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Growth and Yield Responses of Zucchini (*Cucurbita pepo* L.) Under Varying Agriphotovoltaic Growing Conditions

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Abstract

Present study aims to assess the impacts of the different agriphotovoltaic growing conditions on growth characteristics and yield of zucchini. The experiment was laid out in a restricted randomized block design (RBD) with seven treatments replicated thrice. Among seven treatments, treatment of planting zucchini in between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance showed statistical superiority in growth parameters such as plant height (74.02 cm), leaf area (489.10 cm^2), SCMR value (89.46) and it required minimum days for first flower initiation (18.33 days), days for 50% flowering (22 days), maximum number of flowers (29.51), minimum flower drop % (32.84%). Further, the maximum number of fruits per plant (11.33), yield per plant (2.12 kg/plant), yield per plot (50.78 kg/plot), yield per hectare (58.78 ton/ha) and highest values of root parameters such as root length (25.86 cm), root fresh weight (23.92 g) and root dry weight (6.23 g) were recorded in same treatment. While treatment T_6 recorded lowest leaf miner incidence (11.11%).

Keywords: Agriphotovoltaic, Growth, Photovoltaic panel, Yield, Zucchini

Introduction

Zucchini (*Cucurbita pepo* L.) or summer squash is an exotic vegetable which has recently been popularized in India. It is also called as vegetable marrow, field pumpkin in various regions of the world. Fast food is becoming more and more

popular in urban areas in India. As zucchini is utilized as a topping in several fast-food items including pizza, burger, etc. there is greater demand to grow it. Farmers may benefit greatly from the cultivation of zucchini because the crop has short growing season and high potential yield as well as growing demand in market which can make more money.

To achieve long-term environmental stability, shifting to renewable energy is crucial for reducing carbon footprints and combating climate change. With the aim to mitigate the severe effects of climate change such as increased droughts, flooding, heavy rainfall, heat waves, etc., introduction of clean renewable energy sources is essential. Solar power is one of the most easily available and plentiful source among all cleaner and renewable energies (Malu *et al.*, 2017; Moreira *et al.*, 2020). Photovoltaics has been widely used for energy generation. The substantial land requirements of conventional PV farms to meet rising energy demands often result in land use conflicts. Agrivoltaics, a novel approach that combines agricultural production with solar electricity generation with PV, presents a promising solution to mitigate climate change. Agriphotovoltaic (APV) is the simultaneous use of the same land for solar photovoltaic (PV) power generation and agricultural activities.

The APV system is emerging concept with few studies investigating how crop productivity responds to photovoltaic systems. Therefore, a wide range of research efforts will be necessary to optimize crop productivity, develop effective management strategies for the APV system and fully exploit the potential benefits the GM-APV system offers. Very scanty information is available on research aiming to enhance zucchini crop yield under solar panels and it has not been empirically investigated. Therefore, present investigation conducted with the objective to study zucchini crop growth and yield performance under various agriphotovoltaic growing conditions.

Materials and Methods

Present study was carried out at Agriphotovoltaic Research Project, Manwat run under Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani during the *rabi* season of the year 2024-25. The field is categorized into four sections- three agrivoltaic (APV) and one open *i.e.* control section (non APV). The agriphotovoltaic site includes areas below photovoltaic panels, in between panels and open area outside the photovoltaic system. The photovoltaic panel specification includes three types of panels, all with 20% efficiency and 11°tilt. The ground clearance of panels varies as 3.75 m (bifacial), 1.75 m (monofacial) and 1.75 m (bifacial) with pitch distance of 5.65 m, 7.5 m and 10 m, respectively.

The experiment was carried out in restricted randomized block design consisting of seven treatments with three replications. The nursery raising of "Himani" zucchini variety seeds was done in pro-trays. Zucchini seedlings were transplanted after 15 days of sowing on main experimental plot at spacing 60 × 60 cm under photovoltaic panel, in between the photovoltaic panel rows and in open field condition. Treatment details consist of planting zucchini in the treatment T_1 – below 1.75 m monofacial photovoltaic panel height with 7.5 m pitch distance, treatment T_2 – in between 1.75 m monofacial photovoltaic panel height with 7.5 m pitch distance, treatment T_3 – below 1.75 m bifacial photovoltaic panel height with 10 m pitch distance, treatment T_4 – in between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance, treatment T_5 – below 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance, treatment T_6 – in between 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance and treatment T_7 – control *i.e.* open field condition (non APV). All plant growth parameters were recorded at 75 days after transplanting (DAT). Leaf area was measured using LI-3100C leaf area meter. Chlorophyll index was measured using chlorophyll meter termed as SCMR (SPAD chlorophyll meter reading). Yield parameters were recorded at the time of harvest. While root parameters were recorded after harvest. The data collected during experimental study was statistically analyzed using Analysis of Variance (ANOVA) method given by Panse and Sukhatme (1985).

