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RESEARCH ARTICLE

# Agrivoltaics system: Sustainable approach for okra cultivation and energy stability

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## Abstract

The growing population and energy-intensive industries are raising global energy demand, which can be mitigated by the sustainable use of agrivoltaics systems (AGV). AGV is a notion by which agricultural regions can be used for crop cultivation and photovoltaic electricity production by erecting solar collectors 2-5 m above the ground. In semi-arid and arid areas, the microclimate created under AGV systems is extremely favourable for plant development. AGV systems have several synergistic benefits, including lowering total radiation levels on spices and herbs, thereby increasing yield and promoting water conservation by lowering evapotranspiration and lessening the consequences of high radiation. The present research brought forward an understanding of an AGV system ideal for growing okra. The average moisture content in the soil was found to increase by 2-8 % with a decrease in light intensity by 40 ± 5 % during the summer season, having an additional decrease in air temperature by 2.5 ˚C. The soil surface temperature was also decrease by 8-15 % subsequently, which proved beneficial for plant growth. The AGV system was found to protect protected plant saplings during heavy rains in the rainy season, with a higher germination rate. The change in microclimate data suggests that a better crop growth climate can be obtained under the AGV system alongside energy production throughout the year. Heavy shade significantly reduced okra yields, causing stunted growth and fewer fruits. This study highlights the crucial need for adequate sunlight for okra, a sun-loving plant that requires ample sunshine for optimal fruit development and photosynthesis. Additionally, the techno-economic study also shows that the AGV project can improve economic benefits to the farmers.

## Keywords

agrivoltaics system; crop performance; energy; humidity; light intensity; soil temperature

## Introduction

The continued depletion of fossil fuel reserves and the drive to switch to renewable and clean energy resources has been constantly instigating ideas to develop a parallel system for sustainable development of energy and food security. This has led to the introduction of Agrivoltaics systems or commonly known as AGV systems. This cutting-edge method enables solar panels and crops to share the same land, offering various advantages like boosting farmers' income through multiple revenue sources and optimizing the use of land efficiently alongside green energy production (1). Over the last decade solar energy has gained the attention of scientists and the public, leading to a multitude of beneficial applications. The world population is expected to reach around 10 billion by 2050. With the growing population and growing industries to meet future needs, there is requirement to find a new method of food and energy production from the same field (2). While fossil fuels like coal, gas and oil offer certain advantages, their non-renewable nature and harmful environmental impact, caused by the release of greenhouse gases, are undeniable concerns (3). The development of renewable energy sources is engrossed for meeting the future energy demand and simultaneous replacement of using fossil fuels. In 1980 AGV systems were first proposed to duel the use of lands for agriculture production and solar energy generation in between solar arrays (4, 5).

The concept of AGV systems advanced with elevated solar panels below land spaces used for agriculture crop production. AGV system integrates solar electricity generation from cropland to upraise land-use efficiency and an unusual chance for proper interaction with greater crop production, more electricity generation, reduce water demand, decrease carbon emissions and more prosperous for human living (6--8). The generated electric power from solar cells also can be used for electrokinetic applications for the reclamation of soil characteristics (9). To meet humanity's energy needs, solar photovoltaic (PV) technology has made tremendous strides, due to its large, clean and sustainable source of energy. AGV systems utilize solar panels installed elevated above the ground to integrate the growing of agricultural crops with the generation of electricity on the same plot of land. Based on past studies, AGV can increase the productivity of land while encouraging the expansion of renewable energy generation. Though this element is still extensively researched, it is expected that its adoption will alter microclimatic conditions and affect crop productivity. Due to the somewhat diffuse nature of solar energy, huge surface areas are required to reach that prediction and deliver the corresponding greater part of total global demand with PV (10, 11). Adopting aggressive building integrated PV and rooftop PV can meet a large portion of this requirement but the use of vast areas of land for solar farms will intensify competition for land resources as the need for energy and food production rises and vies (12).

The use of AGVs systems improves land use efficiency in numerous significant ways. In areas with a shortage of arable land, AGVs maximizes the productivity of valuable land by enabling land to be used for both farming and solar energy generation. Farmers can double the utility of their land by adding solar panels to their fields so they can produce electricity and crops at the same time (dual land use). Utilizing less water due to decreased soil temperature and evaporation, AGV systems increase crop productivity overall. Furthermore, improved soil moisture conditions can lead to lower water loss from evaporation, which may increase crop yields. An extension of the growing season may be possible thanks to the microclimate that PV panels create. The shading provided by PV panels can reduce temperature fluctuations in regions with extreme weather, potentially extending the growing season and lessening crop stress.

Increased crop productivity overall and more frequent harvesting may result from this. Resource management is made more effective by AGV systems. These systems aid in maximizing water use and enhancing soil health by lowering water evaporation and reducing heat stress. AGV systems help to lower greenhouse gas emissions and promote environmental sustainability by fusing agriculture with renewable energy. AGV systems are adaptable to diverse climatic and soil conditions because they can be made to accommodate a wide range of agricultural practices and crops. Because of its adaptability, PV panel configurations and shading levels can be tailored to maximize crop growth and energy production.

