

Research paper

Development of agrivoltaic insect net house to enhance sustainable energy-food production: A techno-economic assessment

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ARTICLE INFO

Keywords:

Agrivoltaics
Insect net house
Sustainable energy and food production
Structural analysis

ABSTRACT

Agrivoltaics (AV) systems are the simultaneous land utilization for sustainable energy and food production. However, AV may not be suitable for some crops that require rigorous pest management. This study has applied an innovative approach, combining AV with an insect net house to cultivate capsicum. The 1.8 kW AV system has been installed at a 3-m elevation to facilitate unrestricted tractor manoeuvrability for various farming operations. The structure can withstand winds as high as 140.4 km/h. The system has a 3,612-kWh energy capacity and a 51.41 kg food production capacity. The system's energy and food conversion efficiency are 14.09 % and 154.8 %, respectively, compared to the traditional systems. Economic metrics like a 2.20 benefit-cost ratio and a 9.39-year payback period have been included in the findings. Further, the land equivalence ratio is 1.97, indicating a better system than traditional AV and agriculture approaches.

1. Introduction

Researchers have observed a substantial increase in investments in sustainable energy as economies recover from the pandemic and to handle the worldwide shortage of energy. Compared to 2021 statistics, annual investments in renewable energy have shown significant growth compared to investments in fossil fuels (24 % versus 15 %) in 2023 [1]. Projections indicate that the energy sector will see a total investment of 2.8 trillion USD by 2023. Funding for clean energy, which includes nuclear power, power storage, grids, low-emission fuels, and efficiency enhancements, amounts to over 1.7 trillion USD [1]. Fossil energy and electricity will get just over \$1 trillion in funding, of which coal will make up 15 %, and gas and oil for the remaining. The proportion of fossil fuel investments to those made in renewable, green energy is 1.7:1, marking a shift from a 1:1 ratio just five years ago [1]. Several factors have contributed to this surge in renewable energy investments. Among these are improved economics in the context of fluctuating fossil fuel costs and increased efforts in Europe, Japan, China, and other regions. Goals for energy security and the environment are closely aligned, especially in economies that depend heavily on imports. It is projected

that over 90 % of the entire investment in energy generation will go towards low-emission power by 2023–24 [1]. Solar energy stands out, with over USD 1 billion per day anticipated to be made in energy from sun in 2023, surpassing spending on upstream oil for the first time [1]. China and the European Union are leading the world in annual clean energy investments, as depicted in Fig. 1.

Most clean energy investments are directed towards the solar energy sector and electric vehicles. Key components of the solar energy sector include solar power plants, off-grid systems, pumping systems, rooftops, etc. However, the installation of a large number of solar plants requires more land than conventional power plants. To address these land issues AV systems are being introduced as an emerging technology worldwide.

Agrivoltaic systems are being investigated to optimize the application of agricultural land and combine crop production with the generation of solar energy from the same piece of land [2]. Standard agricultural machinery can be used beneath the PV modules which are elevated to a certain height above the earth's surface. When building photovoltaic facilities technical adjustments can be made to retain as much as 60–70 % of the Photovoltaic active radiation (PAR) that reaches the plants below the AV [3,4]. This approach allows for a simultaneous

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<https://doi.org/10.1016/j.rineng.2024.103228>

Received 29 July 2024; Received in revised form 1 October 2024; Accepted 23 October 2024

Available online 24 October 2024

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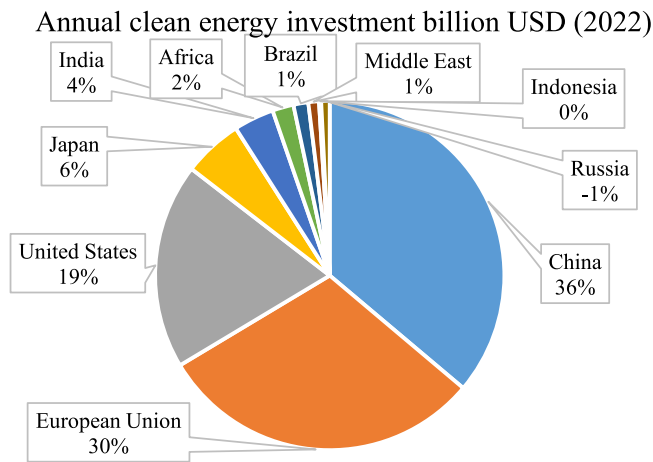


Fig. 1. Annual clean energy investment throughout the world.

increase in land productivity and farm revenue by achieving sufficient power yields [5]. Evaluating the suitability of AVs in agricultural systems necessitates an examination of how they affect microclimatic conditions and crop yields. Nevertheless, there is a shortage of scientific literature investigating AVs' influence on agricultural yields in the context of microclimatic variations [2]. Although AV systems research has mainly focused on modelling and simulations, there is still a dearth of real-world experimental data accessible for analysis [6,7].

Agrioltaic systems have been used to cultivate a variety of lettuce cultivars in one of the few studies carried out with actual field trials. The findings showed that the harvestable yields had not been significantly impacted by the photovoltaic modules above despite the results changing according to the particular lettuce cultivar and the spacing between these modules [8]. In the semi-shaded area near the AV facility, there has been a decrease in water loss due to evapotranspiration [9]. Other microclimatic parameters, such as humidity and air temperature, have not changed much except for reduced solar radiation and soil temperature in the presence of AV [10]. The primary method for evaluating the effects of AV is modelling research, except for specific crops like maize and lettuce, as shown by the study conducted in 2019 [11]. Furthermore, studies of horticultural crops such as cherry tomatoes and chiltepin peppers also provide insights beyond modelling study [12].

Through simulations using a 40-year climate dataset, researchers found that non-irrigated conditions increased maize grain yields when employing AV. Grain yields experienced a decline when subjected to irrigation [13]. Conversely, researchers have determined that a 20 % reduction in sunlight exposure would correspond to a 20 % decline in rice production outputs [14]. Studies in artificial or organic shading environments like those in agroforestry systems can offer essential insights because crop production under AV is anticipated to be primarily limited by reduced solar radiation [15,16]. Depending on the strength and timing of applying shade, winter wheat has exhibited grain production reductions of up to 50 % [17]. However, it's important to remember that mild shadowing has been shown to boost wheat grain yields [18]. Concerning potatoes comparable findings have been shown with increased shading leading to reductions in tuber quantity and overall tuber yields [19]. However, shading had been observed to boost potato tuber yields in places with higher solar exposure when applied during specific developmental periods or times of the day [20]. Grass crops respond to shade more differently than other crops, exhibiting both increases and declines in output, highlighting the significance of the kind of plant under study and the local climate [21]. The majority of this research uses shade via netting structures, which results in differences in microclimatic conditions and shading patterns, which has limited the application of the results [2]. Simultaneously, a socio-techno-economic assessment has been carried out to develop a

suitable sustainable energy system for remote agricultural areas in developing nations with the result that people can use their farming land to eliminate their reliance on LPG for cooking and electricity for energy [22].

Another study is going on spectral-splitting concentrator agrivoltaics (SCAPV), which may efficiently absorb extra light energy from photosynthetic processes for solar power generation without affecting plant production. SCAPV reflects the remaining light spectrum to produce power while transmitting a specific light spectrum for plant development. According to field tests, SCAPV may reduce plant heat dissipation by around 50 % and increase plant biomass by 13 %. Meanwhile, SCAPV has the most excellent solar energy efficiency at 9.9 %. The total efficiency of solar energy conversion exceeds the photosynthesis's theoretical limit [23].

