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A non-traditional Agrophotovoltaic installation and its impact on cereal crops: A case of the BRRI-33 rice variety in Bangladesh

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ABSTRACT

Traditional Agrophotovoltaic (APV) installation (i.e., basic row layout with minimum or no usage of the space underneath the solar PV panels) is responsible for a vast amount of agricultural land waste as no regular crops are grown under the shade of APV. Bangladesh is no exception to this trend. A primary in-person survey of about 50 solar irrigation pumps (SIPs), i.e., APVs, in Bangladesh, shows that on average, 13.77 decimal or 7,200 sq.ft. of land is used for each APV system installation. If 10,000 SIPs are installed by 2027 in Bangladesh, as targeted by the government through Infrastructure Development Company Limited (IDCOL) by employing the same procedure, the land wastage would be 1,652 acres. Notably, this is a critical issue for a country like Bangladesh with a scarcity of agricultural lands. According to World Bank data, agricultural land in Bangladesh was about 80% in 1989 and reduced to 76% in 2020 due to population growth and urbanization. Therefore, to reduce agricultural land waste a non-traditional APV installation procedure, along with its shading impact on the BRRI-33 rice variety (a major crop in Bangladesh), has been investigated in this study. The results show that discontinuous sunlight has an insignificant impact on BRRI-33 rice production, and APV might be installed in the cultivating area for irrigation purposes. This non-traditional APV installation has a statistically insignificant impact on rice yield. For instance, the 100 grains' yield variation was between 1.45 and 4.82%, which is insignificant. Additionally, the APV shade does not negatively impact soil p^H level, and shadow helps keep the soil temperature low and ensures less irrigation. Hence, the proposed non-traditional APV installation could achieve sustainable agriculture and energy development through efficient land use at least in the case of the BRRI-33 rice variety.

1. Introduction

Globally, energy sources, particularly electricity generation, are becoming green and sustainable, and one of the crucial reasons behind this transition is the United Nations' sustainable development goals [1]. Solar PVs are one of the most common renewable energy generation technologies [2]. Many different installation forms are now available, such as utility-scale, roof-top solar, and solar home systems in rural areas of developing countries [3,4]. Solar PV is also proven to be one of the effective primary light sources during

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an emergency [5].

To mitigate negative climate change and ensure a sustainable future renewable energy application is crucial for every energy-consuming sector, including agriculture [6]. Agrophotovoltaic[1] (APV) is a new application of solar technology that allows energy and crop production on the same land [7]. In Germany, it was found that APV could increase farming productivity by 160% [8]. The APV is becoming popular in many countries, such as the USA, Japan, South Korea, China, France, and India [8,9]. For example, APV was found potential as electric vehicle charging station in rural Oregon, USA [10]. It was also reported that "*APV's dual function of agricultural yield protection while simultaneously generating solar power increases the economic output per area and enhances farmers' resilience against the impacts of global warming by securing and diversifying their sources of income*" [11]. Globally, the total installed capacity reached about 2.8 GW in 2020 [12].

In Japan, a study assessed the sector-wide social impact of APV and found that overall global and future generational-level impact is positive. The study conducted 514 surveys; of which, there were farm operators (153), workers in the agricultural sector (153), and local residents (208). Regarding total local impact, about 28% was found positive, 56% and 17% were neutral and negative, respectively [13]. Another study in Japan investigated new functional units (FU) for APV systems, namely the modified area-based FU and the monetary-based FU, and found them beneficial for crop production [14].

In Bangladesh, the APV in the form of a solar irrigation pump (SIP) has been used in rural areas to irrigate agricultural lands. A government-owned non-bank financial institution, Infrastructure Development Company Limited (IDCOL), finances renewable infrastructure projects in Bangladesh and aims to install about 10,000 SIPs by 2027. IDCOL has installed about 1,515 SIPs till March 2021 in Bangladesh, with a capacity of about 40 MWp [15]. However, some barriers still hinder the progress of renewable generations, such as the land requirement for solar PV installation. For instance, it was estimated that by 2030, the land requirement for utility-scale solar installation in the USA could lose around 2 million acres of land [16]. It was reported that for the ground-mounted solar PV system, the land underneath the panels in or near the agricultural field is traditionally unused [17].

