e. 0.5 m sowing distance from center of 1.75 m monofacial panel height with 7.5 m pitch distance where there is only main stem growing and plant try to develop existing pods without forming more clusters.

The result showed in fig. 6, that maximum number of pods per plant (32.44) observed in treatment T₇ i.e. 3 m sowing distance away from center of 3.75 m bifacial panel height with 5.65 m pitch distance and minimum number of pods per plant (12.52) observed in treatment T₁ i.e. 0.5 m sowing distance away from center of 1.75 m monofacial panel height with 7.5 m pitch distance. Continuous shade affects the soybean pod number by increasing the pod abortion. Under PV panel there was low PAR causing decline in sucrose production which trigger rapid increase in ABA level in young pods. ABA suppresses sugar transport into pod which starves embryo and aborts. Later, ABA and low auxin trigger increase in ethylene, so aborted pod drop off. Potenza *et al.* (2022) [1] studied that under an APV system the number of pods per plant were reduced. Shade reduces number of flower per plant, stimulate flower and pod abscission which negatively affect number of pod per plant. Pods on branches made a much larger contribution to total pod load (Egli *et al.*, 2005) [2].

In case of three seeded pod, maximum number of three seeded pod (9.33) observed in treatment T₇ i.e. 3 m sowing distance away from center of 3.75 m bifacial panel height with 5.65 m pitch distance and T₁₂ i.e. 4.5 m sowing distance away from center of 1.75 m bifacial panel height with 10 m pitch distance. Minimum number of three seeded pod (6.00) observed in treatment T₁ i.e. 0.5 m sowing distance away from center of 1.75 m monofacial panel height with 7.5 m pitch distance (11.33). In case of two seeded pod, maximum number of 2 seeded pod (23.33) observed in treatment T₇ i.e. 3 m sowing distance away from center of 3.75 m bifacial panel height with 5.65 m pitch distance (79.00). Minimum number of two seeded pod (5.67) observed in treatment T₉ i.e. 0.5 m sowing distance away from center of 1.75 m bifacial panel height with 10 m pitch distance and T₁ (6.00) i.e. 0.5 m sowing distance away from 1.75 m monofacial panel height with 7.5 m pitch distance. The results corroborate with finding of Nagasuga *et al.* (2019) [3] in soybean, shading decreased seed weight and the numbers of pod. Also seed number per plant in soybean and seed number per capsule in sesame between photovoltaic conditions and open field conditions were recorded by Lee *et al.* (2022) [4].

The result showed that different agriphotovoltaics system severely affected seed yield per plant. The maximum seed yield per plant (9.08 gm) obtained in treatment T₇ i.e. 3 m sowing distance away from center of 3.75 m bifacial panel height with 5.65 m pitch distance and minimum seed yield per plant (3.97 gm) obtained in treatment T₁ i.e. 0.5 m sowing distance away from center of 1.75 m monofacial panel height with 7.5 m pitch distance. Soybean yield ha⁻¹ on open condition is 27-30 qtha⁻¹. Below panel there is 38.13 % to 53.83 % decrease in yield per plant as compared to in between or Non-PV system but simultaneously, there was also electricity generation on same field. There was 5.58 % increase in yield in treatment T₇ i.e. 3 m sowing distance away from center of 3.75 m bifacial panel height with 5.65 m pitch distance. The huge difference between below panel and in between panel is due to intense shading, which limits photosynthetically active radiation, reduces photosynthetic rate and decrease availability of photosynthates for seed development. Similar findings observed by Potenza *et al.*, (2022) [1] in soybean the yield reduction experienced under the shade of the APV system is associated with a negative impact of shade during the pod set stage. Soybean grain yield in the open fields was significantly higher than that under the APV system (Jo *et al.*, 2022) [5].

The result showed that different test weight of soybean is influenced by different agriphotovoltaics system. Maximum test weight (13.50) was recorded in treatment T₁₃ i.e. 0.5 m sowing distance away from center of 1.25 m bifacial panel height with 10 m pitch distance. The increase in seed weight below panel formed fewer total seeds due to shaded conditions. There was limited number of developing seeds which act as stronger individual assimilate sink, accumulating more mass and giving higher test weight. While, minimum test weight

(12.47) were recorded in treatments T_4 i.e. 4.5 m sowing distance away from center of 1.75 m monofacial panel height with 7 m pitch distance and T_{16} i.e. 4.5 m sowing distance away from center of 1.25 m bifacial panel height with 10 m pitch distance which was below panel treatments.