Collaborative production occurs when photovoltaics manage greenhouse temperature, humidity, and light intensity. A solar system installed on a greenhouse roof is one example of this [24]. In one study, researchers looked at how solar radiation distribution in greenhouses affected petunias and berries' growth. Flexible and permanent photovoltaic panels use 20 % of the rooftop space. No statistically significant difference exists between the plant growth rates in the controlled plots and greenhouses and those in the non-photovoltaic greenhouse. However, there has been a difference in the greenhouses' lowering of solar radiation intensity [25]. Another group of researchers looked at the effects of having flexible solar cells shade rooftops on tomatoes' crop output and physical traits, comparing them to tomatoes grown in a greenhouse culture. In terms of their morphological characteristics or yields, no statistically significant changes had been found after 193 days between the tomatoes from solar greenhouses and open fields. Tomatoes produced in the PV greenhouse had a 0.3 brix greater total soluble solids content than tomatoes grown in the control plots [26]. Another researcher studied the distribution of humidity, temperature changes, and sun light inside a PV greenhouse. Half of the roof of this greenhouse is covered with solar panels a total of 68 kWp in capacity. These solar panels reduced the intensity of sun light on the rooftop by 64 %. It has been observed that solar radiation has stronger on the sidewalls of the greenhouse and weaker in the central area. However, during the winter season there has been no significant difference in solar intensity between the rows of plants. As a result, to choose the best cropping pattern and design of PV greenhouse the distribution of solar radiation has been analysed [27].

Field tests are necessary to gather reliable information on how AV technology affects crop productivity in different locations. Table 1 displays the outcomes of experimental studies performed by various nations under different environmental conditions and with various AV specifications. Most of the experimental work has been carried out in European and Asian countries.

Simultaneously, according to the Information from the Energy Administration's (EIA) 2022 report in the United States, utility-scale electric power plants with a minimum capacity of 1 MW generated roughly 4.11 trillion kWh of electricity from various energy sources in 2021. This activity released an estimated 1.65 to 1.82 billion Mt (metric tons) of carbon dioxide (CO₂) emissions. This equates to approximately emission of 0.371 kg of CO₂ per kWh of electricity [28]. As a result, this research can help to achieve the following SDGs: SDG 7 ("Clean Energy") by reducing carbon emissions through the generation of clean and sustainable energy, SDG 8 ("Decent Work and Economic Growth") by providing farmers with a dual income stream and SDG 13 ("Climate Action") by reducing carbon emissions.

Conventional AV and AV with greenhouse systems have a few disadvantages. These are (1) normal AV cannot control microclimate, which reduces crop productivity; (2) normal AV fails to control pests and insects, which further reduces crop output, and (3) AV with greenhouses is the only realistic option for microclimate control, but it can be prohibitively expensive for small-scale farmers. To overcome these challenges, an innovative AV integration solution termed an AV insect net

Table 1

The output of experimental research conducted by different nations under different specifications of AV systems.

Reference	Country/ Year	Specification of AV system	Crops	Findings
[2]	Germany/ 2021	Distance between rows: 9.5 m (2.8 times the width of the module row) 5.5 m/8 m (open area facing the work/top edge).	Celery	Under panels, crop height increased by 14 % but bulk yield dropped by 18.9 % in 2017 While crop height and bulk yield increased by 30.6 % and 11.8 % respectively in 2018.
[29]	South Korea/ 2021	5.42 m in height, with 32 %, 25.6 % and 21.3 % shading rates.	Mung bean, Sesame, corn, soybean and kidney bean	Shade reduced yields of sesame, soybean, mung beans, and kidney beans by 7 %, 13 %, 21 % and 26 % respectively at 21.3 % shading. Sesame production dropped by 53 % at 32 % shading and 30–44 % for other crops whereas Maize yields increased by 6 % at 25.6 % shading.
[30]	Spain/ 2021	5 m height, 27° tilt and 9.5 m spacing between supported structures.	Potato is alternated with oilseed rape, onion, faba bean and fodder maize. dry pea, tomato, melon, onion and carrot	Crop yields have been reduced for Carrot, maize, melon, rape, onion, dry pea, potato and tomato by 10 %, 17 %, 7 %, 20 %, 6 %, 23 %, 15 % and 5 % respectively under shade.
[31]	South Korea/ 2022	3.3 metre in height, 1.5 m spacing between rows and Shading at a 30 % rate.	Forage crops: rice, onion, garlic, rye, soybean, bean and maize	Underneath the panels, rice plant and fodder crop height has gone up by 3.8 cm and 7.4 m respectively. Rice production decreased by 18.7 % in 2018 and 8.9 % in 2019, while bean and soybean production decreased by 73.3 % and 68.7 %, respectively, while onion and garlic output decreased by 14.6 % and 18.7 %.
[32]	South Korea/ 2022	Structure's height is between 4 and 5 metres.	Potato, soybean, sesame and rice	Except for sesame no effect on growth. Potato yields have been reduced by 3 %, sesame by 19 %,

Table 1 (continued)

Reference	Country/ Year	Specification of AV system	Crops	Findings
[33]	Italy/ 2022	Height between 4 and 4.5 metres There are 12 metres between each row of tracker panels. There are four treatments applied: 27 %, 16 %, 9 % and 18 % shade.	Soybean	soybean yields by 18–20 %, and rice yields by 13–30 %. The plant lengths were recorded under panels at 9 % shade (98.25 cm), 27 % shade (90.81 cm), 18 % shade (86.95 cm), and 16 % shade (87.8 cm). The study found that grain production increased by 4.4 % in 16 % of shaded treatments compared to sun light conditions, but decreased in the rest of the treatments.
[34]	India/ 2022	The SPV structure's bottom and upper edge heights has been 0.46 m and 1.68 m accordingly. The distance between rows have been 0 .65m.	Turmeric	Increased food and energy output. The payback period has been 9.49 years, with a 1.73 LER.

house is required. It serves the dual purpose of an AV and an insect net house system. However, no research has been conducted on AV insect net house systems.

This research aims to replace conventional insect net houses with more reliable AV insect net houses and examine how this facility affects crop output and microclimate conditions in India. AV insect net house is a workable plan to achieve self-sufficiency, increase electricity independence from fossil fuels and supporting sustainable development goals. The study has been conducted at the Junagadh agricultural university's research farm to test the technology under realistic circumstances. The significant contributions of our research in this context are:

1. Innovative AV insect net house system for enhancing energy-food production.
2. Elevated structure for better agricultural activities on the same land use.
3. Chessboard pattern of the solar panel configuration is used for maximum energy harvesting, resulting in better techno-economic performance of the AV insect net house.

As per the experimental output, both medium and large-scale AV insect net houses can be adopted for future sustainable development worldwide.

2. Materials and methods

The experiments on developing an AV Insect net house have been conducted at the experimental research farm in Junagadh agricultural University (21.5° N, 70.1°E). This location undergoes a tropical dry and wet environment that also leans towards warm semi-arid climate

featuring two well-defined periods: a rainy season that runs from June to September and a dry season that runs from October to May. The nearby Arabian Sea notably influence the climate. In the summer, the temperature typically varies between 28 and 38 °C (82 to 100°F), while the average solar radiation ranges from 5 to 8 kWh/m²/day. During winter, temperatures usually range between 10 and 25 °C (50 and 77° Fahrenheit). From June through September, the city encounters precipitation caused by the southwest monsoon, with an annual average that falls within the range of 800 to 1200 mm (31 to 47 in).

The initial step in creating an AV insect net house involves assessing the arrangement of solar panels. There are generally two prevalent solar photovoltaic panel layouts in use. The first uses a full-density design while the other uses a half-density (HD) arrangement. The extensive shading caused by the full-density (FD) design of solar panels on the ground can impede plants' photosynthesis, leading to slower plant growth and diminished crop yields. It's crucial to give the right circumstances for the growth of vegetables and commercial agricultural crops; sunlight plays a vital role in this process. The chessboard pattern has been used in the current study's solar panel configuration to improve the system's performance. This configuration minimizes shading on the ground facilitating better plant growth.

The annual path of the sun in the northern hemisphere, as depicted in Fig. 2, guides the optimal positioning of solar panels to maximize power generation. The sun's path is a little bit lower in the southern sky because India is located in the northern hemisphere. To account for this solar panels are usually set to face south and are generally fixed at an angle of approximately ±5° from the latitude with an additional inclination of 19.75°. The specifics regarding the solar panel configuration can be found in Fig. 3.