So far majority of past research on AGV systems on simulations and modelling, with limited field experiments (13). While several studies have investigated the effects of AGV on lettuce cultivars, with variable results depending on cultivar and panel orientation, the general impacts of AGV on crop production remain fundamentally unexplored (14). One field study reported that lettuce yields were unaffected by AGV, though solar radiation was reduced by nearly 30 % due to shading from the mounted panels (15). Additionally, water loss through evapotranspiration was decreased under the partial shade provided by the AGV facility (16). It is revealed that the orientation of solar PV panels benefits by reduced leaf evapotranspiration, enhanced water use efficiency, and temperature regulation (17). Another study reported that AGV system PV panel shade decay of photosynthetically active radiation (PAR), encompassing light in the 400–700 nm range, can trigger the adaptive response known as the shade avoidance syndrome. While other studies on AGV effects on crops like corn and tomatoes are limited, some research indicates potential yield increases in non-irrigated maize (18, 19). It was also reported that AGV shading can reduce rice yields by 20 % (19).

Optimum microclimate condition for a crop is one of the important concerns for crop growth and yield. AGV system affects microclimate conditions, resulting in an effect on crop growth, yields and cropping duration. The impact of AGV systems depends on numerous factors, including type of crop species, environmental circumstances and crop management practices (20). Shading may result in increased production in certain cases, but its effects can be negative or negligible under different conditions (21, 22). Past studies have deep-rooted that the shade by PV panels can increase biomass production in chicory and lettuce (16, 23, 24). Crop yields in AGV systems vary significantly, there is need of in-depth investigation to understand the impact on food security across different locations, crops and technologies. The aim of this study is to explore the potential of AGV systems shadow effect on okra (*Abelmoschus esculentus*.) cultivation. Our research specifically delves into the influence of shade generated by PV panels effect on microclimate and okra crop performance. The okra crop was selected due to its global prevalence and commercial significance as well as its vital role in human diets. Okra is widely cultivated and consumed across the world.

## Materials and Methods

### Study area

All field and laboratory experiments were performed in The Neotia University campus in South 24 Parganas, West Bengal, India. South 24 parganas covers an area of about 8165.05 $^{2}$km and is between latitudes 21°29'0" north and 22°33'45" north and longitudes 88°3'45" east and 89°4'50" east. Temperatures in the area range from 13.6 to 40 $^{0}$C, humidity in the range 71 % to 85 % with an annual rainfall of 1750 to 1770 mm. The most common soil types are loamy soil, which covers 194330 ha, clay-loamy soil, which covers 101050 ha and clay soil, which covers 93280 ha. The study plot soil average bulk density is 1.72 g/cc and the soil type is sandy clay loamy soil (Fig. 1A).

### Experimental plan

The study has been divided into 3 different conditions (treatments) such as before, after and under AGV system

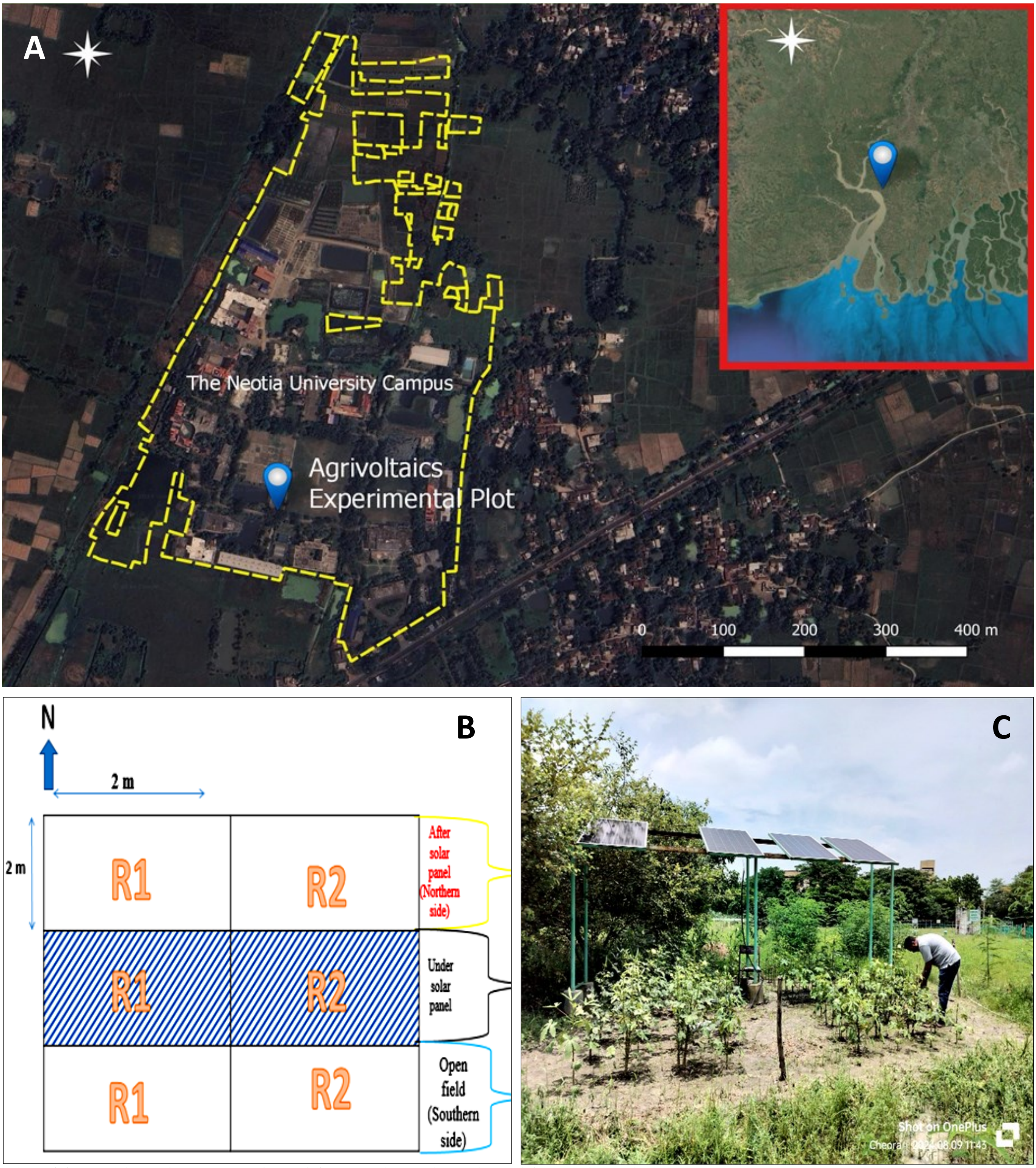


**Fig. 1.** (**A**) Map of the study experimental area. (**B**) Layout of AGV cultivated area. (**C**) AGV. cultivated area.