The data from table 2 showed that maximum harvest index (49.75) obtained in treatment T_7 i.e. 3 m sowing distance away from center of 3.75 m bifacial panel height with 5.65 m pitch distance and minimum harvest index (28.36) obtained in treatment T_1 i.e. 0.5 m sowing distance away from center of 1.75 m monofacial panel height with 7.5 m pitch distance. There was increased in harvest index in between panel and Non-PV system as compared to below panel due to adequate availability of PAR which allocate photoassimilates for development of reproductive sink (pod and seed development) and below panel shading plant trigger shade avoiding response expanding maximum energy on petiole and hypocotyls elongation. Similar findings were obtained in soybean, below panel decreasing the photosynthetic rate decreases harvest index (Shan *et al.*, 2022) [6]. Mani *et al.* (2025b) [7]

studied that in between interspaces which gave comparable yield with open space cultivation can be successfully used for soybean cultivation.

Seed germination percentage was taken within one month after harvesting by drying seed upto optimum moisture. This test was performed to know the seed qualities for seed production under agriphotovoltaics. The findings showed that maximum germination percentage (98.67 %) obtained in treatment T_4 i.e. 4.5 m sowing distance away from center of 1.75 m monofacial panel height with 7.5 m pitch distance and T_{12} i.e. 4.5 m sowing distance away from center of 1.75 m bifacial panel height with 10 m pitch distance. Minimum germination percentage (61.33 %) obtained in treatment T_{13} i.e. 0.5 m sowing distance away from center of 1.25 m bifacial panel height with 10 m pitch distance. Shading from solar panel during grain filling stage limits photosynthate supply from plant to developing seeds. This leads to poor nutrient reserve accumulation within seed cotyledon, resulting lower physiological maturity, reduced seed vigour and poor germination rate.

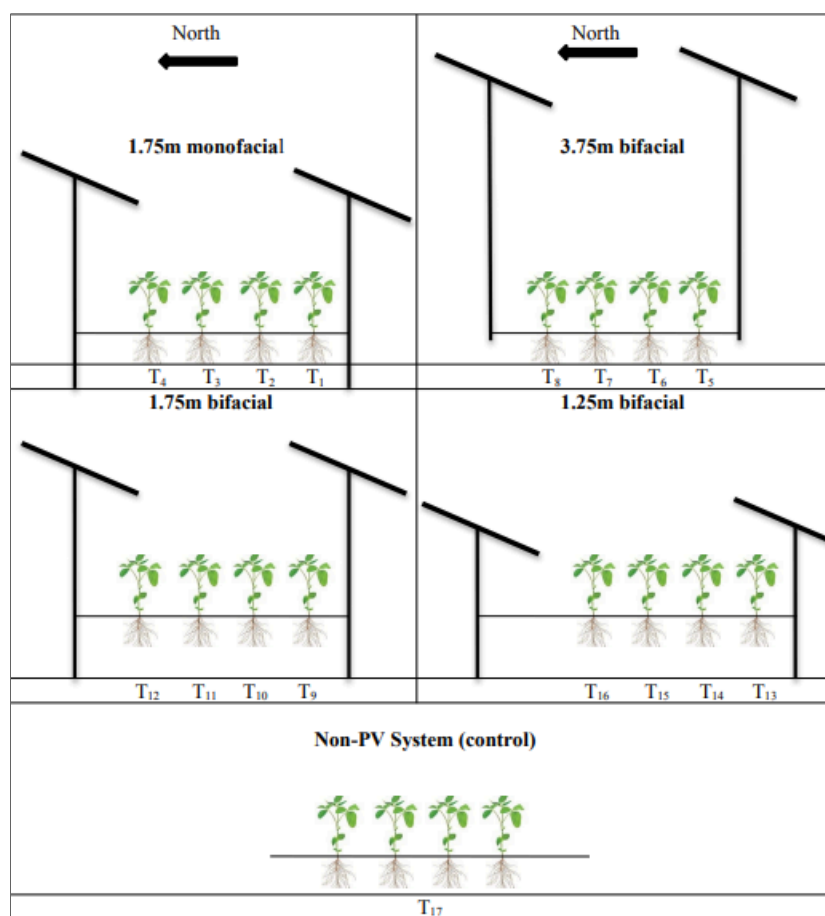


Figure 1. Placement of treatments below (0.5 m), partially below (1.5 m) and in between (3 m and 4.5 m) of solar panels.