Researchers are calculating the shading pattern on the 21st of December when the location of the sun is at peak declination position of -23.44°. The shading pattern at peak declination and at 9am is longest throughout the year. If researchers take into account their row-to-row measurements on this day, then no shadow will cross over into another panel for the whole year. Initially, the slanted length of the shadow is calculated by researchers using the sun altitude angle as shown in Fig. 4. The azimuth and altitude angles for December 21st at 9am are 137.37° and 18.58° respectively. Thus, researchers have two triangles to measure the shadow's most significant length. To allow for a range of tractor-operated agricultural operations the structure's height has been fixed at 3 m.

Solar panel's slant shadow is calculated using Eqs. (1)-3. At the same time, the row-to-row distance may be calculated using Eqs. (4) and 5. The solar azimuth and latitude angles determine the row-to-row distance of the panel, which researchers adjusted to 1.37 m for ease of panel cleaning and to maximize solar radiation. The panels are spaced

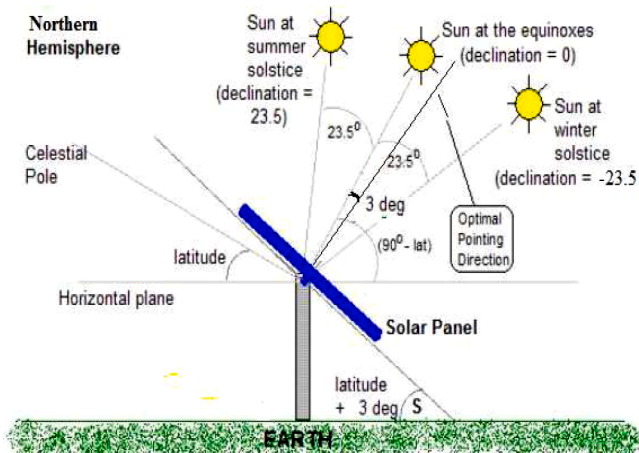


Fig. 2. Illustrates the variation in the sun's declination over a year.

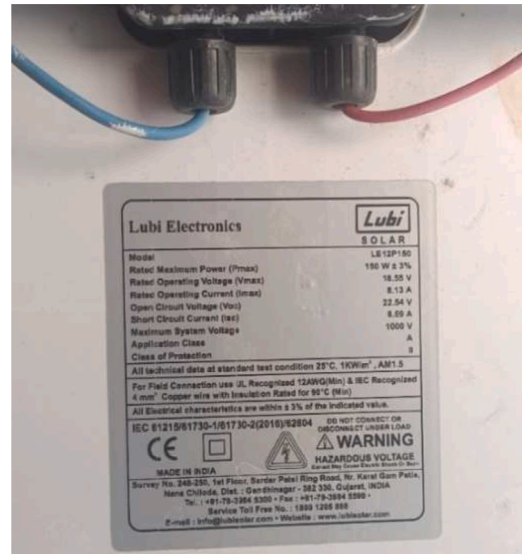


Fig. 3. The specifications of solar panel.

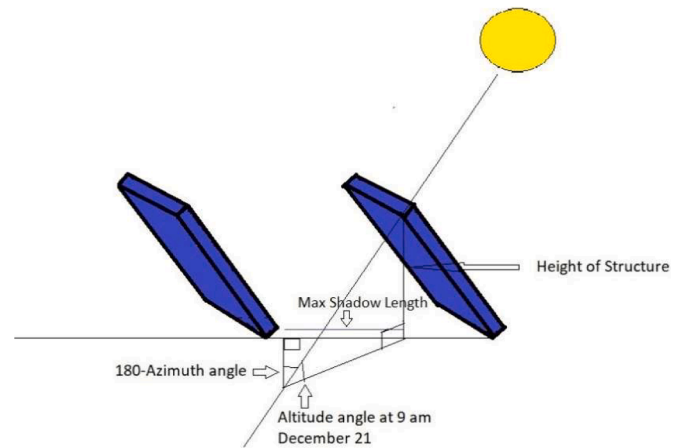


Fig. 4. Illustrate the sun angles that represent its location on 21st December.

0.67 m apart to create a structure that resembles a chessboard. An AV insect net house's conceptual view (see Fig. 5) is explained in detail.

Calculation of sun angles

$$\delta = 23.45 \sin \left[\frac{360 * (284 + d)}{365} \right] \quad (1)$$

Where,

d day count from 1st January

$$\sin \alpha = \sin L_{lat} \sin \delta + \cos L_{lat} \cos \delta \cosh \quad (2)$$

Where,

- α Solar altitude angle
- L_{lat} latitude of the location
- h Hour angle
- δ Solar declination angle

$$\tan \alpha = H/S_l \quad (3)$$

Where,

- H Height of AV
- S_l Slant length of shadow

$$\cos (Az) = (\sin \alpha * \sin L_{lat} - \sin \delta) / \cos \alpha * \cos L_{lat} \quad (4)$$

Where,

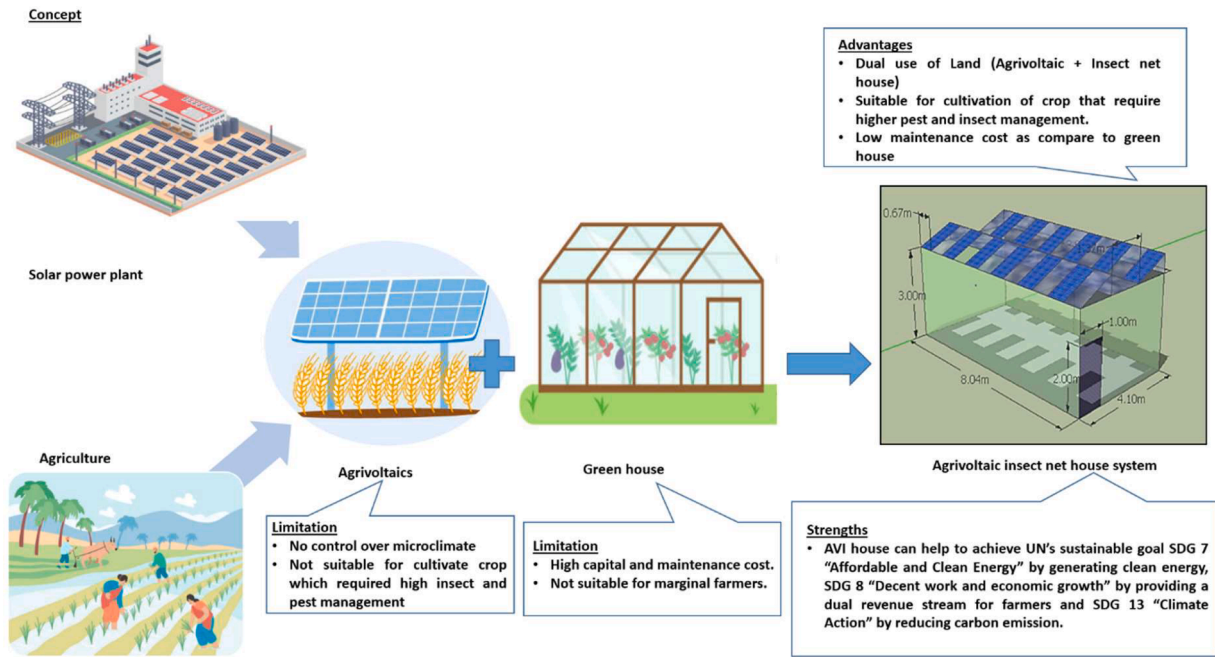


Fig. 5. Conceptual view of the AV insect net house.

Az Solar azimuth angle
 α Solar altitude angle
 L_{lat} latitude of the location
 δ Solar declination angle

$$\sin(180 - Az) = \text{Maximum shadow length}/S_i$$

$$\text{Maximum shadow length (m)} = \sin(180 - Az) * S_i \quad (5)$$

The AV insect net house has undergone a structural analysis utilizing Design Pro software to enhance the choice of materials. The design considers a maximum wind velocity of 140.4 km/h (39 m s⁻¹), the highest wind speed expected in the Junagadh region. The structural components are made using various dimensions of CRC pipes, as outlined in Table 2. The selection of these particular material dimensions for the structure installation, which can withstand wind velocity of about 140.4 km/h. The AV structure comprises 692.50 kg of yst-310 grade square pipes, which have been carefully selected for their suitability in this design.

