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ORIGINAL PAPER

Techno-economic analysis of agrivoltaic system for affordable and clean energy with food production in India

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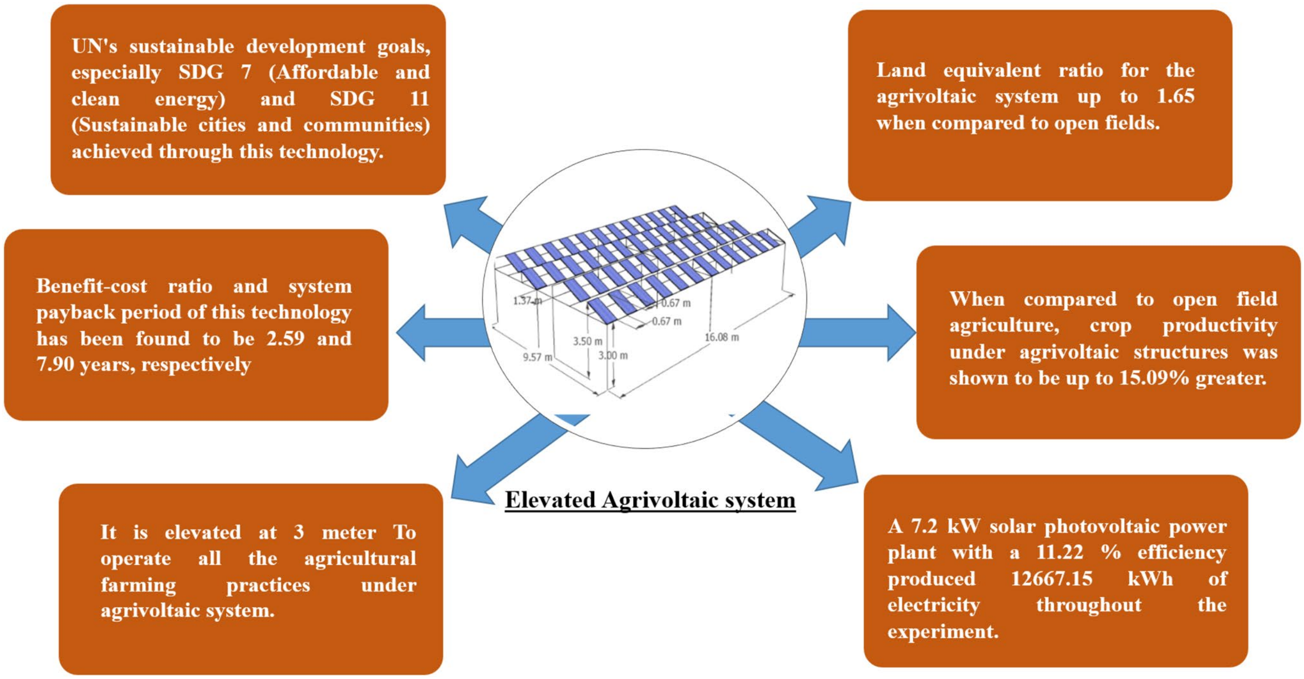
Abstract
The effects of population growth, climate change, and global economic expansion are concerning for food and energy security. For a nation like India, the agrivoltaic system is a center of photovoltaic and agricultural production as it is better suited to achieving the United Nation's sustainable development goals, especially SDG 7 (Affordable and clean energy) and SDG 11 (Sustainable cities and communities). The agrivoltaic solar power plant system generated 12667.15 kWh from September 2017 to August 2018 with a system efficiency of 11.22%. The height of agrivoltaic structure has been determined 3 m to perform agricultural operations underneath it. A shade-tolerant tomato crop has been cultivated in an open field and an agrivoltaic structure using four different types of land treatments in the proposed experimental study. The land equivalent ratio is obtained greater than open field treatments up to 1.65 for all treatments and environments. The benefit/cost ratio has been determined to be as high as 2.59 with the lowest payback period of 7.90 years. Crop productivity under agrivoltaic structures has been higher in all treatments up to 15.09% as compared to open field agriculture. Agrivoltaic technology is a novel and sustainable technology for farmers in the future.

Extended author information available on the last page of the article

Graphical abstract



Keywords Agrivoltaic · Tomato crop cultivation · Final and reference yield · Land equivalence ratio

List of symbols

P	Power generated by solar panel (W)
V	Output voltage of solar panel (V)
I	Output current of solar panel (A)
Y_F	Final yield (kW h/kWp)
Y_R	Reference yield (kW h/kWp)
PR	Performance ratio (%)
CF	Capacity factor (%)
$\eta_{sys,m}$	Monthly system efficiency (%)
A_m	Total solar panel area (m^2)
E_{AC}	AC energy output (kWh)
$P_{PV, Rated}$	Rated output power (kW)
H	Total in-plane solar insolation (kW h/m^2)
G	Reference irradiance (kW/m^2)
LER	Land equivalent ratio (dimensionless)
$Y_{cropin\ AV}$	Total crop yield from AV system (kg)
$Y_{monocrop}$	Total monocrop yield (kg)
$Y_{electricity\ AV}$	Total electricity generation from AV system (kWh)
$Y_{electricity\ PV}$	Total electricity generation from the conventional photovoltaic system (kWh)
CRF	Capital recovery factor (numerical value)
SV	Salvage value (INR)
ASV	Annual salvage value (INR)
SFF	Salvage fund factor (numerical value)

Introduction

As a result of recent population growth, the world's population is currently 7.7 billion and is expected to rise to 8.5 million by 2030 or 9.7 billion in 2050 (World population prospects 2019). As a consequence of this, our necessities are expanding. According to the International Energy Agency (IEA 2023), around USD 2.8 trillion will be invested in energy in 2023. More than USD 1.7 trillion is going to clean energy, including renewable power, nuclear, grids, storage, low-emission fuels, efficiency improvements, and end-use renewables and electrification. To cope with these immense requirements of energy with zero carbon footprint on the environment, institutions are aiding the transition to a sustainable energy paradigm. Renewable technologies are gaining importance throughout this circumstance. The photovoltaic system is essential in this because it has global accessibility, simplicity of use, cheap maintenance and financing costs, increased efficiency, and durability. One of the most important advantages of this system is the LCOE (levelized cost of energy) is reduced (Victoria et al. 2021). According to the IEA, solar PV generation is the second largest of all renewable technologies in 2021 after wind as it increased by a record 179 TWh (up 22%) in 2021 to exceed 1000 TWh. However, agri-food production is no longer feasible on the vast areas of land set aside for grid-connected PV facilities. The probability of meeting that increasing food requirement brought on by population growth is negatively affected by such a reality, especially in areas having limited land and exponential growth of population (Weselek et al. 2019). The first obstacle is the requirement of land because 20,000 m^2 (or roughly five acres or two hectares) of land is required to build a 1.0 MW solar PV power plant per National Renewable Energy Laboratory (NREL 2013). The agricultural industry offers a lot of space for solar energy use. Farm irrigation, building cold storage facilities in remote areas, and other uses of extra electricity generated from agrivoltaic (AV) systems can help farmers make more money. As a result, capturing solar energy on a farmer's field can be compared to harvesting a different crop and can function as some sort of insurance even if it does not rain. It can also guarantee optimal land utilization which makes the AV system a novel and game changer for future needs.

The AV system is a combination of PV and agricultural output on the same piece of land to address this issue. Since SPV plants are often ground-mounted, not all types of crops can be grown underneath them and also cannot be used for farming activities that can be carried out by machinery. After noticing these issues, the height of AV has been taken as 3 m in this proposed work. Numerous studies have been conducted in this area of elevated AV, but they typically use solar panels with half or full densities, which always create harsh shadows in the same location which block photosynthesis. In response to this issue, in this proposed work researchers designed elevated AV systems in the chessboard pattern so that shadows do not stay in one place for a long period of time and move continuously throughout the day to make it possible for agriculture to take place underneath them. Goetzberger and Zastrow first put forth this idea in 1982 (Goetzberger et al. 1982). Nevertheless, this takes three decades before it will be deployed in test AV plants. Since then, a series of researches have evaluated the performance of AV facilities from an agriculture and power perspective. But the fact is that there are not enough economic or research facilities (Agostini et al. 2021; Irie et al.2019; Leon et al. 2018).

The productivity of the land and farm revenue can both be increased at the same time by achieving sufficient power yields (Marrou et al. 2013c; Schindele et al. 2020; Trommsdorff et al. 2021). The impact on microclimatic conditions and crop yield is a significant consideration when considering the viability of AV use in agricultural systems. The effects of microclimatic variances under AV on agricultural yields are currently unknown because there are almost no references to them in the scientific literature (Weselek et al. 2019). The majority of AV system studies to date have centered on simulations and modeling (Amaducci et al. 2018), while actual data from actual field experiments are still hard yet to come. (Marrou et al. 2013a, b, c; Weselek et al. 2021).