To be more specific, Agrophotovoltaic, that is, solar irrigation pumps in Bangladesh, are installed on agricultural land and one of the crucial reasons is to increase renewable energy generation as energy intensity is increasing in the agricultural sector in Bangladesh [18]. A primary in-person survey of about 50 SIPs in Bangladesh shows that on average, 13.77 decimal or 7,200 sq.ft. of land is used for a SIP installation. Most importantly, the area is fenced and isolated (see Fig. 1 (a)), and these lands are not used for cultivation (see Fig. 1 (b)). Thus, the installation of 1,515 SIPs up to March 2021 wasted agricultural land of about 250 acres. If 10,000 SIPs are installed by 2027 in Bangladesh, as targeted by IDCOL through the same procedure, the land wastage would be 1,652 acres. A study found that 25–80% solar penetration in the electricity generation fuel mix will occupy 0.5–5% of land in the regions, including the EU, Japan, South Korea, and India [19]. This might not be a problem for countries with a large geographical area. However, in a densely populated developing country like Bangladesh with a scarcity of agricultural land, a waste of approximately 1,652 acres by 2027 would be a great concern. Although there might be some solutions to this problem in other countries (e.g., Ref. [20]), the solution that works in one country might not be applicable to other countries due to many different factors including social, economic, technical, and environmental issues. For instance, one of the proposed solutions to the shading impact of APV is the use of semi-transparent PV (STPV) modules [12] or vertically mounted APV systems [21]. However, further research is necessary to increase the STPV cell's efficiency and investigate the 'photomorphogenic effects due to the reduced infrared wavelengths'. Hence, one of this work's primary objectives is to identify an effective APV installation solution that could solve this problem in a developing country, particularly focusing on Bangladesh.

Numerous studies in the literature studied the impact of APV on crop production. For instance, Ott et al. (2022) analyzed the environmental effects of APV. One of their crucial findings is that applying APV to agricultural land could reduce water consumption by 14–29% [22].

A recent study found that "*no crop type has an exactly proportional decrease of yield due to an increased level of shading,*" and they reported that due to APV shading, different crops' growth, and yield responded differently [23]. For instance, maize and grain legumes significantly lose yield; whereas up to 40% shade could benefit berries, fruits, and fruity vegetables. A similar result was also found in the USA, where fruit production was twice as great under the APV panel [24]. At the same time, the study also found that due to the use of APV, the water use efficiency was found to be 157% greater than that of the standard cultivation method. Similarly, the APV has great potential on grape farms [25].

Although the vertically tilted bifacial APV might be expensive, it was found effective in reducing energy losses due to dust [26]. However, depending on the region and environment, a tradeoff between monofacial tilted PV panels facing North/South and the vertical East/West facing bifacial PV panel could be made for APV application.

A simulation study on water budget and crop production for APV systems in France found that it is possible to increase the efficiency of land use and water productivity simultaneously by decreasing irrigation amounts by 20%, even if it means a 10% lower yield or a slight extension of the harvest season [27]. Another study in France found that dynamic photovoltaic panels in APV systems could be used to achieve a very high productivity per land area unit while keeping the biomass production of lettuce near or equal to full-sun conditions [28]. The authors also concluded that agricultural objectives could be met while increasing land use efficiency with associated photovoltaic production by deriving optimized controlled tracking scenarios as a function of the gross margin of crop production.

In the USA, an analysis showed that APV is one of the effective ways for dual use of agricultural land and the farmers cultivating

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[1] Also known as Agrivoltaic.


(a) (b)

Fig. 1. A surveyed solar irrigation pump in Jashore district (a) installed solar panels for the pump, the area is fenced and isolated [traditional Agrophotovoltaics], (b) unused area underneath the solar panels.

crops such as alfalfa, cotton, and barley are capable of producing 5, 4.7, and 1.5 times more energy than is needed for residential purposes within the Phoenix Metropolitan Statistical Area [29].

Evidently, studies in the literature investigated the impact of shading from APV on different crops at different geographical locations and predominantly in the developed world such as Germany, Japan, the USA. For instance, it was found that potato production under the APV is more economically beneficial than wheat production in the winter [11]. The crops that were investigated previously predominantly potato, winter wheat, spring barley, lettuce, beetroot, leeks, celery, flowers, ginseng, Chinese cabbage, pointed cabbage, clover, celeriac, spinach, peas, bush beans, chard, radishes, chiltepin pepper, jalapeño, and cherry tomato [11,24]. A list of crops studied with respect to APV can be found in Ref. [30]. However, none of the previous studies considered the APV shading impact on rice, a major cereal crop and staple food in developing countries like Bangladesh. As per the report of the FAO (Food and Agriculture Organization) of the United Nations, Bangladesh has held the third-place position in the world for rice production for four years in a row [31]. Half of the nation's protein consumption comes from rice, which accounts for two-thirds of the nation's overall calorie requirements. The Bangladesh Bureau of Statistics estimates that 10% of the country's GDP is made up of agriculture and horticulture, with rice accounting for half of this total [32].