land, wherein the growing performance of okra was compared (Table 1). The layout of the cultivated area with photovoltaic panel (shaded) and open area without panel are shown below figure (Fig. 1 B-C). Each treatment was conducted with 2 replicates (R1, R2). Photovoltaic panels (PVs) of 1 × 2 m were used for the study. A total four PVs was arranged in East–West orientated strips by inclined southward direction with a tilt angle of 25 ° at 3 m above ground (southern side faced) to allow mechanical cropping of the plants below, using tractors (Fig. 2).

**Table 1.** Field dimensions of the experimental plot.

| Growing Condition | Treatments | Field area (R1 + R2) |
|---|---|---|
| Open field-southern side | T1 | 4 + 4 $m^2$ |
| Under solar panel | T2 | 4 + 4 $m^2$ |
| After solar panel-northern side | T3 | 4 + 4 $m^2$ |

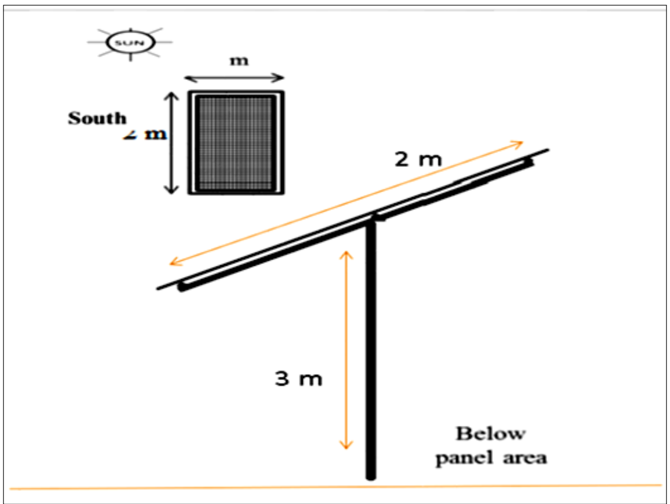


**Fig. 2.** Design of solar PV installation in AGV study plot.

## Crop management

Okra (*Abelmoschus esculentus* L.) crops have been cultivated on 2 crop cycle (November-January 2023 and May–July 2024) by maintaining plant-to-plant spacing of 40 cm for 3 different treatments. NS 7801 variety of okra seeds were cultivated for the 2-sowing season (Fig. 1C).

## Data collection

The following climatic condition data were collected for the study, such as air temperature, soil surface temperature, relative humidity, light intensity and plant canopy temperature. The study was also conducted on soil physical properties to understand the effect of AGV system on soil moisture content on monthly basis. Crop physiological properties also monitored for 15 days inter till 75 days after planting (DAP).

## Air temperature

Air temperature data were collected in the study plot, under the photovoltaic panel (shaded area) and before the photovoltaic panel (open area- southern side) and after the photovoltaic panel (northern side) with 3 replicates in three days' interval. Air temperature data were measured for the study plot using digital thermometer at 1.5 m height from the soil surface at 3 different times respectively 9 AM, 1 PM and 4 PM and analysed on monthly average basis for the study plot.

## *Soil surface and canopy temperature*

Soil surface and canopy temperature data were collected in the study plot, under the photovoltaic panel (shaded area) and before the photovoltaic panel (open area- southern side) and after the photovoltaic panel (northern side) with 3 replicates in 3 days' intervals. Soil temperature data were collected for the study plot using infrared thermometer for soil at 3 different times respectively 9 AM, 1 PM and 4 PM and analysed on monthly average basis for the study plot.

## Relative humidity

Air humidity data were collected in the study plot, under the photovoltaic panel (shaded area) and before the photovoltaic panel (open area- southern side) and after the photovoltaic panel (northern side) with 3 replicates in 3 days' interval. Air humidity data were taken for the study plot using digital hygrometer at 1.5 m height from the soil surface at 3 different times respectively 9 AM, 1 PM and 4 PM and analysed on the monthly basis for the study plot.

## Light intensity

The amount of available light was taken in the study plot, under the photovoltaic panel (shaded area) and before the photovoltaic panel (open area- southern side) and after the photovoltaic panel (northern side) with 3 replicates in 3 days' interval. The amount of available light data was collected for the study plot using Lux meter at the soil surface in three different times respectively 9 AM, 1 PM and 4 PM and analysed on the monthly average basis for the study plot.