2.1. Crop cultivation

The capsicum crop has been used to test the insect net house as it has market demand, climatic adaptability, better yields, and pest management. Krishna (Pahuja), an F1 hybrid capsicum variety, has been chosen as the sowing variety. The month of October has been chosen as the sowing season. However, the researcher planted the crop in December and harvested it through the end of March. Traditional farming techniques have been employed to cultivate the crops.

Table 2
 Materials with specifications utilised in structure.

Component	CRC Square Pipes (All dimensions are in mm)	Dimensions (m)	Kg m ⁻¹ (kg)	Total (kg)
Columns	100 × 100 × 4	12.00	11.73	140.76
Beam	72 × 72 × 4	24.28	8.22	199.58
Main Frame	50 × 50 × 4	32.88	4.98	163.75
Purlin	50 × 25 × 4	48.56	3.88	188.41
Total				692.50

2.2. Land equivalent ratio (LER)

LER is a metric employed to evaluate land productivity in the context of mixed cropping systems [35]. This indicator enables the assessment of how the combined productivity of different crops or a combination of trees and crops compares to that of monocultures when cultivated on the same land area. The utility of LER extends to various systems where two or more types of production are integrated on the same land unit. This concept has been proposed for application in novel AV insect net house systems, allowing for calculating the LER for such systems using Eq. (6).

$$LER = Y_{\text{cropin AVI}}/Y_{\text{monocrop}} + Y_{\text{electricity AVI}}/Y_{\text{electricity PV}} \quad (6)$$

Where,
 Y_{cropin AVI} Crop yield inside AV net house (kg),
 Y_{monocrop} Crop yield in open field (kg),
 Y_{electricity AVI} Total power output from AV net house (kWh),
 Y_{electricity PV} Total power output from traditional photovoltaic system (kWh).

Here in this case researchers always get >1 LER because of adding the generation of electricity to the crop cultivation ration.

2.3. Performance parameters of AV insect net house

The AV insect net house performance has been assessed in accordance with guidelines provided by the International Energy Agency (IEA). Schematic diagram of an AV insect net house is shown in Fig. 6. The formula used to evaluate the relevant parameters is as follows: [36,

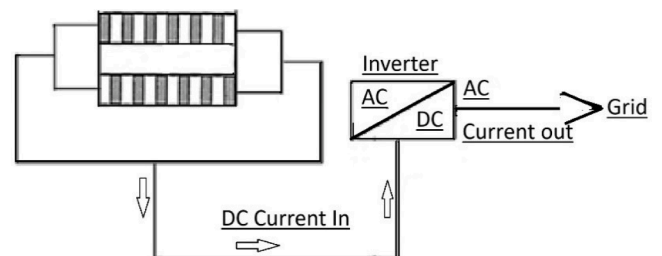


Fig. 6. Schematic diagram of AV insect net house.

37]

Power output from the AV insect net house can be calculated using Eq. (7).

$$P = V \times I \quad (7)$$

Where P = Power output of solar module (W),
 V = Voltage output (V),
 I = Current output (A).

The formulas for the total output energy daily (represented as $E_{AC,d}$) and monthly (represented as $E_{AC,m}$) are given in Eq. (8).

$$E_{(AC,d)} = \sum_{t=1}^{24} E_{(AC,t)}, E_{(AC,m)} = \sum_{d=1}^n E_{(AC,d)} \quad (8)$$

Where,

n Total days in month,
 $E_{(AC,t)}$ Hourly energy output (AC) (kW h),
 $E_{(AC,d)}$ Daily energy output (AC) (kW h),
 $E_{(AC,m)}$ Monthly energy output (AC) (kW h),

The energy production has been determined by calculating the power generated by the AV insect net house system in 30-minute intervals using the inverter. The ultimate efficiency, referred to as the cumulative AC energy produced by the SPV power plant over a specified time frame (whether it's a day, a month, or a year), is calculated by dividing this total by the rated output capacity of the installed PV system, as expressed in Eq. (9).

$$Y_f = \frac{E_{AC}}{P_{PV,Rated}} \quad (9)$$

Where,

Y_f Final yield (kW h/kWp),
 E_{AC} Output energy (AC) (kWh),
 $P_{PV,Rated}$ Output power (kWp).

The proportion of the total solar insolation in plane (H_t) by the reference irradiance (G) is known as the reference yield. This parameter signifies the equivalence in the amount of time solar energy is received at the reference irradiance level, and it can be expressed using Eq. (10).

$$Y_r = \frac{H_t}{G} \quad (10)$$

Where,

Y_R Reference yield (h)
 H_t Solar insolation (kW h/m²),
 G Reference irradiance (kW/m²).

The ratio of final yield (Y_f) to the reference yield (Y_R) is known as performance ratio (PR) [38]. It signifies the overall losses within the system during the conversion process from DC rating to AC output. In mathematical terms, the PR can be represented as Eq. (11).

$$PR (\%) = \frac{Y_f}{Y_R} \times 100 \quad (11)$$

The ratio of the actual annual energy output ($E_{AC,a}$) of the AV insect net house system to the output of the same PV at full rated power (PV, rated) (24 h/day) for year is called capacity factor (CF). Capacity factor can be calculated using Eq. (12).

$$CF = \frac{E_{AC,a}}{P_{PV,a} \times 8760} \times 100 \quad (12)$$

Where,

CF Capacity factor (%),
 $E_{(AC,a)}$ Output energy (annual) (kW h),
 $P_{PV,a}$ Output energy at full rated power (annual) (kW h).

The ratio of actual energy output per unit area to the total in-plane solar radiation is known as system efficiency. The system efficiency can be calculate using Eq.13.

$$\eta_{sys,m} = \frac{E_{AC,m}}{H_t \times A_m} \times 100 \quad (13)$$

Where,

$\eta_{sys,m}$ Efficiency (monthly) (%),
 $E_{(AC,m)}$ Output energy (monthly) (kW h),
 H_t In-plane solar insolation (kW h/m²),
 A_m Area (m²).

2.3.1. Financial metrics

After deducting the seasonal salvage value, the production cost is the sum of the fixed, maintenance, and operating costs. It can be evaluate using Eq. (14). The AV insect net house system's fixed cost has been calculated using formula 15.

$$\text{Production cost (PC)} = FC + MC + OC - SSV \quad (14)$$

Where,

FC Fixed cost (INR/area),
 MC Cost of maintenance (INR/area),
 OC Cost of operation (INR/area),
 SSV Seasonal salvage value (INR/area).

Fixed Cost, $FC = AC$

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

$$CRF = \frac{i(i+1)^n}{(i+1)^n - 1} \quad (15)$$

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

Where,

AC Annual cost,
 CRF Capital recovery factor,
 CI Capital investment,
 n AV structure's life span (25 years),
 i Interest rate (9 % on CI).

The expenditure associated with upkeep throughout the experimentation phase has been regarded as 2 % of the fixed expenditure. The maintenance expenditure and the seasonal salvage value of the structure have been assessed separately utilizing Eqs. (16) and 17.

$$MC_{AVI} = 0.02 \times FC \quad (16)$$

$SSV = ASV$

Here, $ASV = SSF_{AVI} \times SV_{AVI}$

$$SSF_{AVI} = \frac{1}{[(i+1)^n - 1]} \quad (17)$$

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

Where,

ASV Salvage value annually,
 SSF_{AVI} Salvage fund factor,
 SV_{AVI} Salvage value

The cost of an insect net per year can be calculated using Eq. (18), and the life of an insect net has been taken as 3 years.

$$\text{Cost of insect net} = \frac{\text{Area of insect net} \times \text{Cost of insect net}}{\text{Life span} \times \text{Area of Insectnet house}} \quad (18)$$

Gross revenue has been determined by considering the current market price of the crop/energy as well as its production achieved per unit area. The benefit-cost ratio is calculated by dividing the present value of benefits by the present value of costs. A benefit-cost ratio of 1 or higher indicates the project's viability. The benefit-cost ratio (BCR) has been calculated using Eq. (19).

$$\text{Benefit - Cost Ratio} = \frac{\sum_{t=1}^{t=n} B_t}{\sum_{t=1}^{t=n} C_t} \quad (19)$$

Where,

B Benefit (INR),
C Cost (INR).