Depending on the intensity and timing of the shade application, grain production decreases of up to 50% have been seen for winter wheat (Artru et al. 2017; Dufour et al. 2013). However, researchers also found that wheat grain yields increased under light shading circumstances (Li et al. 2010). Similar findings have been seen for potatoes, where greater shading reduced tuber quantity and total tuber yields (Schulz et al. 2019). However, shade has been found to increase potato tuber yields in areas with strong sun radiation when used at particular developmental phases or times of day (Kuruppuarachchi 1990).

Forage crops have more varied yield responses to shade, showing both yield gains and decreases, demonstrating the importance of the examined species and climatic location (Pang et al. 2017). The transferability of the results to AV is constrained because the majority of these studies apply shade utilizing netting constructions, which would produce different shading patterns and microclimatic heterogeneities (Weselek et al. 2019).

AV system crop yields have been lower than the control. This happened as a result of how shade affected agricultural yields. Crop yield is impacted by shading, notably crop weight. Therefore, the quantity of light intensity for the plants grown under the panels might be improved by reducing the number of solar panels installed in the planted area. Researchers observed that crop output has been still lower than the control despite the usage of a low-density PV setup (Jing et al. 2022). This problem might be resolved with the use of a solar tracking system. Despite the solar tracking system being used to improve the amount of light shining under the solar panels, the research discovered that it had lower yields than the control. The solar tracking system, fixed system, and control system all experienced similar growth rates. As a result, even though the planting process has been constant, the harvesting time may change based on whether solar panels are present. The study found that there has been no appreciable change in crop yield quality, even though crop production varied between AV systems and open field farming (Moon and Ku 2022).

In relation to India to determine the techno-economic viability of an AV system, some study has been done. The result shows enhanced energy and food production. The LER has been 1.73 and the Payback period has been 9.49 years for turmeric crops (Giri et al. 2022a). The researchers also conducted a second study to create an AV system to maximize land utilization for the production of clean energy and food. Three distinct kinds of design approaches have been shown in the study to provide an effective system. The optimum system is determined to be a double-row array design capacity of a 6 kWp AV system with an average yearly income of 2308.9 USD, a land equivalent ratio of 1.42, and a payback period of up to 7.6 years, respectively (Giri et al. 2022b). In Odisha, India, more study is conducted on the topic of access to solar energy for livelihood security. To improve the security of people's livelihoods, a few significant off-grid technologies, such as photovoltaic lighting systems and water pumps, have been constructed and put into place in Odisha's urban and rural areas. A 20 Wp polycrystalline solar panel powers a 12 V 10 Ah Li-ion battery in 6–7 sunny hours, allowing the small solar street light to run a 12 V 9 W LED light for up to 10 h every day (Giri et al. 2023). In Gujarat, India, additional research has been conducted to determine the amount of electricity generated by a photovoltaic system. A 7.2 kW power plant in that research produces 10,104.77 kWh of energy with an efficiency of 12.07% (Patel et al 2023). To accomplish the Smart Shift from Photovoltaic to AV Systems for Land-Use Footprint, further work is being done in India. The goal of the government is to increase the number of AV systems in the vast dry plains, as stated in this report. An AV farmer may serve the consumers for 5 INR/kWh and sell the agricultural harvest in parallel with current energy tariffs. Installing a techno-ecological AV system on farmers' property may optimize electricity generation, water gathered for irrigation, and crop output ratio (Giri et al. 2021).

The results of recent field studies conducted by different countries under an AV system are shown in Table 1. Field testing is required to get trustworthy data about the impact of AV technology on agricultural productivity. To evaluate the technology under practical conditions, the proposed work has been carried out at the Junagadh Agricultural University, Gujarat, India. The proposed study aims to determine the effects of an AV facility on agricultural productivity, microclimate conditions, and techno-economic performance. Agrivoltaics seems to be a reasonable plan in this scenario for increasing electrical independence from the burning of fossil fuel achieving self-sufficiency, and contributing to the UN Sustainable Development Goals. Researchers are examining its techno-economic performance concurrently with crop growing to ensure farmers' revenue through the production of electricity free of carbon emissions.

Material and methods

The proposed research work has conducted studies on the cultivation of the tomato (*Lycopersicon esculentum* L.) crop under a specially constructed SPV (solar photovoltaic) power plant (AV) from September 11, 2017 to February 28, 2018, at the College of Agriculture Engineering and technology, Junagadh agricultural university, Junagadh (21.5 N, 70.1 E). In Junagadh, there are two different seasons: a dry season from October to May and a wet season from June to September. The city has a tropical wet and dry climate that borders on a hot semiarid environment. The Arabian Sea and the Gulf of Cambay are close together, which has an impact on the climate. Summertime temperatures range from 28 to 38 °C (82 to 100 °F), with 5.5 to 8.0 kWh/m2/day of typical solar radiation. They fluctuate between 50 and 77 °F (or 10 and 25 °C) throughout the winter. It experiences 1000 to 1200 mm of rainfall annually, most of which occurs during monsoon (June–August) season.

The experimental SPV power plant structure, originally previously designed and installed at the Department of Renewable Energy Engineering, has been considered for this study. To ease complex farming operations under AV structure through farm machinery like tractors, the height of the structure has been set at 3 m. The tilt angle of solar panels has been computed as per the latitude angle of the experimental location. Generally, there are two types of solar panel configuration in AV structure: half density and full density. The full-density solar panel configuration AV structure hurts crop cultivation due to the harsh shadow on the ground. (Sekiyama and Nagashima 2019). Keep in mind the shadow problem in the proposed work researchers considered half-density solar panel configuration AV structure. Half-density solar panels have less effect of shadow on crop production as compared to full-density solar panels. Half-density solar panel chessboard-type structure has been selected for design because the crop under the AV structure received consistent solar radiation the whole day due to the continuous movement of the shadow of solar panels

Table 1 The crop yield of recent field studies and AV conditions by different countries

Crop	AV structure	Agrivoltaic condition yield (kg/m)	Open filed condition (kg/m)	Country/year	Reference
Bok choy	Conventional PV power plant	0.1	1.15	Thailand/2022	Kumpanalaisatit et al. (2022)
Winter cabbage	Conventional PV power plant	0.32	0.35	Korea/2022	Moon and Ku (2022)
Kiwifruit	Low-density PV panel system	1.66	1.71	China/2022	Jing et al. (2022)
Corn	High-density PV panel system	3.23	3.35	Japan/2019	Sekiyama and Nagashima (2019)

on the ground. The chessboard-type configuration creates a shadow that has been moving continuously throughout the day, hence is no place under the structure where the complete darkness. This chessboard panel helps to maintain the solar radiation consistently to all the plants under it so, chessboard-type configuration is selected for the design and development of the structure. Table 2 contains detailed specifications of solar photovoltaic power plants. This SPV power plant occupied 153.88 m^2 area for 7.2 kW capacity, i.e., 0.047 kW/m^2. The SPV power plant has been created to minimize crop shadowing effects and maintain a level of land use with the traditional SPV power plant design, so that the quantity of energy produced per unit of land area remains unchanged. Specifications of materials used for the above-mentioned SPV power plant are presented in Table 3.

The SPV panels have been shown as a dark-colored box. Each row of the SPV plant had 12 panels (each with a 150 W output capacity) positioned in the south-facing direction. The lowest end of the panels has been at 3.50 m above ground level. A total of 48 panels have been installed in four rows with a 1.36 m space between each row. A 1.36-m corridor has been provided in the center of the steel-framed building for convenient inspection and observation of the crop grown underneath the SPV power plant. The specification of solar panels is listed in Table 4. The top, side, front, isometric view, and photographic view of the AV structure are shown in Fig. 1.

The International Energy Agency analyzed the SPV power plant's performance (IEA). For the performance analysis of the SPV power plant, the following performance metrics have been taken into account. (Sharma and Chandel 2013). A schematic diagram of SPV power plant output is shown in Fig. 2. To store electricity, batteries have been employed in an AV system with a 7.5 kVA hybrid inverter. Although the initial cost may be higher, it can offer backup power for agricultural irrigation and other electrical tasks in the event of a power outage. When there is no sunlight (due to monsoon) or a collapse in the wiring or solar panels, this 7.5 kVA hybrid inverter can charge the batteries using AC power; otherwise, DC is utilized to charge the batteries.