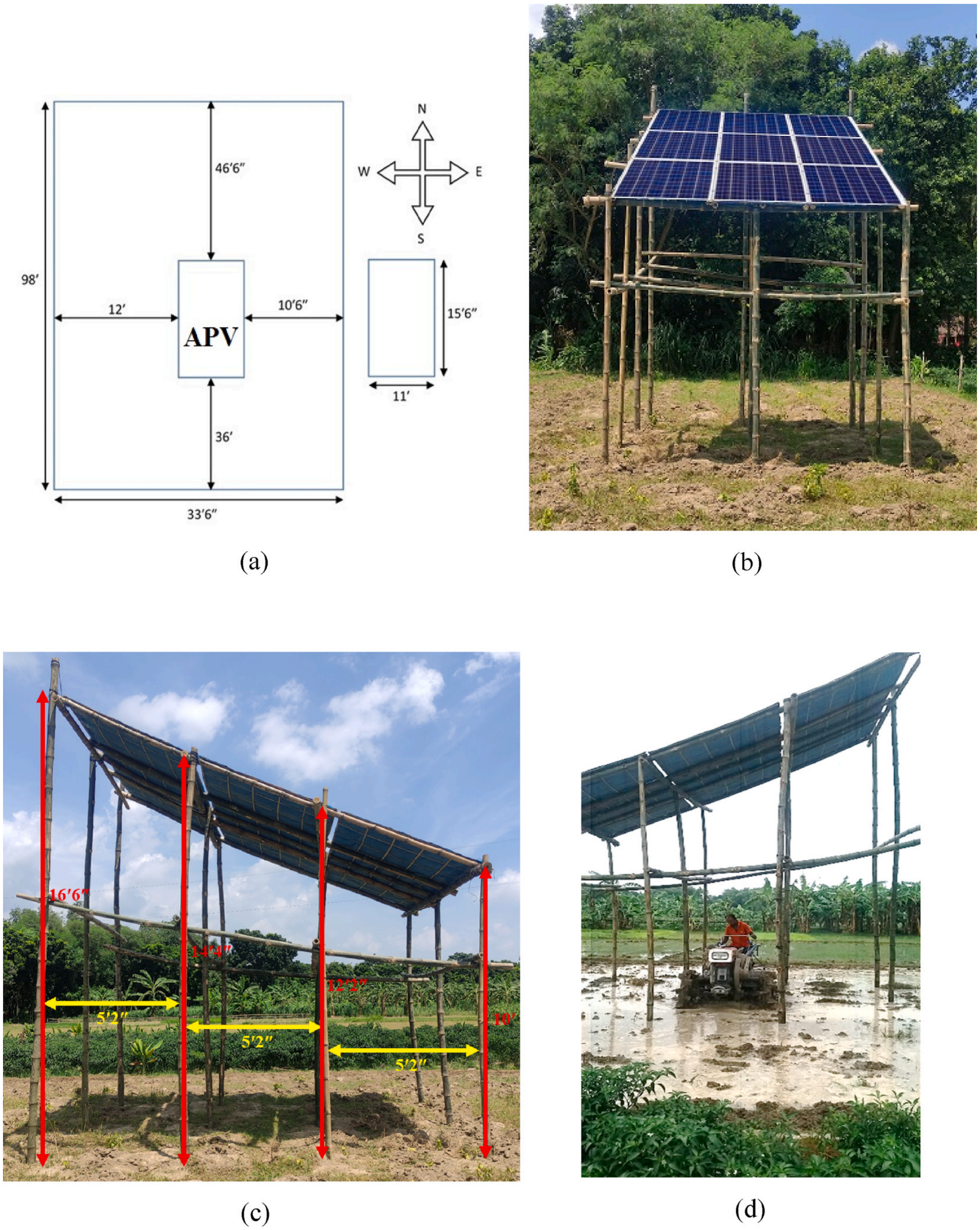
A recent study also indicated the future research scope of the APV by focusing on "…. ..*how the region-specific shade pattern varies for a given PV module configuration and the corresponding implications for the cropping practices*" [20]. Likewise, another study also indicated the future research scope as "… *additional solar infrastructure designs and configurations should be considered, to better understand trade-offs in energy output and plant productivity; and additional installations around a biogeographic gradient should be explored to quantify the relative impacts*" [24]. In addition, Dinesh and Pearce (2016) also recommended that it is essential to continue investigating this field and to analyze the outcomes of APV farming in various crops and locations worldwide to determine its full potential [33]. Hence, this study is novel for a number of reasons: first, as the authors are concerned, this would be the first study that investigates the shading impact of APV on rice crops. Second, the study is conducted in a temperate climate region with plenty of solar irradiation and limited fossil fuel reserves, where alternate energy generation techniques are crucial. Third, this investigation has been conducted in a developing country context, whereas most previous studies were in developed countries. Notably, the findings from developed countries might not suit developing economies due to many factors (e.g., barriers), including social, economic, environmental, and technical [34]. Hence, the impact of APV at different geographical locations with their major crops should be investigated separately. Finally, this study will underpin in identifying a suitable APV installation procedure to minimize agricultural land waste.