## Soil physical properties

Soil properties data were measured for the study plot by collecting soil samples using core cutter and further laboratory tests being performed. Initially, soil physical properties such as soil texture and soil bulk density were measured for the study plot after collecting soil samples using core cutter at 0-15 cm depth with 3 replicates for each sampling point. To find the impact of AGV shade effect on soil moisture condition under the study plot for each treatment 2 replicates are being planned. So, for changes in soil moisture percentage a total of 144 (48 × 3) soil samples was collected and measured soil moisture percentage using gravimetric method. Mean monthly soil moisture at 0-15 cm depth was measured by gravimetric methods using weight balance and oven drier at 105 °C for 24 h for the study plot, under the photovoltaic panel (shaded area) and before the photovoltaic panel (open area- southern side) and after the photovoltaic panel (northern side) with 3 replicates.

## Crop parameters

For conducting experiment, the field is subdivided into 3 different conditions such as before, after and under AGV system land, wherein the growing performance of Okra (*Abelmoschus esculentus* L.) crop was compared. The okra crop parameters such as plant height, number of leaves, leaf area index and yields was monitored for each treatment with 2 replicates. Biometric observations like height, number leaves, leaf area index and yields were observed periodically during crop period. Following observations was observed over crop period. The biometric characteristic of okra was observed at an interval of 15, 30, 45, 60 and 75 days after planting.

## Results

### Soil physical properties

Soil properties data were measured from the study plot and the following data were obtained, viz. average bulk density for the study plot is 1.72 g/cc, The estimated texture is respectively sand 60.07 %, clay 23.67 % and 16.26 %. As per the USDA classification scheme, soil samples are then classified using the USDA textural triangle as sandy clay loam. The Fig. 3 shows monthly basis average soil moisture percentage for 0-15 cm depth of soil for the study area. The soil moisture percentage data suggested that the southern side of the panel has the lowest moisture percentage in comparison to other 2 treatments and 20 % and 28 % higher moisture content was found under panel and northern side panel area respectively in comparison to open field condition (southern side).

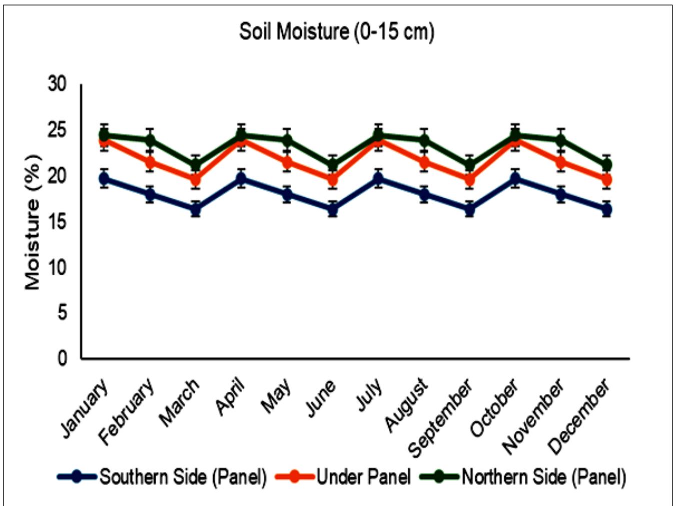


**Fig. 3.** Mean soil moisture changes for different plots (Values are in means ± SD (n = 3)).

### Microclimate

### *Air temperature*

Increased temperatures, a greater chance of drought and increased radiation stress on crops are all results of climate change. The AGV system protects crops from the effects of climate change by providing more shade for them. It is intriguing to focus on crops that are severely impacted by climate change and whose yields was increased by AGV systems. The air temperature data suggested that the southern side of the panel has the highest temperature and a temperature decrement of approximately 6 % was observed under the panel and approximately 8 % at the northern side of the panel. Comparison of air temperature were plotted for the 3 distinct locations: beneath solar panels, immediately after the panels (northern side), and a control site without panels (southern side) (Fig. 4). This comparative analysis reveals a crucial link between farmland air temperature and crop growth, highlighting the potential impact of solar panel installation on agricultural practices.

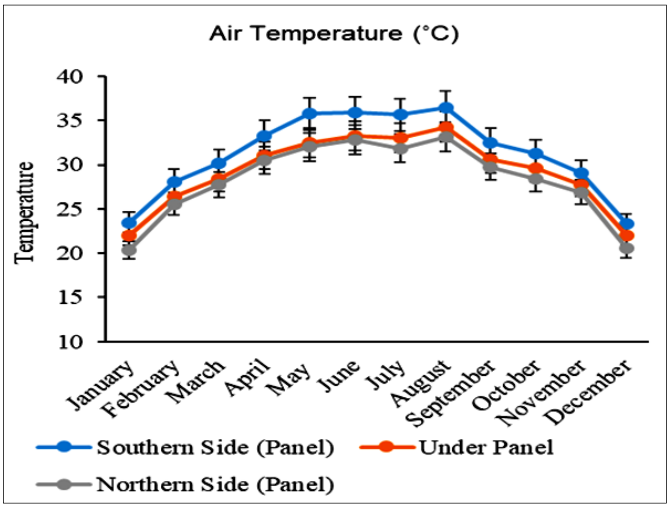


**Fig. 4.** Mean air temperature for AGV study area (Values are in means ± SD (n = 3)).

### Soil surface temperature

Soil temperature is one of the most important factors affecting soil nutrients and soil-moisture density and viscosity (25, 26). The current research found that soil surface temperature across different areas under panel, before panel and after panel of the study area. The soil temperature was significantly lower in under panel and higher in southern side field (open) as shown in Fig. 5. Our results further indicated that the soil underneath AGV is heating up more slowly and less strong compared to open field conditions. This may be advantageous during summertime but can also become adverse, especially in spring when quick soil heating is demanded in terms of nitrogen mineralization. The soil surface temperature of the southern side panel (open field) was height during July (44 $^{0}$C) and lowest during January (25 $^{0}$C) and 35.10 $^{0}$C annual average soil surface temperatures attain. The heights soil surface temperature attains for under panel area during July (39 $^{0}$C) and lowest during January (20 $^{0}$C) and 29.85 $^{0}$C annual average soil surface temperatures attain. The heights soil surface temperature attains for northern side panel (after panel) area during July (41 $^{0}$C) and lowest soil surface temperature attains during January (24 $^{0}$C) and 32.24 $^{0}$C annual average soil surface temperatures attains. The soil surface temperature data suggested that the