Energy generated from the solar panel can be calculated using Eq. 1.

$$\mathrm{P} = VI \tag{1}$$

where P = Power generated by solar panel (Watt), V = Output voltage of solar panel (V), I = Output current of solar panel (A)

The total daily ($E_{\mathrm{AC,d}}$) and monthly ($E_{\mathrm{AC,m}}$) energy generated by the PV system has been calculated by Eq. 2.

$$E_{(\mathrm{AC,d})} = \sum_{t=1}^{24} E_{(\mathrm{AC,t})} E_{(\mathrm{AC,m})} = \sum_{d=1}^{n} E_{(\mathrm{AC,d})} \tag{2}$$

Table 2 Specifications of SPV power plant

Latitude	21.51 ˚N
Longitude	70.47 ˚E
Elevation	107 m
Type of PV module	Poly crystalline
Capacity	7.2 kW
Capacity of each module	150 W
No. of solar panels	48 nos
Inverters capacity	7.5 kVA
Battery	Three batteries (150 Ah)
Type of configuration	Chessboard type

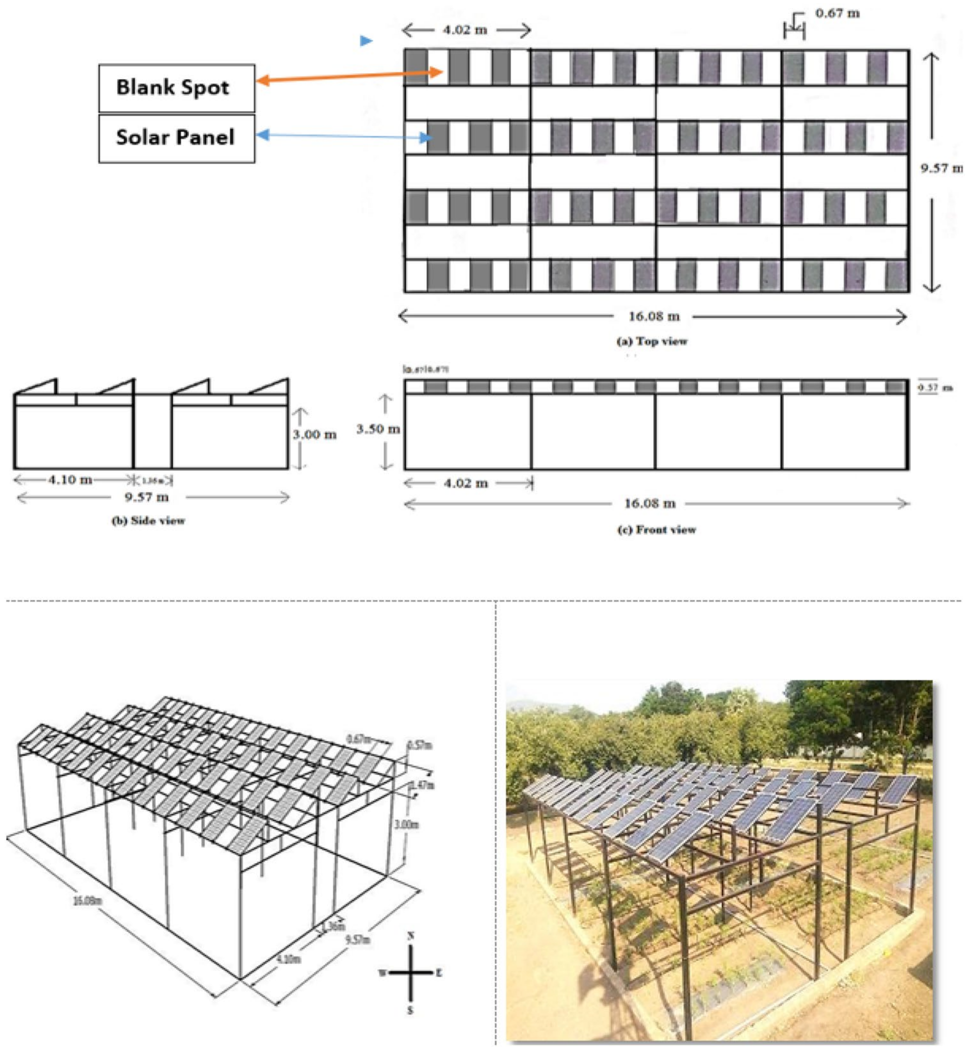
Table 4 Specifications of solar panel

PV module	Specifications
Type of material	Poly crystalline
Make	Universal Solar Group
Model	UPS 150
Maximum power P_{max} (W)	150
Open circuited voltage V_{oc} (V)	22.3
Short circuited current I_{sc} (A)	8.82
Maximum power voltage V_{max} (V)	18.3
Maximum power current (I_{max}) (A)	8.2
No. of cells in a module	(4 × 9) 36 nos
Module dimensions (mm)	1480 × 670 × 35
15.14 Module efficiency (%)	15.15%

Table 3 Specifications of materials used for SPV power plant

Component	Material specification (All dimensions are in mm)	No	Length (m)	Quantity (m)	Weight (kg/m)
Columns	Square CRC pipe 100 × 100 × 6	20	03.00	60.00	1018.80
Main frame (rectangular)	Square CRC pipe 75 × 75 × 5	01	51.30	51.30	495.60
Beam	Square CRC pipe 75 × 75 × 5	05	8.20	41.00	396.10
Purlin	Square CRC pipe 50 × 25 × 4	96	1.48	142.08	551.30

Fig. 1 Top, side, front, isometric view, and photographic view of AV structure



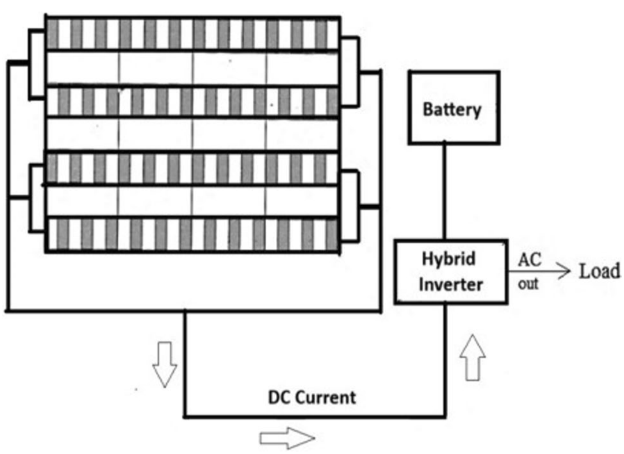


Fig. 2 Schematic diagram of SPV power plant output

where n = Number of days in the month, $E_{(AC,t)}$ = Total hourly AC energy output (kW h), $E_{(AC,d)}$ = Total daily AC energy output (kW h), $E_{(AC,m)}$ = Total monthly AC energy output (kW h).

The instantaneous energy output is obtained by measuring the energy generated by the PV system after the DC/AC inverter for 30 min intervals.

The final yield is defined as the total AC energy generated by the PV system for a defined period (day, month or year) divided by the rated output power of the installed PV system and is given by Eq. 3.

$$Y_F = \frac{E_{AC}}{P_{PV,Rated}} \tag{3}$$

where Y_F = Final yield (kW h/kWp), E_{AC} = AC energy output (kWh), $P_{PV,Rated}$ = Rated output power (kW).

The reference yield is defined as the ratio of total in-plane solar insolation H_t (kWh/m^2) to the reference irradiance G (1 kW/m^2). This parameter represents an equal number of hours at the reference irradiance and is given by Eq. 4.

$$Y_R = \frac{H_t(\text{kWh/m}^2)}{G(\text{kW/m}^2)} \tag{4}$$

where Y_R = Reference yield (kW h/kWp), H_t = Total in-plane solar insolation (kW h/m^2), G = Reference irradiance (kW/m^2).

The performance ratio is defined as the ratio of the final yield (Y_F) to the reference yield (Y_R). It represents the total losses in the system when converting the DC rating to AC output. Therefore, the PR can be expressed as Eq. 5.

$$\text{PR (\%)} = \frac{Y_F}{Y_R} \times 100 \tag{5}$$

where Y_F = final yield (kW h/kWp), Y_R = Reference yield (kW h/kWp).

The capacity factor (CF) is defined as the ratio of the actual annual energy output ($E_{AC,a}$) of the PV system to the amount of energy the PV system would generate if it operates at full rated power (PV, rated) for 24 h per day for a year and is given as Eq. 6.:

$$\text{CF} = \frac{E_{AC,a}}{P_{PV,a} \times 8760} \times 100 \tag{6}$$

where CF = Capacity factor (%), $E_{(AC,a)}$ = Total annual AC energy output (kW h), $P_{PV,a}$ = Total amount of energy generated at full rated power (kW h), Monthly system efficiency can be calculated by Eq. 7. The module size is 1480 mm × 670 mm and there are a total of 48 panels in the AV structure. So, A_m is taken as 47.86 m^2 for 12 panels.

$$\eta_{sys,m} = \frac{E_{AC,m}}{H_t \times A_m} \times 100 \tag{7}$$

where $\eta_{sys,m}$ = Monthly system efficiency (%), $E_{(AC,m)}$ = Total monthly AC energy output (kW h), H_t = Total in-plane solar insolation (kW h/m^2), A_m = Total area (m^2).