The rest of the article is organized as follows: Section 2 describes the data and methods used for this study. Section 3 presents the results and analysis obtained from this work. Section 4 discusses the findings, and the final section concludes the article with limitations and possible future research scopes.

2. Data and methods

2.1. Site selection and APV installation

To check the impact of a new installation type of APV in Bangladesh, the land was selected in Belnagor, Magura district; the site was about 50 km from Jashore. The exact location of the site was 23.519643°N, 89.489545°E (Fig. 2 (a)). Initially, it was planned to select the experimental site in Jashore. However, due to the maintenance cost and a few other factors, such as access to the site, Belnagor was selected. In addition, regarding agricultural characteristics, the Magura district is in the greater Jashore region [35]. Calcareous brown floodplain soils and calcareous dark grey floodplain soils are this region's two main forms of soils. These soil types suit agricultural crop production, particularly cereals, and vegetables [35]. Due to the dry weather, this region requires irrigation for crop production.



(a) (b)

(c) (d)

Fig. 2. Showing the dummy APV setup in the field. (a) position of the APV in the field, (b) the number of required solar PVs, (c) approximate measurements of the new setup-side view, and (d) power tiller movement through the APV pillars while plowing.

The cropping intensity is higher in this region than in other areas of the country [35]. Furthermore, the cost of land preparation for the current study was less than that of the other nearby site in Jashore. Hence, due to the similar characteristics of the land and weather, site selection in Magura will not significantly impact the study conducted.

One of the main objectives of this study is to check the suitability of the newly proposed (within Bangladesh) non-traditional APV installation and its impact on the crops underneath. Hence, a dummy was employed with the same dimension as the actual required PV system instead of an actual solar PV setup (Fig. 2 (b)). The dummy was made from bamboo and polyethylene. The distance between the poles was more than five feet, and the APV height was maintained from ten to sixteen feet six inches to meet the tilting angle (23° and south-facing) of the solar PV (Fig. 2 (c)). The distance between poles was chosen in such a way that a power tiller can easily move through them (Fig. 2 (d)). A 1.5 HP water pump was considered for irrigation with a solar PV capacity of about 1,800 W. Although the solar irrigation pump is proposed for the site, it is not installed as the study's primary objective is to assess the shading impact of solar PV on crops underneath the panels. Thus, a regular irrigation system (diesel-powered pump) was used to irrigate the land.

2.2. *Rice field preparation, plantation, culture, and sample harvest*

The BRRI-33 rice was chosen for this study because it is one of Bangladesh's most widely cultivated high-yield rice varieties. This variety is suitable for Amon season, Bangladesh's main rice growing season. The BRRI-33 rice is also capable of protecting to a few diseases and pests.[2] In addition, this variety requires fewer farming expenditures.

The rice seedlings were grown in a dry bed for four weeks before being transplanted into the experimental field. While developing seedlings in a soft bed, the experimental site was wet-prepared, which included plowing, de-weeding, irrigating, and manuring. A power tiller was used for plowing, and a diesel-powered pump was used for irrigation (as a solar-powered pump was not installed). The experimental field was then split into four plots (see Fig. 3 (a)). The shadow path due to the sun movement is depicted in Fig. 3 (b). The seedlings were collected by pulling them out of the wet bed and immediately manually transplanted into the wet plots with the same planting density in each plot. After transplantation and the establishment of hills, these plots were maintained with standard irrigation, pesticide, herbicide, and fertilizer applications. Different fertilizers and pesticides were applied to the land, as shown in Fig. 4.