The ratio of the structure's overall cost to the lucrative power or agricultural output it produces has been used to assess the payback period of the AV system. Eq. (20) has been used to compute the payback period.

$$\text{Payback period (yr)} = \frac{\text{Capital Investment (INR)}}{\text{Net Profit (INR/yr)}} \quad (20)$$

3. Results and discussion

A conceptual 3D model has been developed using Google Sketch Up software based on the previously mentioned design, as depicted in Fig. 5. After performing material calculations, the study team successfully constructed an AV insect net housing system. A photographic representation of this system using the approach is presented in Fig. 7, where the distance between rows is set at 1.37 m and the spacing between solar panels is set at 0.67 m. The 12 solar panels on the constructed AV insect net house at a height of 3 m.

Researchers measured daily solar radiation at 1h intervals using a solar sun tracking device (see Fig. 8). The sun tracking system consists of two devices: A first-class pyrheliometer (compliant with ISO 9060:1990 standards) is designed for measuring solar irradiance within a range of 0 to 4000 W/m² featuring a sensitivity range between 7 and 15 × 10⁻⁶ V_s per W per square m. It can operate effectively in temperatures ranging from -40 to +80 °C and is suitable for use under humidity conditions ranging from 0 to 100 %. On the other hand, a pyranometer which measures solar irradiance within the 0-4000 W/m² range and detects radiation in the spectral range of 300-3000 nanometres has a sensitivity of 1.0 millivolt per W per square m. It is designed to perform within a temperature range of -35 to +60 °C and is also compatible with humidity levels from 0 to 100 %. At the end of each day the results have been summed up and transformed into kW/m² for that day. Data has been retrieved from the data logger every other day using a LAN-connected computer. The daily amount of available solar radiation is between 5 and 8 kW/m², as shown in Fig. 9. This available radiation data has been used to calculate the efficiency of a solar panel. Solar radiation has been lower during the monsoon season due to a cloudy atmosphere than during the other two seasons.

The annual energy output from an AV insect net house calculated using Eqs. (7) and 8 is presented in Fig. 10, which displays the energy generation for various months. The total energy generation from this facility over the course of a year amounts to 3612.00 kWh, which is higher than traditional power plants and normal agrivoltaic systems [39]. This increased energy conversion is due to the cooling of solar panels from the rear side by plant evapotranspiration. Therefore, the energy conversion efficiency of the system is 14.09 %.

The PV system's total AC energy production for a specific time frame (daily, monthly or yearly) is determined by dividing it by the installed solar photovoltaic power plant's rated output power resulting in the final yield (Y_F). The whole daily solar irradiation expressed in kWhm²/day is divided by the reference irradiation value of 1.0 kWhm² to determine the reference yield (Y_R). As a result, the reference yield may be written as kWh (kW-day)⁻¹, which is the number of hours per day needed to obtain the observed incident energy at the reference irradiance level. Performance ratio (PR) is the term used to describe the relationship between the final yield (Y_F) and the reference yield (Y_R) [41]. The total losses in the system are considered when converting the DC rating to AC output. Depending on variables including location, solar radiation, and weather, the performance ratio ranges typically from 0.6 to 0.8 [40,41]. The performance parameter values, shown in Figs 11 and 12, have been determined by applying Eqs. (9) to 13.

3.1. Economic evaluation of av insect net house

In the Indian market a kg of CRC pipe grade yst 310 costs 40 Indian Rupees (1 INR = 0.12 USD). A forty-mesh insect net with a three-m span has been used to build an insect net house. The cost of the insect net determined by applying Eq. (18) is 30 INR per m². In the AV insect net house 12 SPV panels with a capacity of 150 W are employed at a cost of 3300 INR apiece. Additionally, there are estimated costs of 18,000 INR for installation and the inverter. A detailed list of material requirements and related expenses is provided in Table 3.

Using a 25-year life cycle for the solar power plant construction and a 3-year life span for the insect net, the economics of an AV insect net house have been investigated [42]. This AV insect net house has been put to trial for growing capsicum in the Saurashtra region. The growth of the capsicum crop has been measured during the cultivation period in the AV insect net house and open field, as shown in Fig. 13. It is observed that the height of the capsicum crop is higher inside the AV insect net house as compared to an open field. The photographic view of capsicum production and growth parameters are shown in Fig. 14. The yield from growing capsicum in the AV insect net house and open field has been determined to be 15.60 Mt (51.41 kg) per hectare and 10.20 Mt per



Fig. 7. Experimental set-up of AV insect net house system.



Fig. 8. Sun tracking system with pyranimeter and pyrhemliometer.

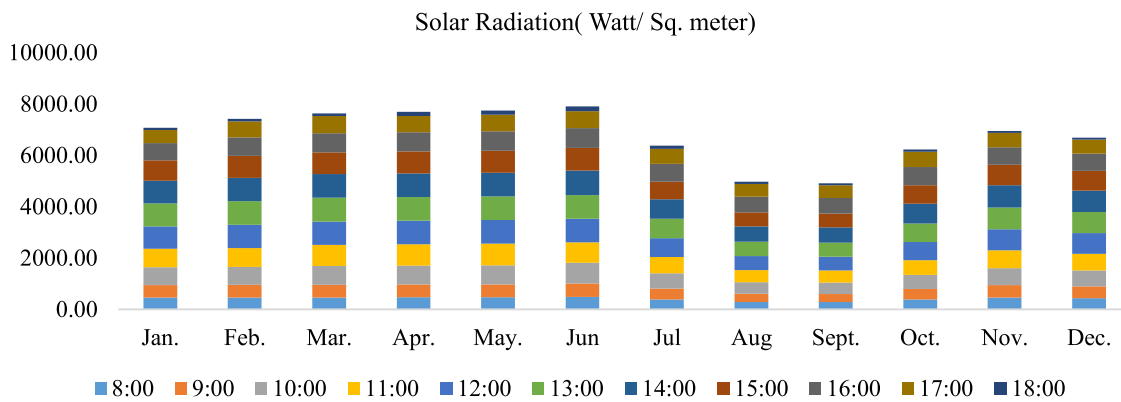


Fig. 9. Solar radiation data throughout the year.

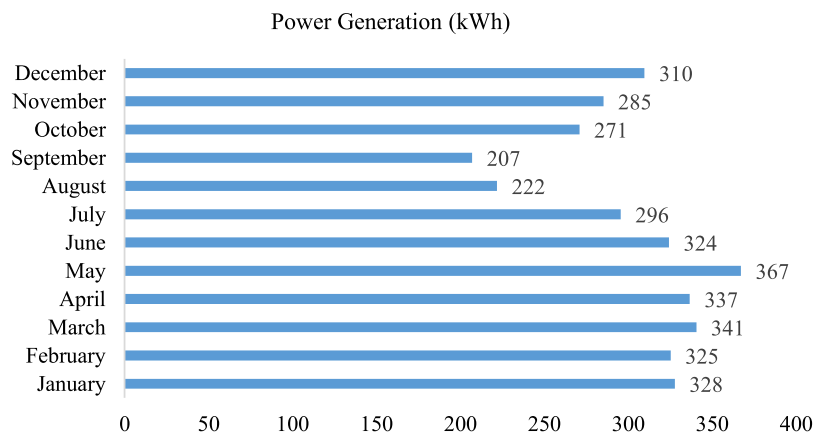


Fig. 10. Energy production from an AV power plant during various months.

hectare, respectively. The food conversion efficiency of the system is 154.8 % higher compared to traditional approach.

The LER is determined by multiplying the proportions of yields in intercropped systems by the yield in a sole-crop scenario represented in Eq. (6). In mixed cropping LER values typically range from 1.0 to 1.3 whereas agroforestry systems tend to exhibit LER values in the range of 1.1 to 1.5.