Performance parameters described above have been evaluated from the measured power generation data of the installed SPV power plant during the total experimental period.

The land equivalent ratio (LER) is a productivity indicator of the land that is used to determine the worth of mixed cropping systems. (Dupraz et al. 2011) An AV system's LER is described as Eq. 8.

$$\text{LER} = {}^{Y_{\text{cropin AV}}}\!/_{Y_{\text{monocrop}}} + {}^{Y_{\text{electricity AV}}}\!/_{Y_{\text{electricity PV}}} \tag{8}$$

where $Y_{\text{cropin AV}}$ = Total crop yield from AV system (kg), Y_{monocrop} = Total monocrop yield (kg), $Y_{\text{electricity AV}}$ = Total electricity generation from AV system (kWh), $Y_{\text{electricity PV}}$ = Total electricity generation from the conventional photovoltaic system (kWh).

Tomatoes have been chosen for production in this proposed study because they are a shade-tolerant crop. Building an AV system in India and evaluating its techno-economic feasibility to attain the highest benefit–cost ratio and shortest payback period is the main objective of the research. To fulfill the objective of the work, researchers chose four different land treatments like silver-black mulch in a raised bed (25 mm), a raised bed without mulch, a flat bed with drip irrigation and control, and a flatbed without a leak. This proposed work has a pole-mounted structure and these poles pose a barrier to the uniform flow of water over the field, so researchers did not opt for sprinkler watering system treatment.

The experimental study included eight treatment combinations and had been set up using a split-plot design with four replications. Table 5 shows that two different types of environments and four different types of land treatments have been selected for the study. Fertilizer is given in the recommended dosage.

(A) Primary Factor:

1. AV crop cultivation (S_1)
2. Open field crop cultivation (S_0)

(B) Land treatment measures.

Silver-black mulch in a raised bed (25 mm) (T_1)
A raised bed devoid of mulch (T_2)
A flat bed with drip irrigation (T_3)
Control, using a flatbed without a leak (T_4)

(C) No. of Replications: 4 (R_1 to R_4).
(D) Total No. of observations: 32.

For this investigation, a split-plot experimental design has been adopted. Figure 3 displays the precise experimental design of multiple treatments and replication plots.

Details of crop cultivation.

Table 5 Treatment combinations

S_1T_1	AV crop cultivation: raised bed with silver black mulch
S_1T_2	AV crop cultivation: raised bed without mulch
S_1T_3	AV crop cultivation: flat bed with drip irrigation
S_1T_4	AV crop cultivation: control (farmer's method)
S_0T_1	Open field crop cultivation: raised bed with silver black mulch
S_0T_2	Open field crop cultivation: raised bed without mulch
S_0T_3	Open field crop cultivation: flat bed with drip irrigation
S_0T_4	Open field crop cultivation: control (farmer's method)

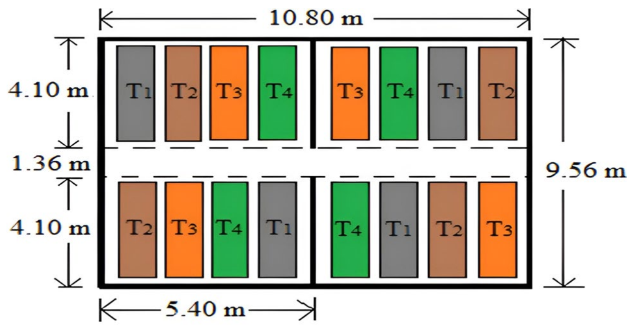


Fig. 3 Crop plantation layout in each environment

(a) Variety: Gujarat Tomato-1 (GT-1)
(b) Season: pre-winter and winter
(c) Date of sowing the Tomato seeds: 06/08/2017
(d) Date of Transplanting: 06/09/2017
(e) Bed spacing: 1.40 top width: 0.65 bottom width: 0.70 m, height: 0.20 m
(f) Plant spacing on a bed (PP × RR): 0.45 m × 0.60 m
(g) No. of rows per bed: 2 (Zig-Zag)
(h) Plot size: 1.40 m × 4.10 m

The AV structure's life has been estimated to be 25 years. (Sodhi et al. 2022) The drip has been estimated to have a 10-year lifespan. The interest rate has been taken as a 9% on capital investments (Sharma et al. 2016). For an SPV power plant, the maintenance cost percentage is 2%, while it is 5% for the drip irrigation system.

Environmental parameters: Measurements of the various environmental variables, such as solar air temperature, relative humidity, and solar radiation, have been made during the study period at intervals of two hours and analyzed from 0:00 to 24:00 h. Instruments used for the measurement of different parameters are enlisted below with specifications:

1. Hobo data logger fixed at five feet above the ground for measurement of air temperature, RH and Light intensity with least count of 0.001˚C, 0.001%, 0.1 lx accordingly.
2. Solari meter for measurement of solar radiation having the least count of 1.0 W/m^2.

Economic indicators: The production cost of the AV system has been calculated using the following Eq. 9.

Production cost:

$$PC = FC + MC - SSV \tag{9}$$

where FC = Fixed cost (INR/area), MC = Maintenance cost (INR/area), OC = Operational cost (INR/area), SSV = Seasonal salvage value (INR/area).

The fixed cost of the AV system has been calculated using formulae 10.

$$FC = AC \tag{10}$$

Here,

$$AC = CRF_{AVI} \times CI_{AVI}$$

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1}$$

$$CRF_{AV} = \frac{0.09(0.09+1)^{25}}{(0.09+1)^{25} - 1} = 0.102$$

where AC = Annual cost, CRF = Capital recovery factor, CI = Capital investment, n = Life of AV structure (25 years), i = Rate of interest (9% on CI for AV structure).

The maintenance cost of the AV structure during crop season has been considered as 2% of the fixed cost of the AV structure. The maintenance cost of the AV structure has been calculated using Eq. 11. The seasonal salvage value of the AV structure has been calculated separately by using Eq. 12.

Maintenance cost of AV structure.

$$MC_{AV} = 0.02 \times FC \tag{11}$$

$$SSV = ASV \tag{12}$$

Here, $ASV = SFF_{AV} \times SV_{AV}$

$$SSF_{AV} = \frac{1}{\left[(i+1)^n - 1\right]}$$

$$SV_{AV} = 0.25 \times FC$$

where ASV = Annual salvage value, SFF = Salvage fund factor, SV = Salvage value (AV structure = 0.25 × CI_{AV}).

The gross revenue has been calculated based on the prevailing average market price of the product and total production obtained per unit area. The benefit–cost ratio is obtained when the present worth of the benefit has been divided by the present worth of the cost. This ratio is a measure of the project's worth to accept a project for a benefit–cost ratio of 1 or greater. BCR has been calculated using Eq. 13.

$$\text{Benefit} - \text{Cost Ratio} = \frac{\sum_{t=1}^{t=n} B_t}{\sum_{t=1}^{t=n} C_t} \tag{13}$$

where B = Total benefit (INR), C = Total cost (INR).

The payback period of the AV system has been calculated from the ratio of the total cost of structure to the profitable electricity cum crop production from it. The payback period has been calculated using Eq. 14.