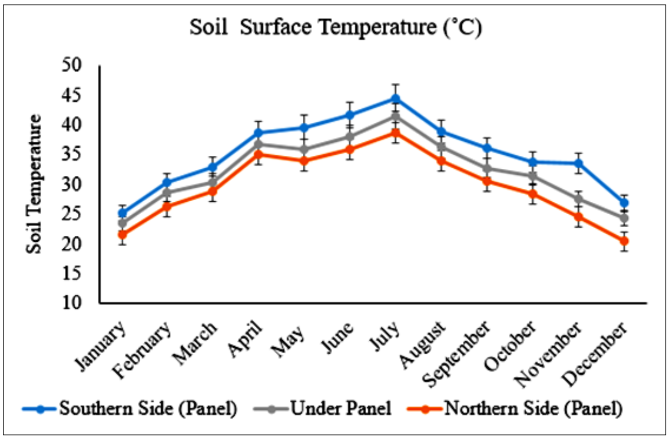


**Fig. 5.** Mean of soil surface temperature for AGV study area (Values are in means ± SD (n = 3)).

southern side of the panel has the highest soil surface temperature and a temperature decrement of approximately 9 % was observed under the panel and approximately 15 % at the northern side of the panel.

## Relative humidity

AGV systems, which integrate solar panels with agricultural land, face unique challenges in managing relative humidity, which plays a major role in crop growth. Relative humidity (RH) has a direct impact on the water relations of plants and indirectly influences leaf growth, photosynthesis, pollination, disease occurrence and ultimately, economic yield. The dryness of the atmosphere, indicated by the saturation deficit (100-RH), decreases dry matter production by regulating stomatal activity and leaf water potential. Our study found that the presence of solar panels leads to increased humidity levels on the northern side of the panel area, while the southern side experiences lower humidity (Fig. 6). The relative humidity data suggested that the southern side of the panel has the decrement of approximately 4 % in compared with under the panel and approximately 9.5 % from the northern side of the panel.

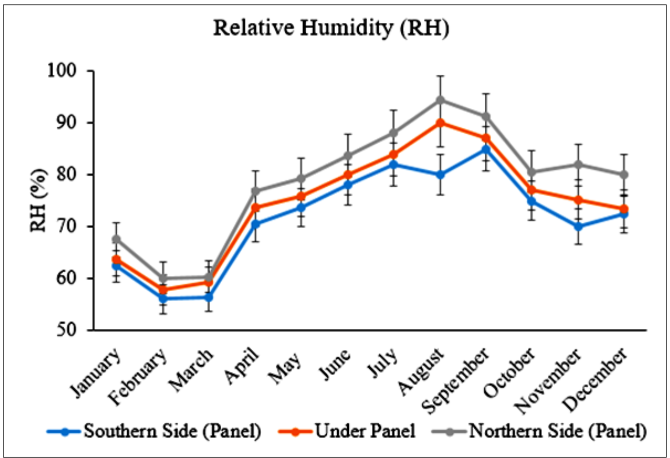


**Fig. 6.** Mean of relative humidity for AGV study area (Values are in means ± SD (n = 3)).

## Light intensity

The current study found that in light intensity at a height of 1.5 m above the ground across different areas were significantly different between different study area. Different study areas monthly average light intensity was plotted for the AGV study (Fig. 7). The light intensity was higher in southern side of panel and lower light intensity was recorded in northern side of PV panel are. The descending arrangement average annual average light intensity for the three different study area was found as southern side panel area, then under panel area and then northern side of 3 m mounted solar panel. These observations light intensity indicated significant variations in between the study areas. In AGV systems the sunlight is blocked by PV panels and others structural parts creates absolute shade and it depends on the relative position of the sun and orientation of PV panels. It is also observed that installation of 3 m mounted PV panels (South faced with $25^0$ inclination) reduced light intensity by 45 % on northern side area and 40 % for under panel area. The light intensity plays a major role in crop production depending upon the light requirement of the crops, okra requires high light intensity for its growth, which is reflected in our crop parameters. The crop growth was found to be better under open conditions, whereas shade loving crops depicted a higher growth rate and crop yield under the AGV panels.

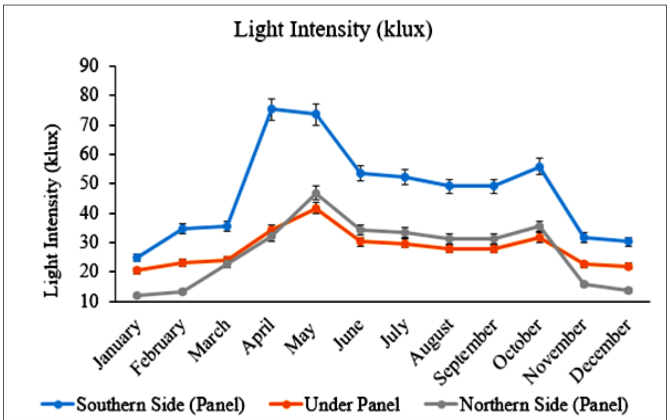


**Fig. 7.** Average monthly basis light intensity (klux) for AGV study area (Values are in means ± SD (n = 3)).

## Canopy temperature

The current study continuously monitored canopy temperature for okra during the cropping period using infrared thermometer (HT-826, Dr. care, Yellow, India) positioned over the canopy area for the different study plots. The collected canopy temperatures were compared on monthly basis for the okra crop for the under-panel area crop canopy and after panel area crop (northern side) canopy and open area crop (southern side of PV panel) canopy. The monthly average data resulted that highest diurnal temperature attained in the southern side panel crop canopy and lowest diurnal canopy temperature attained in the northern side panel crop canopy (Fig. 8).