Table 1. Number of pods per cluster, number of clusters per plant, three seeded pod per plant, two seeded pod per plant, number of pods per plant, seed yield per plant of soybean under different agriphotovoltaics system.

Sr. No.	Treatments	No. of pods cluster ⁻¹	No. of clusters plant ⁻¹	Three seeded pod plant ⁻¹	Two seeded pod plant ⁻¹	No. of pods plant ⁻¹	Seed yield plant ⁻¹
T ₁	0.5 m sowing distance away from 1.75 m monofacial panel height with 7.5 m pitch distance	2.00	6.67	6.00	6.00	12.68	3.97
T ₂	1.5 m sowing distance away from 1.75 m monofacial panel height with 7.5 m pitch distance	2.33	9.00	7.67	11.00	20.08	6.48
T ₃	3 m sowing distance away from 1.75 m monofacial panel height with 7.5 m pitch distance	3.00	10.00	8.00	18.33	26.22	7.47

(continued on next page)

Sr. No.	Treatments	No. of pods cluster ⁻¹	No. of clusters plant ⁻¹	Three seeded pod plant ⁻¹	Two seeded pod plant ⁻¹	No. of pods plant ⁻¹	Seed yield plant ⁻¹
T ₄	4.5 m sowing distance away from 1.75 m monofacial panel height with 7.5 m pitch distance	3.33	10.33	8.00	22.33	30.14	8.23
T ₅	0.5 m sowing distance away from 3.75 m bifacial panel height with 5.65 m pitch distance	2.33	8.33	8.67	8.00	16.57	5.32
T ₆	1.5 m sowing distance away from 3.75 m bifacial panel height with 5.65 m pitch distance	2.67	10.00	9.00	12.50	22.67	7.15
T ₇	3 m sowing distance away from 3.75 m bifacial panel height with 5.65 m pitch distance	3.33	11.33	9.33	23.33	32.44	9.08
T ₈	4.5 m sowing distance away from 3.75 m bifacial panel height with 5.65 m pitch distance	3.00	9.00	6.67	19.67	26.34	8.13
T ₉	0.5 m sowing distance away from 1.75 m bifacial panel height with 10 m pitch distance	1.67	7.33	6.33	5.67	12.52	4.13
T ₁₀	1.5 m sowing distance away from 1.75 m bifacial panel height with 10 m pitch distance	2.33	9.00	8.00	9.00	17.05	4.71
T ₁₁	3 m sowing distance away from 1.75 m bifacial panel height with 10 m pitch distance	2.67	10.00	8.33	21.33	29.22	8.27
T ₁₂	4.5 m sowing distance away from 1.75 m bifacial panel height with 10 m pitch distance	3.00	11.00	9.33	22.67	25.75	8.38
T ₁₃	0.5 m sowing distance away from 1.25 m bifacial panel height with 10 m pitch distance	1.33	7.00	6.67	6.67	13.49	4.48
T ₁₄	1.5 m sowing distance away from 1.25 m bifacial panel height with 10 m pitch distance	2.33	9.00	9.33	9.00	25.79	4.85
T ₁₅	3 m sowing distance away 1.25 m bifacial panel height with 10 m pitch distance	3.17	10.33	8.00	21.33	29.54	8.28
T ₁₆	4.5 m sowing distance away from 1.25 m bifacial panel height with 10 m pitch distance	3.33	10.67	8.33	22.67	31.12	8.49
T ₁₇	Non PV system	3.00	11.00	7.33	22.83	30.30	8.60
	G.M.	2.64	9.41	7.94	15.46	23.64	6.82
	C.D.	0.40	1.63	1.37	2.74	2.88	1.12
	S.E.(m)	0.14	0.57	0.48	0.95	1.00	0.39
	C.V.	9.31	10.44	10.39	10.66	7.33	9.83

Table 2. Test weight, harvest index and seed germination percentage of soybean under different agriphotovoltaics system.