Here, $Y_{\text{electricity AVI}}/Y_{\text{electricity PV}} = 0.5$ for half density of AV insect net house

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

$$\text{For AV insect net house} = 15.60/10.20 + 0.5 = 1.97$$

The LER of the system is 1.97 approximately double that of a single land use for only one crop harvesting. The following cost components

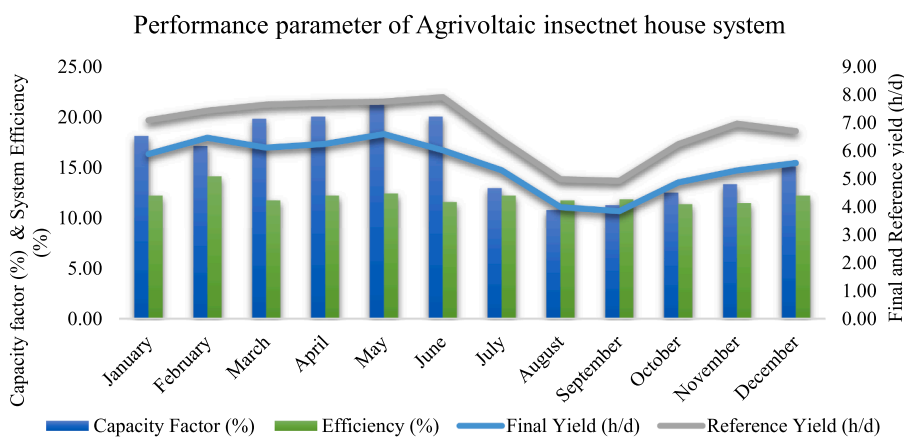


Fig. 11. Performance parameters of AV insect net house for different months.

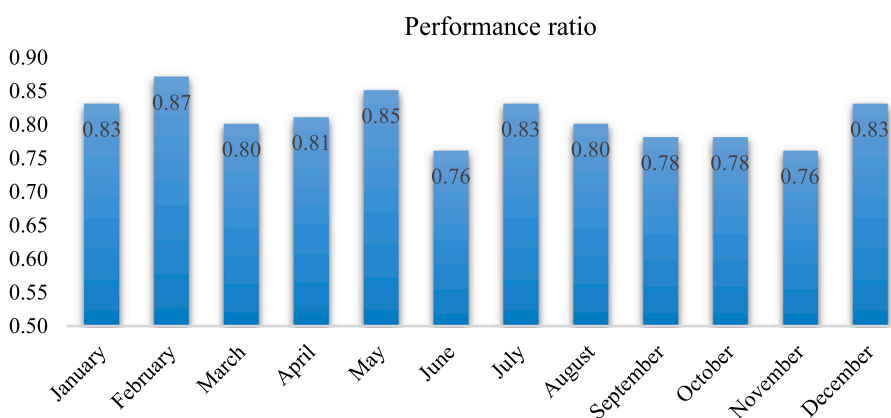


Fig. 12. Performance ratio of AV insect net house.

Table 3

Economics of material used in structure.

Name	Quantity	Cost (INR)	Total (INR)
CRC pipes	692.50 kg	40 / kg	27,700.00
Solar panels	12.00 N	3300 / panel	39,600.00
Installation of plant with inverter and wiring	1.00 N	18,000	18,000.00
Insect net	105.80 m ²	30 / m ²	3174.00
Total			88,474.00

listed in Table 4 has been considered to calculate the operational cost of Capsicum cultivation as per National Horticultural board. Five-year sensitivity analysis of capsicum price is given in Fig. 15 as per local vegetable market. The price of capsicum in the market fluctuated between 22 and 30 INR from 2018 to 2022. Hence, the revenue generated from the capsicum crop has been taken as 30 INR/kg.

The annual fixed cost of an AV structure is 273.76 INR/ m², with maintenance expenses amounting to 5.47 INR / m², which equals 2 % of the fixed cost as described in Eqs. (15) and 16. Additionally, the AV insect net house has a SSV of 87.90 INR / m², as indicated in Eq. (17). So, the production cost of the power plant on a yearly basis is 191.33 INR/ m². On an annual basis, the total cost of production for the AV insect net house system amounts to 223.43 INR/m². Following the formula in Eq. (8) this system yields a total of 109.57 kWh /m² per year leading to an income of 383.50 INR /m² at a rate of 3.50 INR per kWh by the Indian Government’s PM Kusum Yojna policy. Because only the 4 months of the year have been used for the cultivation of the capsicum crop the production costs and revenue costs of the AV insect net house are computed on a seasonal basis. There are a total of three seasons and the revenue and production cost for the AV insect net house system amount to 127.83 INR/m² and 74.47 INR/m² respectively. The economic calculation of capsicum cultivation under AV insect net house is shown in Fig. 16 and Table 5. Benefit-to-cost ratio and the payback period of AV insect net house have been calculated using Eqs. (19) and 20 respectively. AV insect net house has a BCR of 2.20 and a PBP of 9.39 years. Farmers with small land holdings can profitably utilize these AV insect net house systems.

The AV insect net house system outperforms existing half and full-density AV systems. As we all know, we can’t control insect and pest

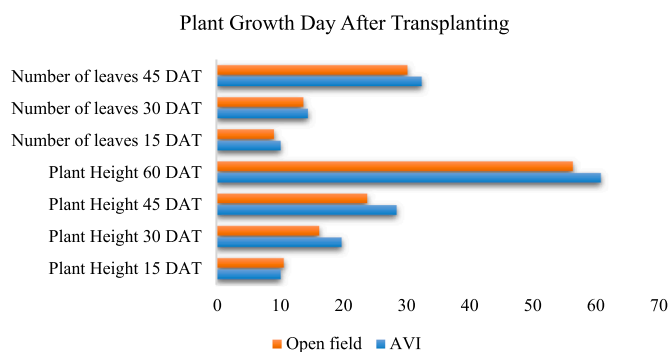


Fig. 13. Growth parameters of capsicum cultivation.



Fig. 14. Measurement of plant parameters.

Table 4
Investment for agricultural activities.

Items	Investment (in INR)
Field preparation	6000
Nursery and planting/sowing	8000
Weeding	10,000
Plant protection	12,000
Fertilizers	8000
Wages	5000
Total per hectare	49,000
Total INR/m ²	4.9

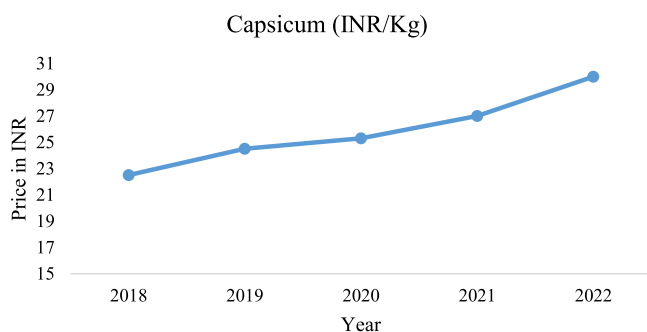


Fig. 15. Sensitivity analysis of capsicum price over 5 years in Gujarat.

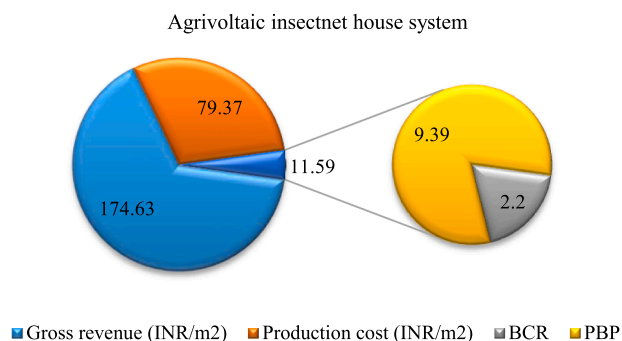


Fig. 16. Performance of capsicum in AV insect net house system.

problems in AV systems; therefore, crop output suffers as a result. Researchers achieved higher yields and a better land equivalence ratio in the AV insect net house system. Therefore, the proposed approach of AV insect house has been tested and validated for future studies and development. Table 6 compares an experimental investigation of an AV insect house with relevant research.

The above results indicate a feasible and viable system for sustainable energy-food production and development of society.