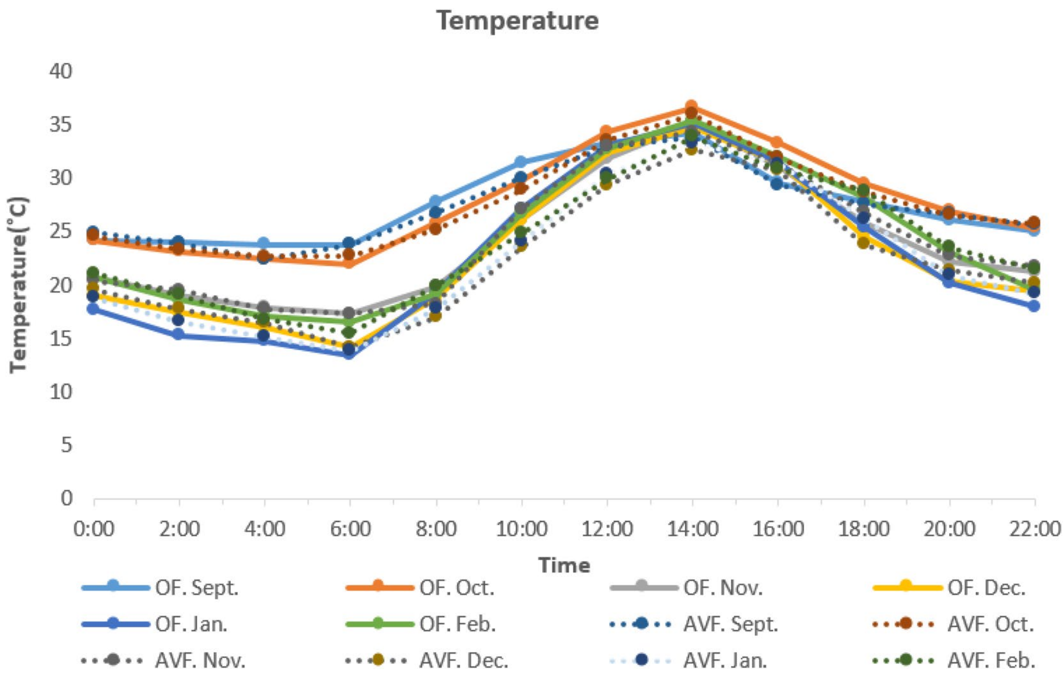
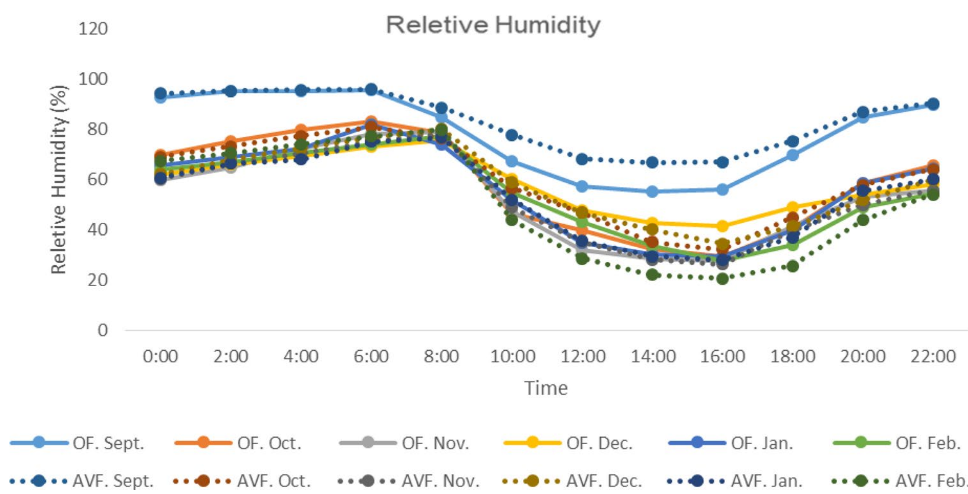


Fig. 4 Weekly hourly average temperature (˚C) for different months

Fig. 5 Weekly hourly average RH (%) for different months



$$\text{Payback period (yr)} = \frac{\text{Capital Investment (INR)}}{\text{Net Profit (INR/yr)}} \tag{14}$$

Results & discussion

The average temperature inside an agricultural photovoltaic system stays up to two degrees lower than that of an open field during the day, and vice versa at night as shown in Fig. 4. Similarly relative humidity has been found 8 to 10% higher in AV systems during the experimental period as shown in Fig. 5. The reduction in monthly average highest solar radiation under AV structure of shadow area for September has been observed about 55.12%, whereas for October, November, December, January, and February, it has been 77.20%, 77.11%, 75.66%, 76.52%, and 77.38% respectively as shown in Fig. 6. Monthly average solar radiation in the open field is shown in Fig. 7.

Figure 8 depicts an image of the shadow cast by PV panels in an AV system at 9:00, 12:00, 15:00, and 18:00. The crop beneath the AV construction received consistent sunlight throughout the day, as seen by the continuous movement of the shadow cast by the solar panels on the ground because it is designed in the manner of chessboard. The morning shadow cast by panels does not stay in the same

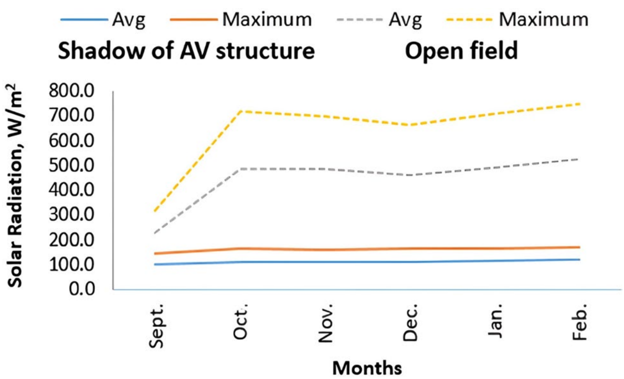


Fig. 6 Weekly hourly average Solar Radiation (W/m^2) for different months

spot at noon or night. Similar to how morning and noontime shadows of panels change location, evening shadows do not.

The total amount of energy produced has been expressed in kWh and measured using Eq. 1. Figure 9 displays the monthly energy output determined for the experimental period. The entire energy output for the year 2017–18 (Sept. 17-0ct.18) is measured by Eq. 2. A total of 12,667.15 kWh of energy is generated from the 7.2 kW solar power plant. The energy generation has been higher in summer as compared to other seasons due to high solar radiation in the summer season.

The proposed cultivation period has been completed in 165 days. For statistical analysis of crop parameters, a two-factor completely randomized design has been used in the proposed experiment. The performance ratio is the ratio of the final yield (YF) to the reference yield (YR). The full system's losses are represented when converting a DC rating to an AC output. PR typically ranges from 0.6 to 0.8, depending on the region, amount of sun exposure, and weather. This investigation's results for the performance ratio, capacity factor, and system efficiency have been strikingly similar to those of previous research (Sharma and Chandel 2013) as shown in Table 6. The average system efficiency during the experimental period, i.e., September'17 to August'18 has been found as 11.22%. All the performance parameters have been calculated using Eqs. 3, 4, 5, 6, 7.

Two factorial completely randomized design (FCRD) is used to evaluate the effect of different environments and treatments on crop parameters. For various treatment combinations, the total crop yield from each treatment and the crop yield per unit area are shown in Table 7.

The findings presented in Table 8 demonstrated that the environment had a significant impact on the quantity of fruits produced per plant. Due to various treatments, there have been noticeable changes in the amount of fruits per plant. The impact of various treatments and the environment on the quantity of fruits produced by a plant has been determined to be nonsignificant.

The findings in Table 8 showed that the environment had a significant effect on each fruit's weight. Due to various treatments, as shown in Table 8, there have been significant weight disparities between each fruit. It has been found that there has been no appreciable interaction between the various treatments and settings on the weight of the fruit. The findings in Table 8 showed that the environment had a significant impact on fruit diameter. Due to various treatments, as shown in Table 8, there have been noticeable changes in the diameter of the fruit. The effects of various treatments and environments combined on fruit diameter have been determined to be insignificant.

The findings in Table 8 showed that the environment had a considerable impact on crop productivity. Because of the various treatments described in 8, there have been noticeable variances in the weight of the fruits per plant. It has been discovered that the interactions between various treatments and environments had no meaningful impact on crop yield.