Sr. No.	Treatments	Test Weight (gm)	Harvest Index	Seed Germination (%)
T ₁	0.5 m sowing distance away from 1.75 m monofacial panel height with 7.5 m pitch distance	13.47	28.36	85.00
T ₂	1.5 m sowing distance away from 1.75 m monofacial panel height with 7.5 m pitch distance	13.23	36.87	90.00
T ₃	3 m sowing distance away from 1.75 m monofacial panel height with 7.5 m pitch distance	12.93	44.55	94.00
T ₄	4.5 m sowing distance away from 1.75 m monofacial panel height with 7.5 m pitch distance	12.47	42.91	98.67
T ₅	0.5 m sowing distance away from 3.75 m bifacial panel height with 5.65 m pitch distance	13.17	37.48	84.67
T ₆	1.5 m sowing distance away from 3.75 m bifacial panel height with 5.65 m pitch distance	13.10	48.33	90.00
T ₇	3 m sowing distance away from 3.75 m bifacial panel height with 5.65 m pitch distance	13.00	49.75	95.00
T ₈	4.5 m sowing distance away from 3.75 m bifacial panel height with 5.65 m pitch distance	13.13	48.88	93.33
T ₉	0.5 m sowing distance away from 1.75 m bifacial panel height with 10 m pitch distance	13.33	34.19	75.67
T ₁₀	1.5 m sowing distance away from 1.75 m bifacial panel height with 10 m pitch distance	13.07	43.20	91.67
T ₁₁	3 m sowing distance away from 1.75 m bifacial panel height with 10 m pitch distance	13.00	48.45	94.67

(continued on next page)

Sr. No.	Treatments	Test Weight (gm)	Harvest Index	Seed Germination (%)
T ₁₂	4.5 m sowing distance away from 1.75 m bifacial panel height with 10 m pitch distance	12.97	48.91	98.67
T ₁₃	0.5 m sowing distance away from 1.25 m bifacial panel height with 10 m pitch distance	13.50	30.20	61.33
T ₁₄	1.5 m sowing distance away from 1.25 m bifacial panel height with 10 m pitch distance	13.10	48.19	83.67
T ₁₅	3 m sowing distance away 1.25 m bifacial panel height with 10 m pitch distance	12.63	48.25	85.00
T ₁₆	4.5 m sowing distance away from 1.25 m bifacial panel height with 10 m pitch distance	12.47	48.31	91.33
T ₁₇	Non PV system	13.03	49.45	95.67
	G.M.	13.04	43.37	88.73
	C.D.	0.59	7.08	3.92
	S.E.(m)	0.21	2.46	1.36
	C.V.	2.73	9.81	2.65

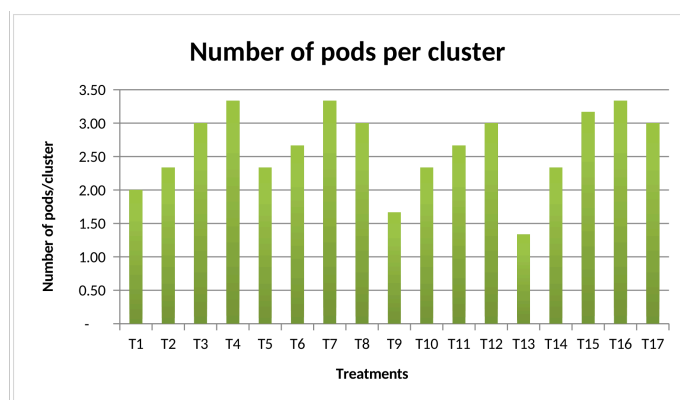


Figure 2. Effect of different APV condition on number of pods per cluster of soybean