Results and Discussion

Growth parameters: Perusal of data presented in Table 1 clearly revealed that different agriphotovoltaic growing conditions influenced the growth parameters of zucchini significantly. More

plant height (74.02 cm) was observed in treatment T_4 where zucchini planted in between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance which was statistically at par with treatment T_2 (71.84 cm). However, less plant height (60.15 cm) was observed in treatment T_7 *i.e.* control (non APV). The maximum value of leaf area (489.10 cm^2) was recorded in treatment T_4. It was followed by treatment T_2 (480.56 cm^2) and treatment T_1 (475.52 cm^2) which were statistically at par with each other. The minimum value of leaf area (458.46 cm^2) was observed in treatment T_7 *i.e.* (non APV). The maximum SCMR value (89.46) for chlorophyll index was recorded in treatment T_4. It was statistically at par with treatment T_2 (87.96). The minimum value of chlorophyll index (76.35) was observed in treatment T_7. This variation in growth parameters might be due to balanced light regime between bifacial panels with proper spacing which provides optimal condition for plant growth likely due to improved microclimate, better light diffusion and reduced heat stress which are favourable for vegetative growth. According to Hickey *et al.* (2024) shading from solar panels in agriphotovoltaic system reduces evaporation rates by preserving soil moisture and enhances water-use efficiency. The higher light intensity in open field can lead to increased photoinhibition and degradation of chlorophyll molecules while partial shade provides less stressful environment. Similar variations in growth parameters have been reported by Hassanien *et al.* (2018) in tomato and Tang *et al.* (2020) in strawberry.

The maximum number of leaves (28.41) were recorded in treatment T_7 where zucchini planted in open field condition *i.e.* control (non APV). It was followed by treatment T_4 (26.92) and treatment T_2 (25.97) which were at par with each other. The minimum number of leaves (22.84) were observed in treatment T_6. Significantly maximum number of nodes (19.44) was recorded in treatment T_7, however it was statistically at par with treatment T_4 (18.95). While, the minimum number of nodes (16.18) was noticed in treatment T_6. In open field condition full spectrum of light reaches the plant canopy which led to leaf initiation. Zucchini planted in open field condition *i.e.* treatment T_7 yielded the highest number of nodes throughout the growing period, confirming that maximum natural light exposure promote active nodal development. Various studies highlighted same variations which have been documented by Marrou *et al.* (2013) in lettuce, Jo *et al.* (2022) in adzuki bean, Kumpanalaisatit *et al.* (2022) in bok choy.

Flowering parameters: The data pertaining to the flowering parameters of zucchini as affected by different agriphotovoltaic growing conditions is presented in Table 2 which showed significant variation among treatments. Among the various agriphotovoltaic growing conditions under study, lowest number of days (18.33 days) were taken for initiation of first flower in treatment T_4 where zucchini planted in between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance which was significantly earlier than all other treatments. It was followed by treatment T_2 (18.93 days). Whereas, highest number of days for flower initiation (23.74 days) were recorded in treatment T_6. The lowest number of days (22 days) for 50% flowering observed in treatment T_4, however it was followed by treatment T_2 (22.93 days). While treatment T_6 showed highest number of days (29.73 days) for 50% flowering in zucchini. The maximum number of total flowers (29.51) was seen in treatment T_4, however it was statistically at par with treatment T_2 (28.86), treatment T_1 (27.81) and treatment T_7 (27.24). While, the minimum number of flowers (23.34) recorded in treatment T_6. Among the various treatments, minimum flower drop (32.84%) was recorded in treatment T_4 which was at par with treatment T_2 (33.88%). Whereas, maximum flower drop (43.38%) was observed in treatment T_7. The earliest flowering in treatment T_4 might be due to bifacial panels allow partial transmission and reflection of light while the between panel planting ensures moderate shading, avoiding both excess solar stress and deep shade. These conditions are likely to enhance photosynthesis and accelerate vegetative as well as reproductive growth. Angeles *et al.* (2025) reported the positive effect of bifacial systems which provide an optimal balance of indirect light and shade to stimulate flowering. These results are in agreement with Hassanien *et al.* (2022) in chili pepper, Scarano *et al.* (2024) in tomato and Angeles *et al.* (2025) in *Phaseolus vulgaris* L.