3.2. Environmental management and societal benefits

- AV insect net house technology is a significant tool in the fight against climate change as it uses solar energy to generate sustainable power. This is essential for preserving human well-being, wildlife, and the natural environment.
- Solar power has the potential to improve air quality and reduce water usage linked to energy production.
- The partial shading structure keeps moderate microclimate and aids in the decrease of temperature in evapotranspiration process under solar panels (by 1–2 °C), resulting in enhance energy-food yield.
- AV insect net house system can help to achieve sustainable goals SDG 7 “Affordable and Clean Energy” by generating clean energy, SDG 8 “Decent work and economic growth” by giving a double revenue stream for farmers and SDG 13 “Climate Action” by reducing carbon emission.
- The idea of a net house is replaced by the AV insect net house system in better sustainability towards society.
- Large-scale AV insect net house system can fulfill the world’s tremendous energy and food demand.

4. Conclusion and recommendations

AV insect net house systems offer a compelling economic opportunity for small-scale farmers. This innovative structure has 12 solar panels, each generating 150 W of power. The total capacity of the solar photovoltaic (SPV) system is 1.8 kW, efficiently distributed across an area of 32.96 m², resulting in a power density of 0.055 kW/m². The structure stands at a height of 3 m, facilitating easy farm operations within the system. Advanced structural analysis and design software have been employed to calculate the ideal material strength to ensure its stability in the face of strong winds at 140.4 km/hr. A total of 692.50 kg of yst 310 grade square CRC pipe has been used to constructing the structure. The AV insect net house system achieves peak efficiency at 14.09 % during February when clear skies prevail. This system’s land equivalence ratio (LER) is an impressive 1.97, almost double that of traditional single-use land for crop cultivation. It produces 3612 kWh of electricity, equivalent to 109.57 kWh/m², contributing to a reduction in carbon emissions and providing the farmer with an additional income of 174.63 INR/m². Farmers enjoy a net profit of 95.26 INR/m² throughout the season. The BCR of the AV insect net house stands at 2.20, significantly outperforming traditional greenhouses. This is attributed to the ability of farmers to generate revenue from sustainable and clean electricity, unlike greenhouses, where income relies solely on food production.

The AV insect net house system offers a revolutionary alternative to

Table 5
Economics of capsicum cultivation under AV insect net house.

	Seasonal gross revenue (INR/m ²)			Seasonal production cost (INR/m ²)			Net profit (INR/m ²)	BCR	PBP
	Crop	Solar energy	Total	Crop	Solar energy	Total			
AVS	46.80	127.83	174.63	4.90	74.47	79.37	95.26	2.20	9.39

Table 6
Experimental comparison between the AV insect house and related studies.

Reference	Crop	Location/Year	LER	PBP
Proposed work [2]	Capsicum	Gujarat, India/ 2022	1.97	9.39 years
	Celeriac	Hohenheim, Germany/ 2017	1.31	–
[20]	Jerusalem artichoke, Broad bean (DW), Rape, Garlic (DW), Shallot, Broccoli, Lettuce (DW), Lettuce	Hohenheim, Germany/ 2018	1.62	–
		Hefei, China/ 2021	avg. 1.64 (1.55 to 1.90)	–
[34]	Turmeric	Odisha, India/ 2022	1.73	9.49 years.

traditional net houses, making it a viable solution for small-scale farmers. This innovation holds significant promise for rapidly growing nations like India, grappling with escalating demands for both food and energy. It is an advanced iteration of insect net houses providing a more dependable means of producing clean energy for the community. Notably, this technology contributes to India's progress towards achieving SDGs 7, 8, and 13.

Funding

The authors received no funding from an external source. However, the authors are thankfully acknowledges the receipt of fund from Junagadh Agricultural University and CRP on EA (ICAR) for setting up experimental set up to conduct experiments.

Ethical approval

No ethical approval is needed.

Experiments and field studies on plants

The study complies with local and national guidelines and regulations.

Informed consent statement

This article discusses the ethics of agricultural research techniques and consent to solar energy.

Generative AI and AI-assisted technologies

Not applicable

CRedit authorship contribution statement

Gaurav Gadhiya: Writing – review & editing, Writing – original draft, Methodology, Investigation. **Urvashi Patel:** Investigation, Formal analysis, Data curation, Conceptualization. **Pushpendrasingh Chauhan:** Visualization, Validation, Supervision, Methodology. **Nimay Chandra Giri:** Validation, Supervision, Methodology, Investigation. **Guang-Zhong Yin:** Formal analysis, Methodology, Writing – review & editing. **Rohit Khargotra:** Writing – review & editing, Writing – original

draft, Methodology, Investigation.

Declaration of competing interest

“The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper”.

Acknowledgments

This paper is part of the M.Tech. work and the authors are thankful to the Indian Council of Agricultural Research (ICAR) for supporting the study work through their Consortia Research Platform on Energy from Agriculture. The researchers extend their sincere appreciation to the Department of Renewable Energy Engineering, College of Agricultural Engineering and Technology at Junagadh Agricultural University for their outstanding mentorship throughout the project.

Data availability

Data will be made available on request.

References

- [1] IEA, International Energy Agency world energy investment, 2023 (Accessed: Oct. 03, 2023). Available: <https://www.iea.org/reports/world-energy-investment-2023>.
- [2] A. Weselek, A. Bauerle, S. Zikeli, I. Lewandowski, P. Högy, Effects on crop development, yields and chemical composition of celeriac (*Apium graveolens* L. var. *rapaceum*) cultivated underneath an agrivoltaic system, *Agronomy* 11 (2021) 733, <https://doi.org/10.3390/agronomy11040733>, a.
- [3] N.C. Giri, R.C. Mohanty, Turmeric crop farming potential under Agrivoltaic system over open field practice in Odisha, India, *Environ. Dev. Sustain.* (2024), <https://doi.org/10.1007/s10668-024-05086-3>.
- [4] M. Trommsdorff, J. Kang, C. Reise, S. Schindele, G. Bopp, A. Ehmman, A. Weselek, P. Högy, T. Obergfell, Combining food and energy production: design of an agrivoltaic system applied in arable and vegetable farming in Germany, *Renew. Sustain. Energy Rev.* 140 (2021) 110694, <https://doi.org/10.1016/j.rser.2020.110694>.
- [5] N.C. Giri, R.C. Mohanty, R.C. Pradhan, S. Abdullah, S. Ghosh, A. Mukherjee, Agrivoltaic system for energy-food production: a symbiotic approach on strategy, modelling, and optimization, *Sustain. Comput. Inform. Syst.* 40 (2023) 100915, <https://doi.org/10.1016/j.suscom.2023.100915>.
- [6] H. Dinesh, J.M. Pearce, The potential of agrivoltaic systems, *Renew. Sustain. Energy Rev.* 54 (2016) 299–308, <https://doi.org/10.1016/j.rser.2015.10.024>.
- [7] R.K. Chopdar, et al., Comprehensive review on agrivoltaics with technical, environmental and societal insights, *Renew. Sustain. Energy Rev.* 197 (2024) 114416, <https://doi.org/10.1016/j.rser.2024.114416>.
- [8] H. Marrou, J. Wery, L. Dufour, C. Dupraz, Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels, *Eur. J. Agron.* 44 (2013) 54–66, <https://doi.org/10.1016/j.eja.2012.08.003>.
- [9] R. Arena, S. Aneli, A. Gagliano, G.M. Tina, Optimal photovoltaic array layout of agrivoltaic systems based on vertical bifacial photovoltaic modules, *Sol. RRL* 8 (2024) 2300505, <https://doi.org/10.1002/solr.202300505>.
- [10] H. Mehrjerdi, A.A.M. Aljabery, Modeling and optimal planning of an energy–water–carbon nexus system for sustainable development of local communities, *Adv. Sustain. Syst.* 5 (7) (2021) 2100024, <https://doi.org/10.1002/adsu.202100024>.
- [11] T. Sekiyama, A. Nagashima, Solar sharing for both food and clean energy production: performance of agrivoltaic systems for corn, a typical shade-intolerant crop, *Environments* 6 (2019) 65, <https://doi.org/10.3390/environments6060065>.
- [12] G.A. Barron-Gafford, et al., Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands, *Nat. Sustain.* 2 (2019) 848–855.
- [13] S. Amaducci, X. Yin, M. Colauzzi, Agrivoltaic systems to optimise land use for electric energy production, *Appl. Energy* 220 (2018) 545–561, <https://doi.org/10.1016/j.apenergy.2018.03.081>.
- [14] A. Weselek, A. Ehmman, S. Zikeli, I. Lewandowski, S. Schindele, P. Högy, Agrivoltaic systems: applications, challenges, and opportunities. A review, *Agron. Sustain. Dev.* 39 (2019) 35, <https://doi.org/10.1007/s13593-019-0581-3>.