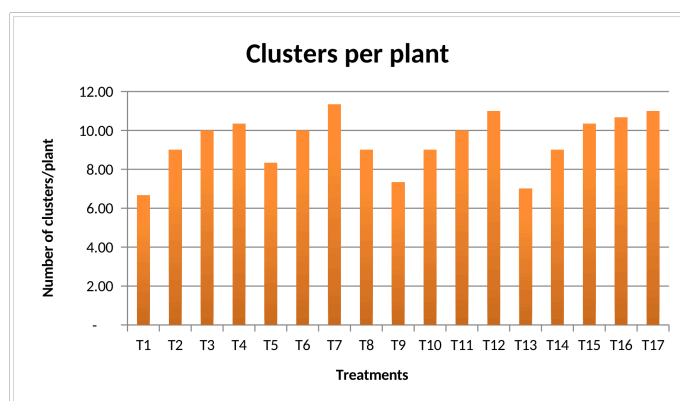


Figure 3. Effect of different APV condition on number of clusters per plant of soybean

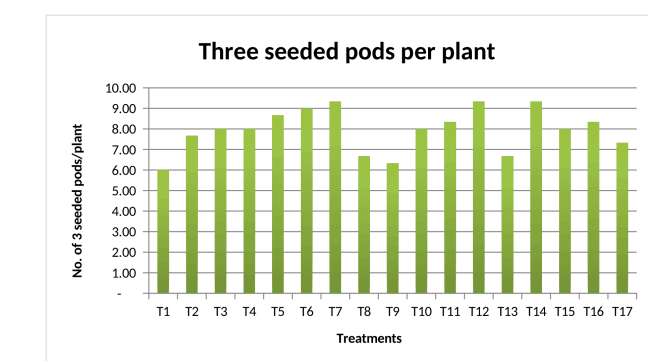


Figure 4. Effect of different APV condition on number of 3 seeded pods per plant of soybean

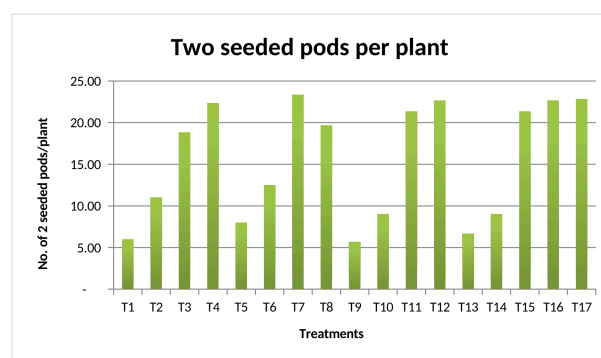


Figure 5. Effect of different APV condition on number of 2 seeded pods per plant of soybean

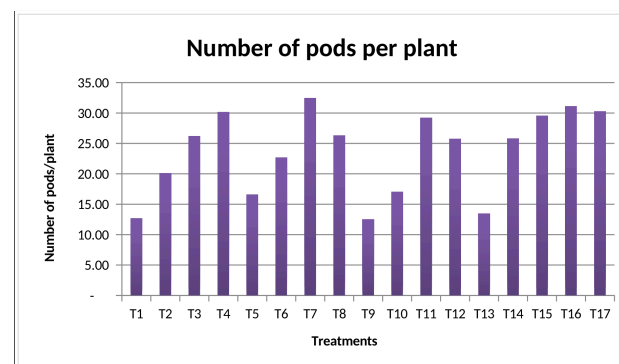


Figure 6. Effect of different APV condition on number of pods per plant of soybean