Yield parameters: It was clear from the data presented in Table 3 regarding yield parameters of zucchini as influenced by different agriphotovoltaic

growing conditions varied significantly. The maximum number of fruits per plant (11.33) was recorded in treatment T_4 where zucchini planted in between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance. It was followed by treatment T_2 (9.67) and T_1 (9). While, minimum number of fruits (6.2) was observed in treatment T_7 *i.e.* control (non APV). The more yield per plant (2.12 kg/plant) was recorded in treatment T_4 outperforming all other treatments under study. It was followed by treatment T_2 (2.02 kg/plant) and T_1 (1.94 kg/plant). However, minimum yield (1.49 kg/plant) was recorded in treatment T_7. The significantly maximum yield per plot (50.78 kg/plot) was recorded in treatment T_4. It was followed by treatment T_2 (48.39 kg/plot) and T_1 (46.46 kg/plot). While, minimum yield (35.78 kg/plot) was observed in treatment T_7. The maximum yield per hectare (58.78 ton/ha) was observed in treatment T_4. It was followed by treatment T_2 (56.01 ton/ha) and T_1 (53.77 ton/ha). The minimum yield (41.42 ton/ha) was observed in treatment T_7. According to Amaducci *et al.* (2018), crops grown under partial shade *i.e.* between solar panel rows can benefit from diffused light that improves canopy photosynthesis and productivity. The higher yield of zucchini planted in between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance might be due to optimal light penetration and moderate temperature which promote better photosynthesis and higher productivity. The lowest yield was observed in open field condition possibly due to higher leaf miner infestation which reduced leaf surface area and photosynthetic capacity, ultimately impacting plant vigour and yield. Similar variations in yield were reported by Hassanien *et al.* (2022) in chili pepper, Hernández *et al.* (2022) in pepper and Witwit *et al.* (2025) in potato.

Root parameters: Effect of different agriphotovoltaic growing conditions on root parameters of zucchini showed significant difference among treatments which is given in Table 4. Among various treatments, the maximum root length (25.86 cm) recorded in treatment T_4 where zucchini planted in between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance over rest of the treatments under investigation. It was statistically at par with treatment T_2 (25.14 cm) and treatment T_1 (24.72 cm). The minimum root length (22.12 cm) was observed in treatment T_7. The maximum root fresh weight (23.92 g) was recorded in treatment T_4 which was statistically at par with treatment T_2 (23.13 g) and treatment T_1 (22.91 g). Whereas, significantly minimum root fresh weight (19.77 g) was observed in treatment T_7. The maximum root dry weight (6.23 g) was noted in treatment T_4. It was statistically at par with treatment T_2 (5.96 g). However, minimum root dry weight (3.96 g) was recorded in treatment T_7. The moderate shading in between panel region may have created a less stressful environment for root elongation and root biomass accumulation by conserving soil moisture and reducing excessive evapotranspiration. These findings are in line with results reported by Kavga *et al.* (2017) in lettuce, Artru *et al.* (2018) in sugarbeet and Mani *et al.* in turmeric (2025).

Leaf miner incidence: In treatment T_6 *i.e.* growing zucchini in between 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance, 11.11% incidence was observed which was lowest incidence. It was at par with treatment T_5 (12.5%), T_3 (13.87%), T_4 (15.27%), T_1 (19.44%) and T_2 (22.22%). In treatment T_7 highest incidence of leaf miner (54.16%) was recorded. The less leaf miner incidence under agrivoltaic treatments, particularly between solar panel rows (T_6 and T_5) can be attributed to the partial shading created by the solar panels which likely altered the microclimate between the panels. These altered conditions may have been less favourable for the oviposition, feeding and development of leaf miner pest. This indicates that the absence of shading and exposure to direct sunlight created an ideal environment for leaf miner proliferation possibly due to warmer temperatures and greater visibility for oviposition by adult flies.

In nutshell, it can be concluded that growing zucchini in between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance consistently outperformed than other treatments under investigation. It showed statistically superior performance in growth parameters such as plant height, leaf area and chlorophyll index, flowering parameters like days for first flower initiation, days for 50% flowering, number of flowers and flower drop%, yield parameters such as number of fruits

per plant, yield per plant, yield per plot and yield per hectare and root parameters *i.e.* root length, root fresh weight and root dry weight.