Paddy growth stage developmental parameters, such as plant height, tiller formation initiation, and number of tillers per hill, were recorded in various growth phases. Different physical parameters such as soil pH, temperature, irradiation, and light intensity were measured weekly until grain formation. Leaf samples were harvested at flag leaf formation time for chlorophyll content determination. After about 90 days of nurturing, the mature paddy was ready to harvest. Each plot's paddy harvesting tasks, such as reaping, stacking, moving, threshing, cleaning, and hauling, were all completed manually on the same day. After harvesting paddy straw and rice from different plots, they were sundried and weighed to get the grain and biomass total yield parameters.

2.3. *Leaf chlorophyll contents determination*

Following the previously reported protocol [36], flag leaf stage leaf samples from different plots were collected in a zipper polybag, and their chlorophyll contents were immediately determined. Briefly, fresh samples were ground into a fine paste in a mortar and pestle. The pasted sample was measured and mixed at a 1:1 ratio with 80% acetone (20 mL deionized water added with 80 mL acetone) in a 15 mL falcon tube and left in the dark for 24 h at room temperature (25 °C). Finally, the tube was centrifuged at 15,000 rpm for 5 min at room temperature. The supernatant was used to take a spectrophotometric reading using a UV–Vis spectrophotometer (Thermo Scientific™, USA) at 645 nm and 663 nm wavelengths. Equation (1) [37] is used to find the total chlorophyll contents.

$$Total\ Chlorophyll\ (\mu g\ /\ mL) = 20.2\ (A_{645}) + 8.02\ (A_{663}) \tag{1}$$

Where-

$$Chlorophyll\ a\ (\mu g\ /\ mL) = 12.7\ (A_{663}) - 2.69\ (A_{645})$$

$$Chlorophyll\ b\ (\mu g\ /\ mL) = 22.9\ (A_{645}) - 4.68\ (A_{663})$$

A_{663}, A_{645} represent the absorbance values at the respective wavelengths.

For further detail regarding the calculation, see Ref. [37].

3. Results and analysis

3.1. *Field parameters*

The light intensity was measured using a lux meter, and the variations are depicted in Fig. 5 (a-c) (for data, see Table A1 in the Appendix). Light intensity was the lowest for every area under the APV panel for every measurement time. The average light intensity in the unshaded areas in the morning and afternoon was about three times higher than in the shaded areas. At 12 o'clock, the light intensity was about four times higher in the unshaded area than the shaded ones.

Regarding the soil's p^H value, the average p^H level under the shade varied between 6.31 and 6.44. Whereas for the unshaded areas, it varies between 5.81 and 6.44. In addition, it can be seen that the 25th percentile never went below p^H level 6 in the shaded area. In contrast, in the unshaded area, it went as low as 5.12 (25th percentile). On the other hand, for the 75th percentile, the p^H level remained below 6.87 in the shaded area. The p^H went up to 7 (75th percentile) for unshaded areas. Hence, the soil p^H is more stable in the shade than in the unshaded area. All these variations are illustrated in Fig. 6 (a-c) (for data, see Table A2 in the Appendix).

The soil temperature under the APV panel was found 1 to 2 °C less than the unshaded areas. In the shaded area, the average soil temperature varied between 29.87 and 31.25 °C. In the unshaded areas, soil temperature varied between 30.62 and 32.12 °C. All these changes can be seen in Fig. 7 (a-c) (for data, see Table A3 in the Appendix).

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[2] http://brri.portal.gov.bd/sites/default/files/files/brri.portal.gov.bd/page/5cd283d4_43bf_4b6c_b0a5_a8b6107ee7ac/2020-07-06-11-33-e9037b416b770ce015dc61542e0ccad1.pdf (accessed 24-Apr-2023).