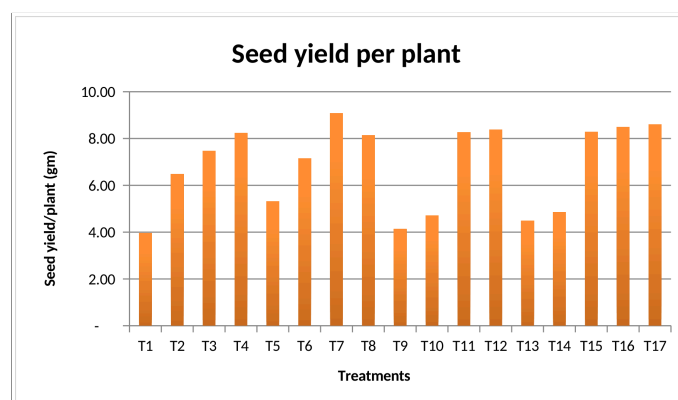


Figure 7. Effect of different APV condition on seed yield per plant of soybean

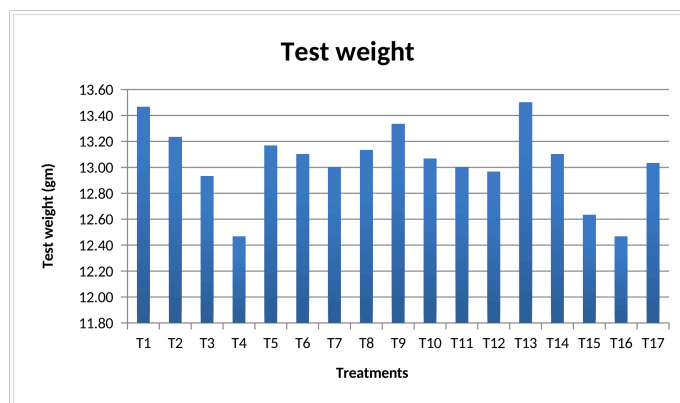


Figure 8. Effect of different APV condition on test weight of soybean

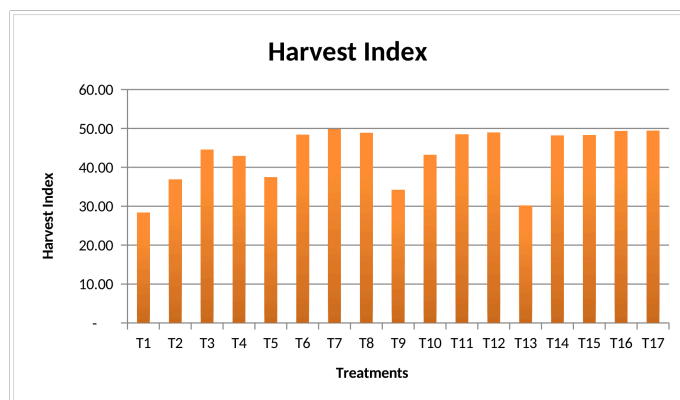


Figure 9. Effect of different APV condition on harvest index of soybean

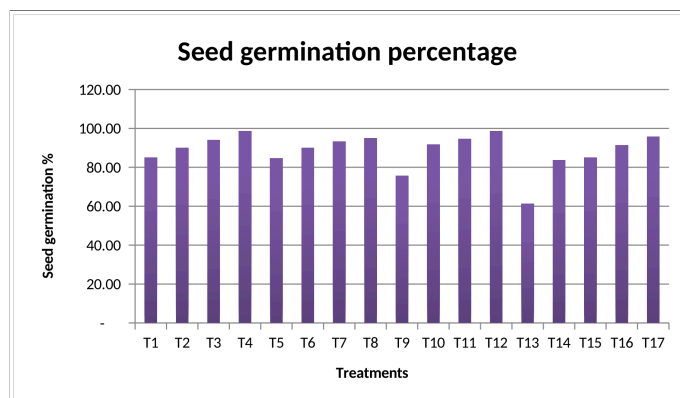


Figure 10. Effect of different APV condition on seed germination percentage of soybean

Conclusion

The study demonstrated that soybean yield attributes like seed yield and seed quality were affected by agrivoltaic (APV) system configuration. The treatment having a 3 m sowing distance away from center of 3.75 m bifacial panel with 5.65 m pitch distance (T₇) produced the highest values for number of pods per cluster, number of clusters per plant, number of pods per plant, seed yield per plant and harvest index performing better than the Non-PV system. In contrast, crops grown directly beneath the panels, particularly T₁ recorded the lowest performance due to prolonged shading, which restricted pod development and assimilate accumulation but showed higher test

weight. Seed yield under below panel conditions declined by 38.13-53.83% compared with in between panel and Non-PV treatment. The highest germination was observed in T₄ and T₁₂ while T₁₃ showed the lowest germination. Overall, the findings indicate that APV systems with higher bifacial panel and adequate spacing can reduce shading effects and sustain soybean productivity and seed quality, making them a more suitable design for integrating crop production with solar energy generation.

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Conflict of interest

The authors confirm that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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