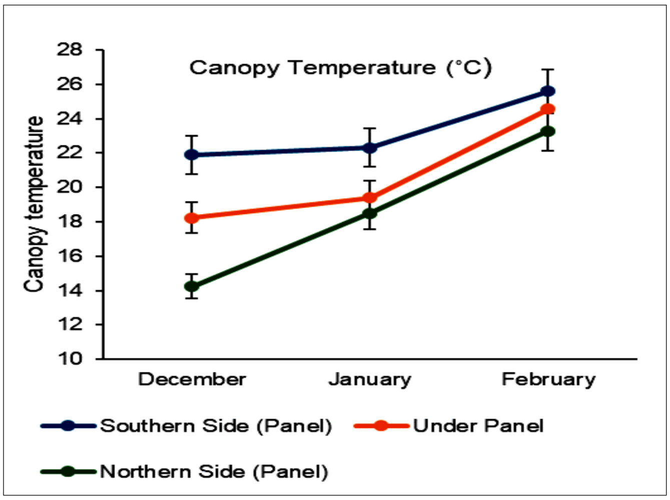


**Fig. 8.** Monthly average canopy temperature for AGV study area (Values are in means ± SD (n = 3).

## Crop monitoring

Okra, a widely cultivated vegetable appreciated for its distinctive taste and nutritional benefits, requires specific conditions for optimal growth. This article delves into the performance of okra crops under an AGV system, specifically focusing on the South 24 Parganas region of West Bengal, India. AGVs, the simultaneous cultivation of crops and solar energy generation, offers a promising approach to sustainable agriculture. Research suggests that okra, a relatively shade-tolerant crop, thrives in the partial shade provided by solar panels due to the increased humidity and reduced water stress. Below section okra plant height, leaf number, leaf area index, yield was discussed on 15 days after planting for AGV.

### Okra plant heigh

To evaluate okra growth, plant height was measured 15 days after planting for each treatment group. Our findings indicate that okra plants in the northern panel area exhibited greater height compared to those in the southern area (Fig. 9). This difference in height may be attributed to the shading effect created by the solar photovoltaic (PV) panel. A t-test was conducted to compare the heights of okra plants in the AGV study area. The *p*-value of 0.035, significant at the 5 % level, suggests a statistically significant difference in plant height between the treatments.

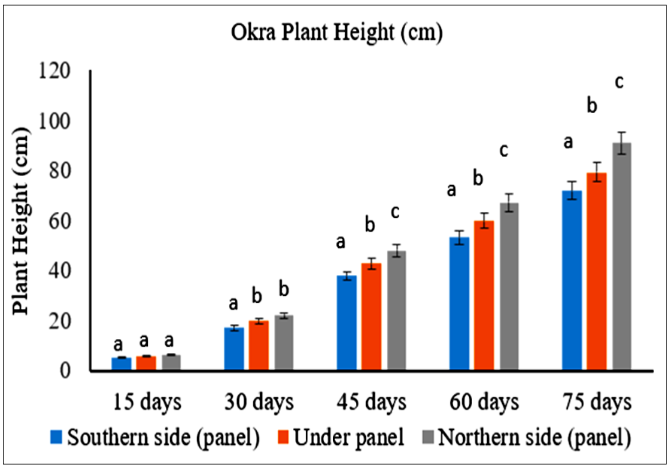


**Fig. 9.** Okra plant height for AGV study area (Values are in means ± SD (n = 3) and different significantly from one to another at P < 0.05).

### Okra number of leaves

The number of leaves on the okra plants in the southern side, under panel and northern side panel area was compared using a t-test. At the 5 % significance level, a statistically significant difference was indicated by the *p*-value of 0.034. On the northern side area of the installed solar PV, the highest leaf count was recorded and on the southern side, the lowest count. On the northern side of the 3-m mounted solar PV panel, the average number of leaves per okra plant was highest, while on the southern side, it was lowest (Fig. 10).

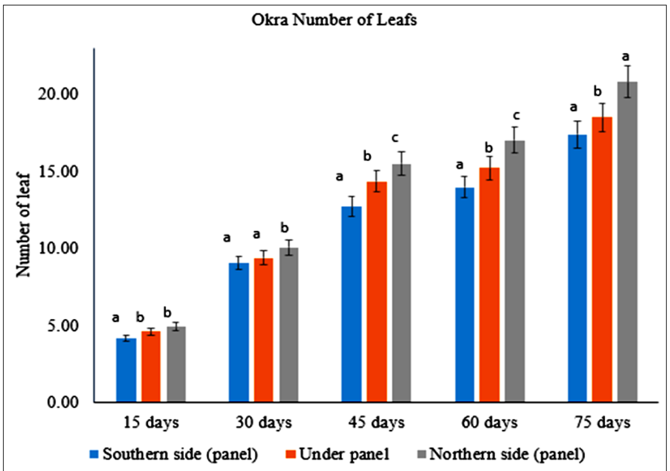


**Fig. 10.** Okra plant number of leaves for AGV study area (Values are in means ± SD (n = 3) and different significantly from one to another at P < 0.05).