Fig. 7 Monthly available solar radiation in open field throughout year

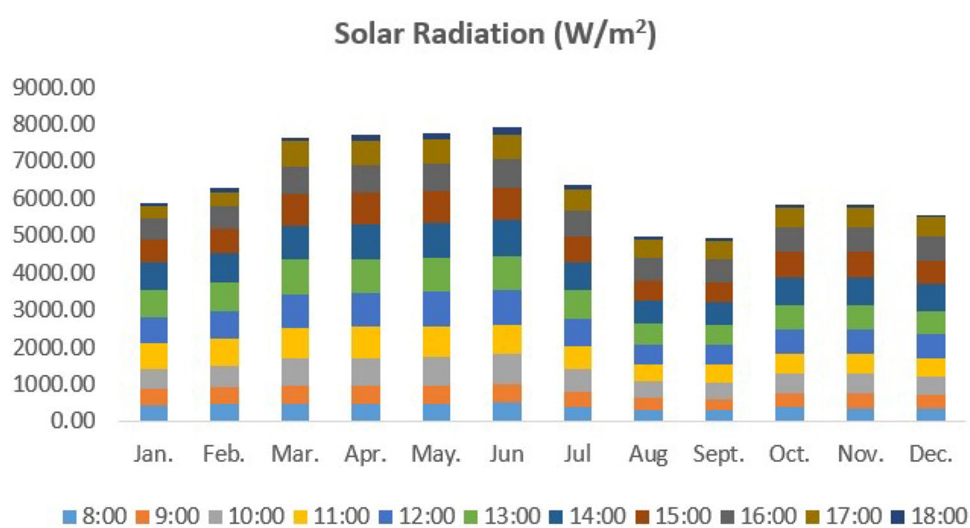


Fig. 8 Movement of shadow over the day during crop growth

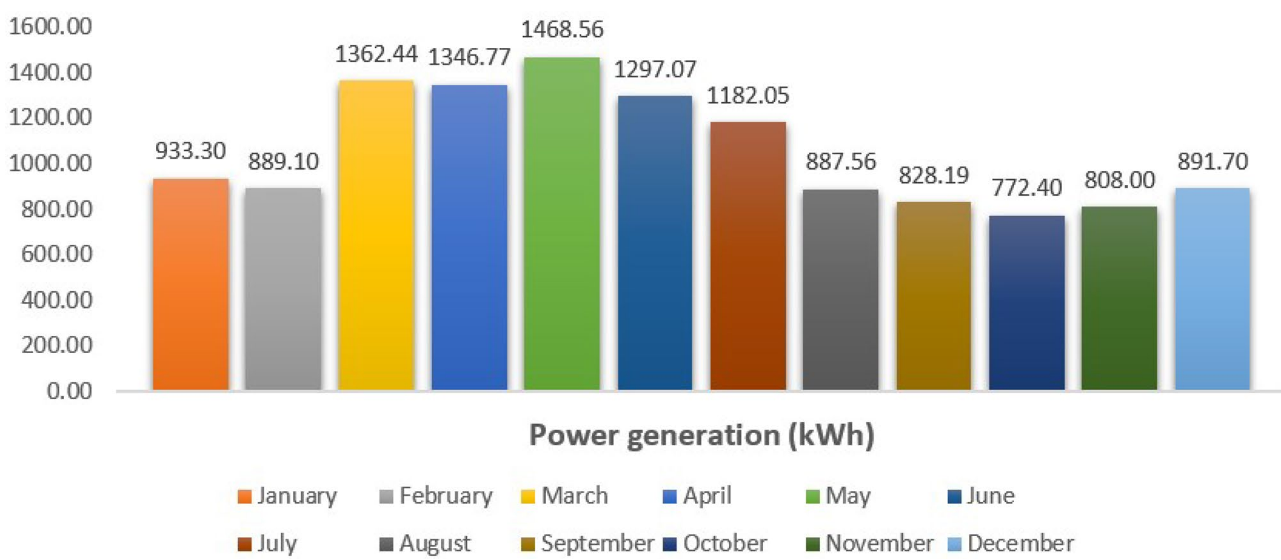


Fig. 9 Monthly energy generation for September 2017 to August 2018 from AV structure

The morphological parameter of the tomato crop in terms of height growth day after transplanting (DAT) in different treatments is given in Fig. 10. The crop yield under AV structure has been observed to be higher than open field cultivation by 15.09% for T_1, 11.95% for T_2, 9.54% for T_3, and 6.98% for T_4 treatment. The findings have been obtained in close agreement with previous research (Abhivyakti et al. 2016). The chessboard pattern-type design of solar power

Table 6 Final yield, irradiation, and reference yield for September 2017 to August 2018

Months	Final yield (h/d)	Irradiation (kW/m^2/day)	Reference yield (h/d)	Performance ratio	Capacity factor (%)	Efficiency (%)
January	4.18	5.89	5.89	0.71	17.42	10.74
February	4.41	6.27	6.27	0.70	18.38	10.64
March	6.10	7.63	7.63	0.80	19.81	11.71
April	6.24	7.70	7.70	0.81	20.00	12.20
May	6.58	7.74	7.74	0.85	21.53	12.41
June	6.00	7.90	7.90	0.76	20.00	11.55
July	5.30	6.38	6.38	0.83	12.92	12.20
August	3.98	4.97	4.97	0.80	10.76	11.71
September	3.83	4.92	4.92	0.78	11.25	11.82
October	3.46	5.83	5.83	0.59	14.41	8.97
November	3.74	5.82	5.82	0.64	15.58	9.72
December	3.99	5.54	5.54	0.72	16.65	10.96
Overall	4.82	6.38	6.38	0.75	16.56	11.22

Table 7 Tomato crop yield from each harvest

	S_1 (kg)				S_0 (kg)			
	T_1	T_2	T_3	T_4	T_1	T_2	T_3	T_4
Total	137.03	118.70	111.26	82.74	119.06	106.02	101.57	77.31
Yield per unit area (kg/m^2)	5.96	5.17	4.84	3.60	5.18	4.61	4.42	3.36

Table 8 Statistical performance of tomato crop

Treatment	Number of fruits per plant	Fruits weight (g)	Fruits diameter (mm)	Yield (t/ha)
S_0T_1	71.50	37.94	45.28	51.86
S_0T_2	64.76	31.26	43.41	46.18
S_0T_3	62.72	30.74	42.08	44.24
S_0T_4	58.42	24.27	40.31	33.68
S_1T_1	82.44	39.45	47.79	59.69
S_1T_2	72.28	33.09	44.78	51.70
S_1T_3	74.88	32.43	43.28	48.46
S_1T_4	66.63	26.28	41.76	36.03
Environment (S)				
S.Em. ±	0.50	0.19	0.31	0.57
C.D. at (5%)	2.26	0.85	1.42	2.55
C.V. (%)	2.90	2.36	2.89	4.87
Treatment (T)				
S.Em. ±	2.40	0.18	0.19	1.19
C.D. at (5%)	7.13	0.53	0.57	3.53
C.V. (%)	9.81	1.57	1.25	7.24
Interaction ($S \times T$)				
S.Em. ±	3.39	0.25	0.27	1.68
C.D. at (5%)	NS	NS	NS	NS

*C.D. = Critical Difference, C.V. = Coefficient of Variance, S.Em. = Standard Error of Difference

plant permits enough solar radiation under it for good crop cultivation and also behaves as a partial barrier to the harmful direct UV radiation for the crop which has positively reflected on the vegetative and yield parameters. Consequently, the use of chessboard pattern-type solar photovoltaic power plants as AV structures on farms increased the yield of tomatoes.

Usually, mixed cropping systems have LERs between 1.0 and 1.3, while agroforestry systems have LERs between 1.1 and 1.5. An LER of 1.5 means that, by adopting a mixed system, the production of a 1.0 ha farm is as high as the production of a 1.5 ha farm with separate productions. LER has been calculated using Eq. 8.

Here, $Y_{\text{electricity AVI}}/Y_{\text{electricity PV}} = 0.5$ for half density of solar panel.

$\text{LER} = Y_{\text{cropin AVI}}/Y_{\text{monocrop}} + Y_{\text{electricity AVI}}/Y_{\text{electricity PV}}$.

For S_1T_1 treatment = $59.86/51.69 + 0.5 = 1.65$.

For S_1T_2 treatment = $51.70/46.18 + 0.5 = 1.61$.

For S_1T_3 treatment = $48.46/44.24 + 0.5 = 1.59$.

For S_1T_4 treatment = $36.03/33.68 + 0.5 = 1.56$.

Here, the LER for T_1, i.e., Raised bed with silver black mulch under AV system has been found highest, i.e., 1.65 followed by T_2 (1.61), T_3 (1.59) and lowest 1.56 for T_4 treatment (Control or farmer's method). This indicates as