- [15] N.C. Giri, R.C. Mohanty, Traditional versus underneath farming of turmeric and ginger in Odisha, India, *Int. J. Agricult. Stat.* 18 (1) (2022) 189–195, 2.
- [16] A.S.A. Mohamed, H.M. Maghrabie, Techno-economic feasibility analysis of Benban solar Park, Alex. Eng. J. 61 (12) (2022) 12593–12607, <https://doi.org/10.1016/j.aej.2022.06.034>.
- [17] L. Dufour, A. Metay, G. Talbot, C. Dupraz, Assessing light competition for cereal production in temperate agroforestry systems using experimentation and crop modelling, *J. Agron. Crop Sci.* 199 (2013) 217–227, <https://doi.org/10.1111/jac.12008>.
- [18] H. Li, D. Jiang, B. Wollenweber, T. Dai, W. Cao, Effects of shading on morphology, physiology and grain yield of winter wheat, *Eur. J. Agron.* 33 (2010) 267–275, <https://doi.org/10.1016/j.eja.2010.07.002>.
- [19] D.J. Midmore, D. Berrios, J. Roca, Potato (*Solanum* spp.) in the hot tropics V. Intercropping with maize and the influence of shade on tuber yields, *Field Crop Res.* 18 (1988) 159–176, [https://doi.org/10.1016/0378-4290\(88\)90006-8](https://doi.org/10.1016/0378-4290(88)90006-8).
- [20] J. Zheng, S. Meng, X. Zhang, H. Zhao, X. Ning, Increasing the comprehensive economic benefits of farmland with Even-lighting Agrivoltaic Systems, *PLOS ONE* 16 (7) (2021) e0254482, <https://doi.org/10.1371/journal.pone.0254482>.
- [21] K. Pang, J.W. van Sambeek, N.E. Navarrete-Tindall, C.-H. Lin, S. Jose, H.E. Garrett, Responses of legumes and grasses to non-, moderate, and dense shade in Missouri, USA. I. Forage yield and its species-level plasticity, *Agrofor. Syst.* 88 (2017) 287, <https://doi.org/10.1007/s10457-017-0067-8>.
- [22] A.H. Pandiyaswargo, A.D. Wibowo, H. Onoda, Socio-techno-economic assessment to design an appropriate renewable energy system for remote agricultural communities in developing countries, *Sustain. Prod. Consum.* 31 (2022) 492–511, <https://doi.org/10.1016/j.spc.2022.03.009>.
- [23] Z. Zhang, F. Zhang, W. Zhang, M. Li, W. Liu, A.A.A. Omer, J. Zheng, X. Zhang, W. Liu, Spectral-splitting concentrator agrivoltaics for higher hybrid solar energy conversion efficiency, *Energy Convers. Manag.* 276 (2023) 116567, <https://doi.org/10.1016/j.enconman.2022.116567>.
- [24] M. Kumpanalaisatit, et al., Current status of agrivoltaic systems and their benefits to energy, food, environment, economy, and society, *Sustain. Prod. Consum.* 33 (2022) 952–963, <https://doi.org/10.1016/j.spc.2022.08.013>.
- [25] N.C. Giri, R.C. Mohanty, Turmeric crop farming potential under Agrivoltaic system over open field practice in Odisha, India, *Environ. Dev. Sustain.* (2024), <https://doi.org/10.1007/s10668-024-05086-3>.
- [26] R. Aroca-Delgado, J. Pérez-Alonso, A.J. Callejón-Ferre, M. Díaz-Pérez, Morphology yield and quality of greenhouse tomato cultivation with flexible photovoltaic rooftop panels (Almería-Spain), *Sci. Hortic.* 257 (2019) 108768, <https://doi.org/10.1016/j.scienta.2019.108768>.
- [27] M. Cossu, L. Murgia, L. Ledda, P.A. Deligios, A. Sirigu, F. Chessa, A. Pazzona, Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity, *Appl. Energy* 133 (2014) 89–100, <https://doi.org/10.1016/j.apenergy.2014.07.070>.
- [28] EIA, The total annual U.S. electricity net generation and emission by utility-scale electric power plants, 2022 (Accessed: Oct. 03, 2023). Available: <https://www.eia.gov/electricity/annual/pdf/epa.pdf>.
- [29] S. Kim, S. Kim, C.Y. Yoon, An Efficient Structure of an Agrophotovoltaic System in a Temperate Climate Region, *Agronomy* 11 (2021) 1584, <https://doi.org/10.3390/agronomy11081584>.
- [30] G.P. Moreda, et al., Techno-Economic Viability of Agro-Photovoltaic Irrigated Arable Lands in the EU-Med Region: a Case-Study in South-western Spain, *Agronomy* 11 (2021) 593, <https://doi.org/10.3390/agronomy11030593>.
- [31] H. Jo, et al., Comparison of Yield and Yield Components of Several Crops Grown under Agro-Photovoltaic System in Korea, *Agriculture* 12 (2022) 619, <https://doi.org/10.3390/agriculture12050619>.
- [32] H.J. Lee, H.H. Park, Y.O. Kim, Y.I. Kuk, Crop cultivation underneath agro photovoltaic systems and its effects on crop growth, yield, and photosynthetic efficiency, *Agronomy* 12 (2022) 1842.
- [33] E. Potenza, M. Croci, M. Colauzzi, S. Amaducci, Agrivoltaic system and modelling simulation: a case study of soybean (*Glycine max* L.) in Italy, *Horticulture* 8 (2022) 1160.
- [34] J. Widmer, et al., Agrivoltaics, a promising new tool for electricity and food production: a systematic review, *Renew. Sustain. Energy Rev.* 192 (2024) 114277, <https://doi.org/10.1016/j.rser.2023.114277>.
- [35] C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, Y. Ferard, Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes, *Renew. Energy* 36 (2011) 2725–2732, <https://doi.org/10.1016/j.renene.2011.03.005>.
- [36] A. Chalgybayeva, et al., The economic potential of agrivoltaic systems in apple cultivation—a Hungarian case study, *Sustainability* 16 (2024) 2325, <https://doi.org/10.3390/su16062325>.
- [37] U.R. Patel, G.A. Gadhiya, P.M. Chauhan, Case study on power generation from agrivoltaic system in India, *Int. J. Environ. Clim. Change* 13 (9) (2023) 1447–1454, <https://doi.org/10.9734/IJECC/2023/v13i92375>.
- [38] E. Ayora, M. Munji, K. Kaberere, B. Thomas, Performance analysis of 600 kWp gridtied rooftop solar photovoltaic systems at Strathmore university in Kenya, *Result. Eng.* 19 (2023) 101302, <https://doi.org/10.1016/j.rineng.2023.101302>.
- [39] S. Poonia, et al., Techno-economic evaluation of different agri-voltaic designs for the hot arid ecosystem India, *Renew. Energy* 184 (2021) 149–163, <https://doi.org/10.1016/j.renene.2021.11.074>.
- [40] U.R. Patel, G.A. Gadhiya, P.M. Chauhan, Techno-economic analysis of agrivoltaic system for affordable and clean energy with food production in India, *Clean Tech. Environ. Policy* (2024), <https://doi.org/10.1007/s10098-023-02690-1>.
- [41] V. Sharma, S. Chandel, Performance analysis of a 190 kWp grid interactive solar photovoltaic power plant in India, *Energy* 55 (C) (2013) 476–485, <https://doi.org/10.1016/j.energy.2013.03.075>.
- [42] J. Jamal, I. Mansur, A. Rasid, M. Mulyadi, M. Dihyah Marwan, M. Marwan, Evaluating the shading effect of photovoltaic panels to optimize the performance ratio of a solar power system, *Result. Eng.* (2024), <https://doi.org/10.1016/j.rineng.2024.101878>.