### Okra leaf area index (LAI)

Okra plants grown under the AGV maximum shade on the northern side exhibited a significant increase in leaf area index (LAI), reaching 34.68 % higher than those on the southern side (Fig. 11). This enhanced LAI on the northern side is attributed to the shade provided by the installed solar photovoltaic (PV) system, both below and above the mounted panel area. Furthermore, the investigation revealed an overall 17.85 % increase in LAI within the under-panel region. A t-test comparing the LAI of okra plants in the three study plots—the northern side, the southern side and under the panel of a 3 m mounted PV system—produced a p-value of 0.042, indicating a statistically significant difference at the 5 % significance level. The highest LAI for okra during the 75 DAP was 3.37 on the northern side panel, while the lowest LAI was 2.63 on the southern side panel. The shade from the mounted PV system reduces direct sunlight, promoting an increase in leaf area in the panel plots on the northern side.

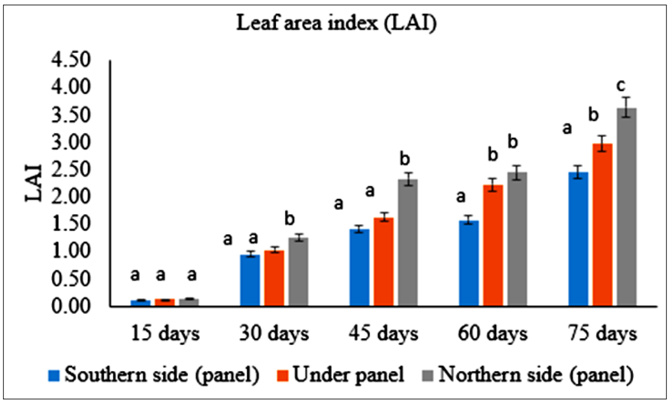


**Fig. 11.** Okra plant LAI for AGV study area (Values are in means ± SD (n = 3) and different significantly from one to another at P < 0.05).

### Okra yields

When evaluating okra yields in an AGV system, several factors have been considered. These include the impact of photovoltaic (PV) panels on okra plant growth and productivity, as well as how this integration compares to traditional farming practices. Northern side of mounted PV panels the okra yield was recorded lowest and higher yield was recorded in the southern side (open field) of the mounted PV (Fig. 12). The variation in yield is due to the

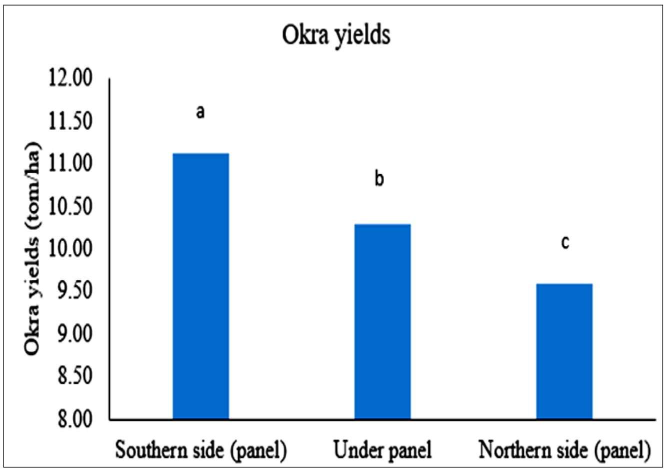


**Fig. 12.** Okra plant yields for AGV study area (Values are in means ± SD (n = 3) and different significantly from one to another at P < 0.05).

southern side of the PV-mounted area receiving full sunlight throughout the day, while the northern side and the area behind the PV mount receiving partial sunlight throughout the day. This study investigated the impact of varying shade levels on okra yields. The results revealed a significant relationship between light exposure and okra production. The heavy shade treatment resulted in the lowest yields, with okra plants exhibiting stunted growth and a markedly reduced number of fruits. These findings underscore the critical importance of optimal lighting conditions for okra growth (Table 2). As a sun-loving plant, okra thrives in abundant sunshine, which is essential for fruit development and efficient photosynthesis.

**Table 2.** Okra crop performance between southern side (panel), under panel and northern side (panel).

| Year | Treatment | Yield (ton/ha) | Plant height (cm) | Number of leaf's | Leaf Area Index (LAI) |
|---|---|---|---|---|---|
| 2023 | Southern side (panel) | 11.00 | 72.64 | 16.25 | 2.55 |
| | Under panel | 10.05 | 81.67 | 18.51 | 3.10 |
| | Northern side (panel) | 9.45 | 93.25 | 20.43 | 3.72 |
| T-Test | | ** | ** | ** | ** |
| 2024 | Southern side (panel) | 11.22 | 71.23 | 15.57 | 2.35 |
| | Under panel | 10.53 | 76.89 | 18.52 | 2.84 |
| | Northern side (panel) | 9.71 | 88.50 | 21.25 | 3.54 |
| T-Test | | ** | ** | ** | ** |

** Significant at 0.05.

### Technoeconomic benefits of AGV

The integration of an AGV system for okra cultivation presents a promising yet challenging scenario regarding its technoeconomic viability. From a technical standpoint, meticulous planning is crucial to seamlessly integrate photovoltaic (PV) panels into okra farming, ensuring a balance between energy production and optimal crop growth. As okra thrives in full sunlight, excessive shading can negatively impact yield. Consequently, the system should be designed to minimize shading, potentially utilizing raised or movable PV panels that allow sufficient light penetration. AGVs farm is business comprised of 2 activities, such as crop production and electric power generation. To understand the profitability of AGV system, annual income and expenditure during the project lifetime has been analysed.