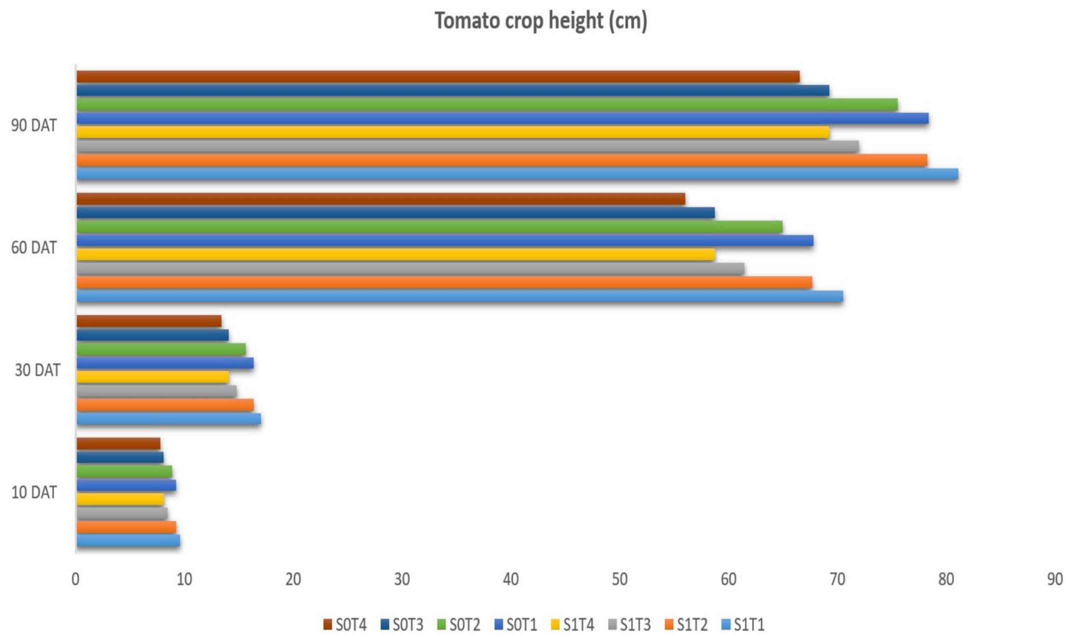


Fig. 10 Height of tomato crop day after transplanting in different treatments

Table 9 The details of capital investment for chessboard-type AV structure

Components of SPV	Quantity	Price	Total (INR)
CRC (yst310) square pipe	2461.70 kg	40 INR/kg	98,468
Structure foundation and Installation	–	50,000	50,000
Solar panels	48.00 N	3300 INR/panel	158,400
Solar panel Installation	–	12,000 INR	12,000
Inverter battery 150 ah	3	13,000 INR	39,000
Hybrid solar inverter of 7.5 kVA with wiring	1.00 N	50,000 INR/panel	50,000
Total cost	407,868		

compared to an open field, productivity in this AV system has been enhanced in all treatments.

Without subsidies, the capital investment per unit area on an SPV power plant has been calculated to be 2650.46 INR/m^2. The fixed cost of the AV structure has been calculated using a 25-year life span of the structure as Eq. 10. The details of capital investment for chessboard-type AV structure are shown in Table 9. Table 10 shows the operational costs for tomato crop cultivation. The economics of tomato crop cultivation is shown in Table 11. The production cost of the AV system and tomato crop cultivation has been calculated as per Eq. 9. The labor calculation and detailed production cost as per Eqs. 9, 10, 11, 12 has been calculated in Appendix A. Equations 13 and 14 have been used to obtain the benefit–cost ratio and payback period. The sensitivity analysis of tomato crop price as per the national horticulture board in the last five years is given in Fig. 11 (NHB 2023). The revenue generated from solar power has been calculated using 3.50 INR/kW as per government policy called Kusum Yojana. (Kerala State Electricity Board Limited 2021).

AV systems maintain an internal temperature that is up to two degrees lower on average during the day than an open field, and the opposite is true at night. During the testing period, relative humidity has been observed 8 to 10% higher in AV systems. During the experimental period, 12,667.15 kWh of total energy has been produced. S_1T_1 treatment combination has the highest crop output, while S_0T_4 treatment combination produces the lowest crop yield. In comparison with open field agriculture, crop productivity under AV structures is higher in all treatments by 15.09%, 11.95%, 9.54%, and 6.98% respectively. The T_1 land equivalent ratio has been calculated at 1.65, whereas the T_4 land equivalent ratio under the AV system has been calculated at 1.56. The overall economic analysis of the AV system for different treatments is shown in Fig. 12. A comparative experimental study of the AV system with related research for validation purposes is given in Table 12.

Table 10 Operational costs for tomato crop cultivation

Different costs	T_1 (₹/m^2)	T_2 (₹/m^2)	T_3 (₹/m^2)	T_4 (₹/m^2)
Seedling cost	00.06	00.06	00.06	00.06
Soil treatment and manure cost	03.00	03.00	03.00	03.00
Cost of silver black mulch	00.85	–	–	–
Fertilizer cost	00.15	00.15	00.15	00.15
Pumping cost	04.30	04.30	04.30	05.73
Labour/supervision cost	02.18	03.12	03.06	05.14
Total	10.54	10.63	10.57	14.08

Table 11 Economics of tomato cultivation for different treatments

Treatment	Gross revenue (₹/m^2)			Production cost (₹/m^2)			Net profit (₹/m^2)	BCR	PBP
	Tomato	Solar energy	Total	Tomato	Solar energy	Total			
S_1T_1	156.99	116.51	273.50	11.18	94.47	105.65	167.85	2.59	7.90
S_1T_2	136.18	116.51	252.69	11.27	94.47	105.74	146.95	2.39	9.02
S_1T_3	127.49	116.51	244.00	11.21	94.47	105.68	138.32	2.31	9.58
S_1T_4	94.82	116.51	211.33	14.08	94.47	108.55	102.78	1.95	12.89
S_0T_1	136.44	0.00	136.44	11.18	0.00	11.18	125.26	12.20	
S_0T_2	121.43	0.00	121.43	11.27	0.00	11.27	110.16	10.77	
S_0T_3	116.42	0.00	116.42	11.21	0.00	11.21	105.21	10.39	
S_0T_4	88.50	0.00	88.50	14.08	0.00	14.08	74.42	6.29	

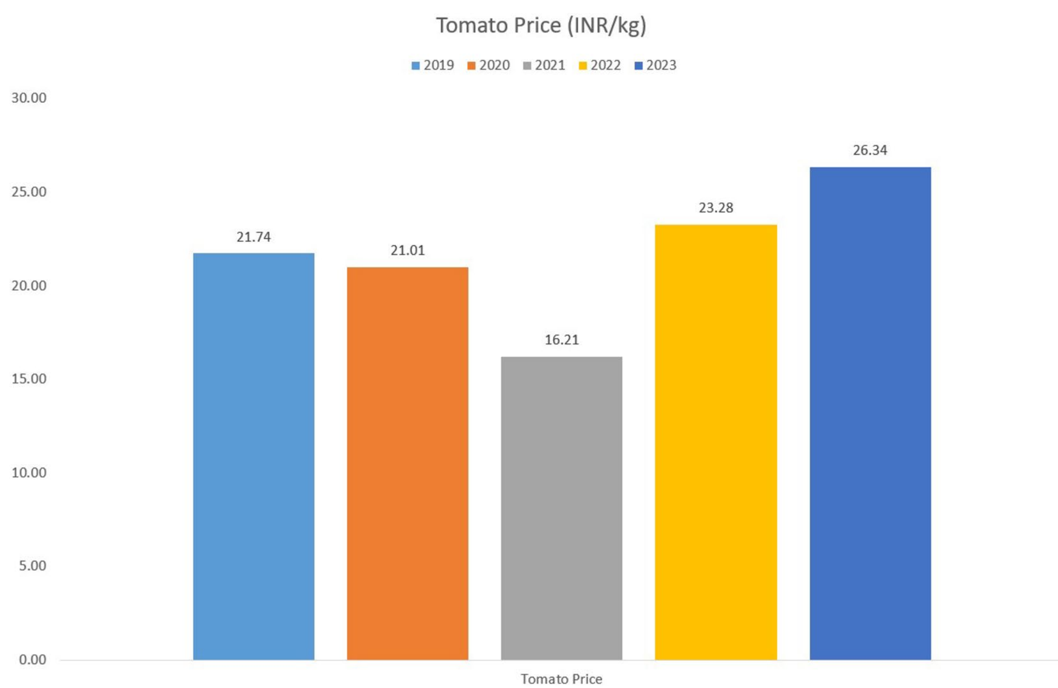


Fig. 11 Sensitivity analysis of tomato crop price as per national horticulture board