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Conflict of interest

The authors declare 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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Table 1. Influence of different agriphotovoltaic growing conditions on growth parameters of zucchini

Tr. No.	Treatment details	Plant height (cm)	Number of leaves	Number of nodes	Leaf area (cm^2)	Chlorophyll index (SCMR value)
T_1	Below 1.75 m monofacial photovoltaic panel height with 7.5 m pitch distance	69.93	25.02	17.49	475.52	86.16
T_2	In between 1.75 m monofacial photovoltaic panel height with 7.5 m pitch distance	71.84	25.97	17.99	480.56	87.96
T_3	Below 1.75 m bifacial photovoltaic panel height with 10 m pitch distance	68.70	23.87	17.06	471.97	85.51
T_4	In between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance	74.02	26.92	18.95	489.10	89.46
T_5	Below 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance	66.95	23.02	16.87	466.74	84.86
T_6	In between 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance	64.37	22.84	16.18	463.39	83.3
T_7	Open field condition	60.15	28.41	19.44	458.46	76.35
S.E m±		0.73	0.44	0.46	1.82	0.97
C.D. @ 5 %		2.23	1.35	1.41	5.61	2.99

Table 2. Influence of different agriphotovoltaic growing conditions on flowering parameters of zucchini

Tr. No.	Treatment details	Days for 1st flower initiation	Days for 50% flowering	Number of flowers	Flower drop (%)
T_1	Below 1.75 m monofacial photovoltaic panel height with 7.5 m pitch distance	19.73	24.67	27.81	35.63 (36.61)*
T_2	In between 1.75 m monofacial photovoltaic panel height with 7.5m pitch distance	18.93	22.93	28.86	33.88 (35.56)
T_3	Below 1.75 m bifacial photovoltaic panel height with 10 m pitch distance	20.93	25.27	26.65	37 (37.42)
T_4	In between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance	18.33	22.00	29.51	32.84 (34.93)
T_5	Below 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance	23.07	28.27	25.72	38.01 (38.02)
T_6	In between 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance	23.74	29.73	23.34	39.69 (39.01)
T_7	Open field condition	20.07	24.73	27.24	43.38 (41.15)
S.E m±		0.12	0.21	0.85	0.29
C.D. @ 5 %		0.38	0.66	2.61	0.89

* Figures in parentheses indicate arcsine transferred values

Table 3. Influence of different agriphotovoltaic growing conditions on yield parameters of zucchini

Tr. No.	Treatment details	Number of fruits per plant	Yield/plant (kg)	Yield/plot (kg)	Yield/ha (ton)
T_1	Below 1.75 m monofacial photovoltaic panel height with 7.5 m pitch distance	9.00	1.94	46.46	53.77
T_2	In between 1.75 m monofacial photovoltaic panel height with 7.5 m pitch distance	9.67	2.02	48.39	56.01
T_3	Below 1.75 m bifacial photovoltaic panel height with 10 m pitch distance	8.40	1.83	43.95	50.87
T_4	In between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance	11.33	2.12	50.78	58.78
T_5	Below 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance	8.13	1.75	41.94	48.55
T_6	In between 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance	7.47	1.64	39.41	45.61
T_7	Open field condition	6.20	1.49	35.78	41.42
S.E m±		0.06	0.01	0.17	0.19
C.D. @ 5 %		0.19	0.02	0.53	0.60

Table 4. Influence of different agriphotovoltaic growing conditions on root parameters of zucchini

Tr. No.	**Treatment details**	**Root length (cm)**	**Root fresh weight (g)**	**Root dry weight (g)**	**Leaf miner incidence (%)**
T_1	Below 1.75 m monofacial photovoltaic panel height with 7.5 m pitch distance	24.72	22.91	5.27	19.44 (26.13)*
T_2	In between 1.75 m monofacial photovoltaic panel height with 7.5m pitch distance	25.14	23.13	5.96	22.22 (28.09)
T_3	Below 1.75 m bifacial photovoltaic panel height with 10 m pitch distance	24.13	21.84	4.98	13.87 (21.84)
T_4	In between 1.75 m bifacial photovoltaic panel height with 10 m pitch distance	25.86	23.92	6.23	15.27 (22.98)
T_5	Below 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance	23.67	21.37	4.42	12.5 (20.68)
T_6	In between 3.75 m bifacial photovoltaic panel height with 5.65 m pitch distance	22.91	20.75	4.19	11.11 (19.45)
T_7	Open field condition	22.12	19.77	3.96	54.16 (47.33)
S.E m±		0.54	0.34	0.21	4.42
C.D. @ 5 %		1.66	1.04	0.64	13.60