#### *Electricity generation*

- No of panel per 24 $m^2$ area = 4
- Assuming same arrangement for 1 ha area, no of panels = 104
- Each panel has a power rating of 300 W under ideal conditions
- Total power generation under 1 ha area = 31.25 Kw
- Effective sunshine for optimum energy production is 9AM to 4 PM
- Total power generation per day = 219 KW/day
- Calculating power generation in a year,
- assuming 10 % day losses due to cloudy conditions = 65700 KW/ha
- Income generation: (65700 KWh x 7 Rs/ unit) = Rs. 459900
- Installation cost at standard government rate: Rs 65000/ KWh
- Total installation cost per ha = 65000 x 31.25 = Rs 2031250
- Maintenance cost at standard rates = Rs 100000/ year
- Break-even point reached at 3 years, then onwards per year income= Rs. 359900

An analysis done for 1 ha land and resulted that the breakeven point reached at 3 years, then onwards additionally per year income (Rs. 359900/ha) generates for adoption AGV system.

### Advantages over normal cultivation

The maximum yield obtained under open conditions is 11.22 ton/ha and 9.26 ton/ha under AGV systems. The additional revenue generated from the electricity will lead to an increase in income generation by 54.5 % in every season, in comparison to only crop production. Thus, it will be beneficial for light intensity loving crops alongside shade loving crops.

## Discussion

The study area is situated in the coastal saline zone in South 24 Parganas of West Bengal. Solar PV panels above crop fields mainly reduce solar radiation as well as some other factors also such as its effects on air temperature, soil temperature, soil moisture condition, incident radiation, air humidity, wind speed and evapotranspiration rate (27-29). The installation of AGV systems will lead to an increase in income generation by 54.5 % in every season, in comparison to crop production. Detailed analysis is provided in technoeconomic analysis. The okra crop being a light intensity loving crop, the yield/ha was increased in open land in comparison to under AGV system, but the higher income generation from electricity production will become much more effective to the farmers. The AGV systems were found to be much more effective for shade-loving crops as it led to an increase in yield/ha in comparison with open field condition. Reported that under the AGV system the microclimatic conditions and crop production change by reducing 30 % photosynthetic active radiation and reported that soil moisture and air temperatures reduced and rain distribution changed (30, 31). AGV system lowered crop temperature by 2.83 °C and 0.71 °C and PV energy generation efficiency improves of 1.13 to 1.42 % and 0.28 to 0.35 % on sunny days and cloudy days, respectively (31, 32). A AGV study in the California desert estimated that 14-29 % of water evaporation was reduced by artificial irrigation water and in the Arizona desert 50 % of water savings (23, 33), which resembles with our data as

20 % and 28 % higher moisture content was found under panel and northern side panel area respectively in comparison to open field condition in southern side. A properly installed and oriented panel in an AGV system makes shadows that reduces water consumption by 20 % and yield decrease by 10 % for light intensity loving crops or, alternatively extension of the cropping cycle (34), which is also justified by our study as there has been a decrease of 7 % under AGV systems. It has been reported that an AGV system decreases the potential evapotranspiration (PET) rate due to decreased solar radiation (32). Another study reported that the net radiation and available photosynthetically active radiation (PAR) for open sun field and under solar PV panel field, found that on under solar panel field lower PAR attains (35-37). Additionally, another study also reported that AGV system effect on organic crop production field (8). Solar PV arrays caused seasonal and diurnal variation in air and soil microclimate, during the summer (reduce temperature up to 5.2 °C) and during the winter (reduce temperature up to 1.7 °C) as compared with controlled area and under PV arrays (38, 39). Under solar PV area reduces direct sun light, which led to reduce air temperature during daytime and warmer during nighttime and retain moisture (40). The greater plant height was found under AGV systems, due to low light intensity. The crop production thus reduced as vegetative growth increased.

## Conclusion

To the best of our knowledge, this study is the first to examine okra cultivation under the shade conditions produced by an AGV system mounted solar PV. The results show that the shade from solar panels changes microclimate conditions such as air temperature, soil temperature, crop canopy temperature, humidity and light intensity which improves soil moisture condition. Since okra is a crop that prefers light intensity, its output per hectare was higher in open land than it was under an AGV system. However, farmers will benefit greatly from the extra revenue generated by the production of energy. When compared to open field conditions, the AGV systems were found to be significantly more successful for crops that prefer shade, as seen by the increase in production per hectare. While partial shade may offer some benefits in certain climates, reducing the overall light intensity temperature can significantly impact production. These insights can guide farmers in choosing appropriate planting locations and shade management strategies to optimize okra yields. Further research is recommended to explore the specific light requirements of different okra varieties and the potential benefits of controlled shade for specific environments. In this way, this work paves the way for an integrated AGV system design that maximizes food and energy output within a specific economic setting.

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## Authors' contributions

AI, SKK, BG and SK designed the experiment. AI, TKM and SK carried out the experiment and SKK and BG performed growth and physiological analysis of plants. KKS and AI performed analysis. AI, SK and BG wrote and reviewed the manuscript. All authors read and approved the final version.

## Compliance with ethical standards

**Conflict of interest**: Authors do not have any conflict of interests to declare.

**Ethical issues**: None.

## Declaration of generative AI and AI-assisted technologies in the writing process

GenAI tools were used to upgrade the language of the manuscript and to reconstruct sentences to remove grammatical error.

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