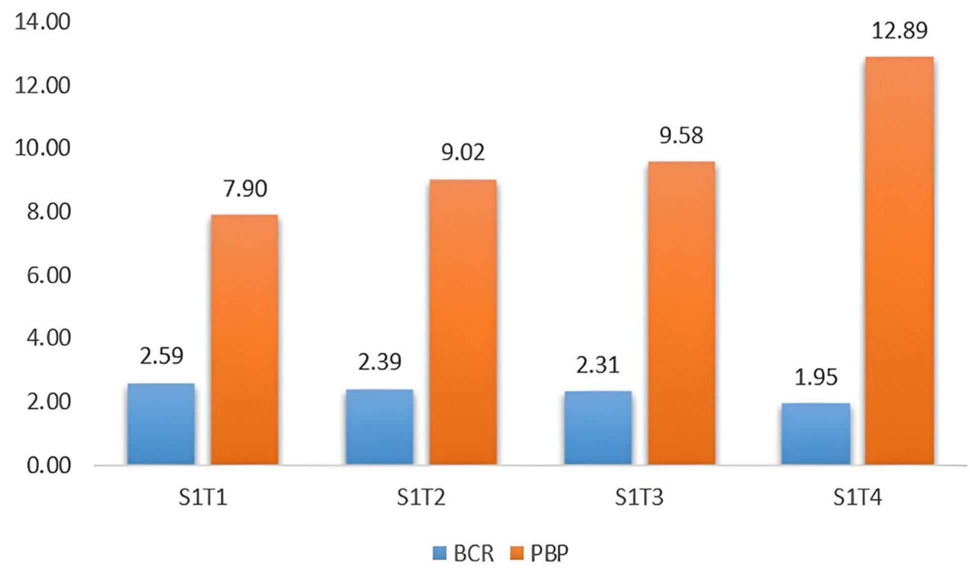


Fig. 12 Overall economic analysis of AV system for different treatment

Table 12 Comparative experimental study of AV system with related research

Year	AV configuration	Crop	Outcome	Country	Reference
2017	Chessboard-type half-density AV system	Tomato	LER of system is up to 1.65. BCR and PBP have been 2.59 and 7.90 respectively. Crop production is higher as compared to open field condition	Junagadh, India	Proposed work
2022	Fixed/three different design	Turmeric	The system's LER and payback period are 1.42 and up to 7.6 years, respectively. Additionally, under the same land use, the socioeconomic metrics of revenue, benefit–cost ratio, and price–performance ratio of turmeric are found to be 187.3 USD, 1.86, and 0.75, respectively	Odisha, India	Giri et al. (2022b)
2022	Fixed/bifacial AV plant	Blueberry	Comparing the E-W wing AV topology to conventional and separate food and energy production, the yield potential has been enhanced by 50% but electrical output has been decreased by 33%	Boston, USA	Katsikogiannis et al. (2022)
2022	Between solar photovoltaic array	Olive tree	The crop would not cover the solar panels because there is space between the collectors. According to this study, the LER for an AV system can rise from 28.9% to 47.2%	Córdoba, Spain	de la Torre et al. (2022)
2021	Fixed/EAS(even lighting AV system)	Lettuce	The EAS showed high LER (average 1.64) and crop quality levels comparable to those attained in a natural state	Hefei, China	Zheng et al. (2021)

Conclusions & recommendations

Agrivoltaic systems maintain an internal temperature that is up to two degrees lower on average during the day than an open field, and the vice versa at night. During the testing period, relative humidity has been observed 8 to 10% higher in agrivoltaic systems. S_1T_1 treatment combination had the highest crop output, while S_0T_4 treatment combination produced the lowest crop yield. In comparison with open field agriculture, crop productivity under AV structures is higher in all treatments by

15.09%, 11.95%, 9.54%, and 6.98% respectively. The T_1 land equivalent ratio has been calculated at 1.65, whereas the T_4 land equivalent ratio under the AV system has been calculated at 1.56. The treatment T_1 had the highest net profit and BCR under the AV system, measuring 167.85 INR/m^2 and 2.59, respectively, and the lowest payback period, 7.90 years, for this treatment without taking subsidies into account. A total of 12,667.15 kWh of carbon emission-free electricity is generated with an efficiency of 11.22% throughout the year.

Since energy demand is expanding due to population growth and the fact that fossil resources are depleting daily, agrivoltaic system is necessary for meeting future power needs. The aforementioned findings suggest that by utilizing agrivoltaic systems, we can generate food and energy efficiently, both of which are essential for human survival. The proposed study's land equivalence ratio of 1.65 indicates that one can produce 1.65 times more on the same area of land in India. The 15.09% increase in tomato output under agrivoltaic conditions compared to open field conditions can be considered as proof that agrivoltaic systems perform better in India than in previous experimental trials conducted worldwide. Agrivoltaic technology is better suited to achieving the UN's sustainable development goals, especially SDG 7 (Affordable and clean energy) and SDG 11 (Sustainable cities and communities). Researchers have to test agrivoltaics for more and more suitable crops for sustainable development.

Appendix: A

A1: Calculation of labor/supervision cost for different treatments

Operations	T_1 (per ha)		T_2 (per ha)		T_3 (per ha)		T_4 (per ha)	
	Labor × day	Man-days	Labor × day	Man-days	Labor × day	Man-days	Labor × day	Man-days
Making of raised bed	2 × 2	4	2 × 2	4	–	–	–	–
Making of furrow	–	–	–	–	–	–	2 × 2	4
Plowing	1 × 1	1	1 × 1	1	1 × 1	1	1 × 1	1
Mulch/drip laying	4 × 1/2	2	2 × 1/2	1	2 × 1/2	1	-	-
Sowing/transplanting	3 × 2	6	3 × 2	6	3 × 2	6	3 × 2	6
Weeding	–	–	2 × 24	48	2 × 24	48	2 × 24	48
Irrigation	–	–	–	–	–	–	2 × 48	96
Fertilizer application	–	–	–	–	–	–	2 × 3	6
Plant training	2 × 12	24	2 × 12	24	2 × 12	24	2 × 12	24
Harvesting	4 × 18	72	4 × 18	72	4 × 18	72	4 × 18	72
Total man-days	**109**		**156**		**152**		**257**	
Labour/supervision cost/m^2	**₹ 2.18/m^2**		**₹ 3.12/m^2**		**₹ 3.06/m^2**		**₹ 5.14/m^2**	

A2: Cost analysis of tomato crop cultivation under AV structure without consideration of subsidy

(i)	Production cost	
	$PC = FC + MC + OC—SSV$	
(ii)	Fixed cost of AV structure	Fixed cost of drip system
	$FC = AC/2.0$	$FC = AC/2.0$
	$AC = CRF_{AV} \times CI_{AV}$	$AC = CRF_{drip} \times CI_{drip}$
	$CRF_{AV} = \frac{0.09(0.09+1)^{25}}{(0.09+1)^{25}-1} = 0.102$	$CRF_{drip} = \frac{0.09(0.09+1)^{10}}{(0.09+1)^{10}-1} = 0.156$
	$CI_{AV} = 2650.46$ ₹/m^2	$CI_{drip} = 17$ ₹/m^2
	$AC_{AV} = 0.102 \times 2650.46 = 270.35$ ₹/m^2	$AC_{drip} = 0.156 \times 17 = 2.65$ ₹/m^2
	Hence, $FC_{AV} = 270.35/2.0$ $= 135.17$ ₹/m^2	Hence, $FC_{drip} = 2.65/2.0$ $= 1.32$ ₹/m^2
	Total FC = 135.17 + 1.32 = 136.49 ₹/m^2 for	
(iii)	Maintenance cost of AV structure	Maintenance cost of drip system
	$MC_{AV} = 0.02 \times FC$ $= 0.02 \times 135.17$ ₹/m^2	$MC_{drip} = 0.05 \times FC_{drip}$ $= 0.05 \times 1.32$ ₹/m^2
	$= 2.70$ ₹/m^2	$= 0.06$ ₹/m^2
	Total MC = 2.70 + 0.06 = 2.76 ₹/m^2	
(iv)	Seasonal salvage value of AV structure	Seasonal salvage value of drip system
	$SSV_{AV} = ASV_{AV}/2$	$SSV_{drip} = ASV_{drip}/2$
	$ASV_{AV} = SFF_{AV} \times SV_{AV}$	$ASV_{drip} = SFF_{drip} \times SV_{drip}$
	$SFF_{AV} = \frac{1}{[(0.09+1)^{25}-1]} = 0.131$	$SFF_{drip} = \frac{1}{[(0.09+1)^{10}-1]} = 0.73$
	$SV_{AV} = 0.25 \times 2650.46 = 662.62$ ₹/m^2	$SV_{drip} = 0.12 \times 17 = 2.04$ ₹/m^2
	$ASV_{AV} = 0.131 \times 662.62 = 86.80$ ₹/m^2	$ASV_{drip} = 0.73 \times 2.04 = 1.49$ ₹/m^2
	Hence, $SSV_{AV} = 86.80/2 = 43.40$ ₹/m^2	Hence, $SSV_{drip} = 1.49/2 = 0.74$ ₹/m^2
(v)	Production cost	
	For tomato	For solar energy
	For S_1T_1 PC = 1.32 + 0.06 + 10.54–0.74	For S_1T_1, S_1T_2, S_1T_3 and S_1T_4
	For S_1T_1 PC = 11.18 ₹/m^2	PC = 135.17 + 2.70–43.40 = 94.47 ₹/m^2
	For S_1T_2 PC = 1.32 + 0.06 + 10.65–0.74	
	For S_1T_2 PC = 11.27 ₹/m^2	
	For S_1T_3 PC = 1.32 + 0.06 + 10.57–0.74	
	For S_1T_3 PC = 11.21 ₹/m^2	
	For S_1T_4 PC = 14.08 ₹/m^2	

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Author contribution All authors contributed to the study's conception and design. Material preparation, data collection, and analysis have been performed by UP and GG. The first draft of the manuscript has been written by UPatel and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available on request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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