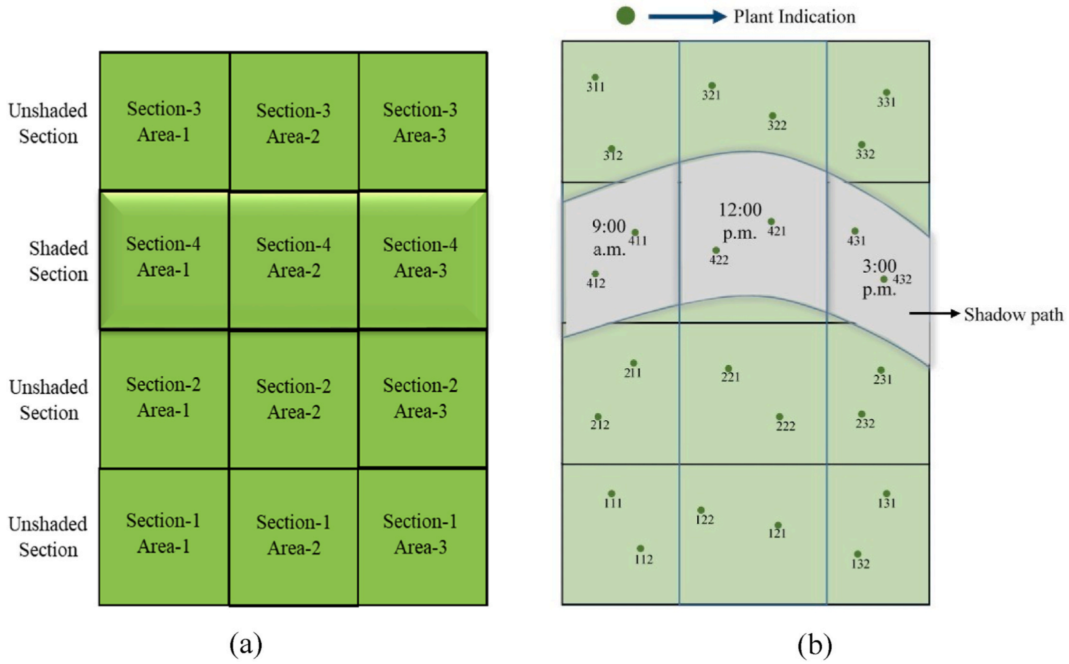


Fig. 3. Showing different plots of the land under observation: (a) illustrated different plots with shaded and unshaded zones, (b) depicts the shadow path due to sun movement and the plants under observation; the number 411 indicates plot-4, area-1, plant-1 and so on.

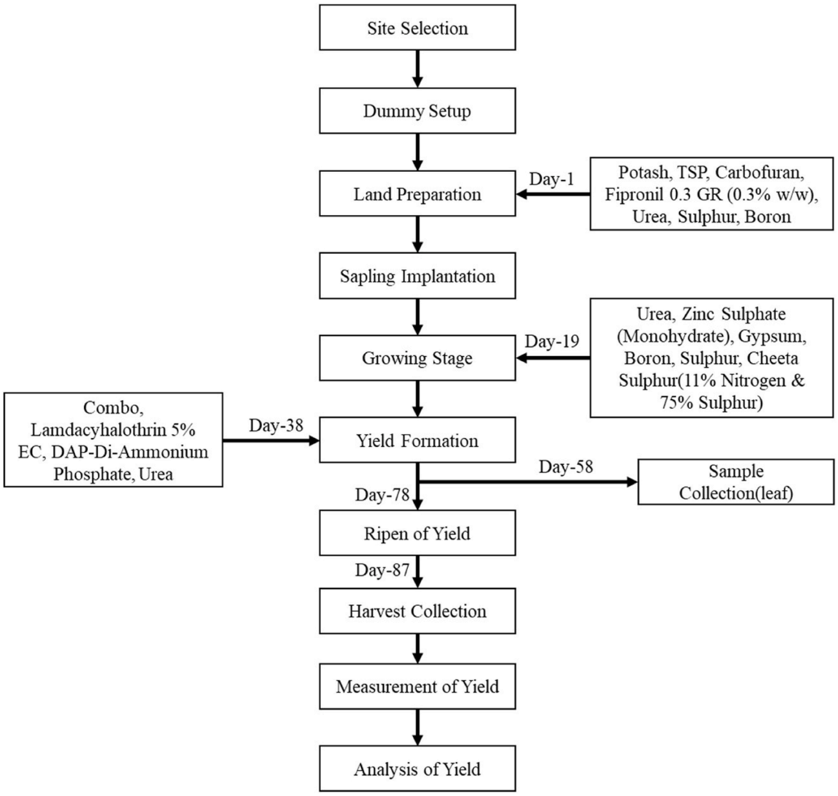


Fig. 4. Steps involved in producing the BRRI-33 rice at the selected site.

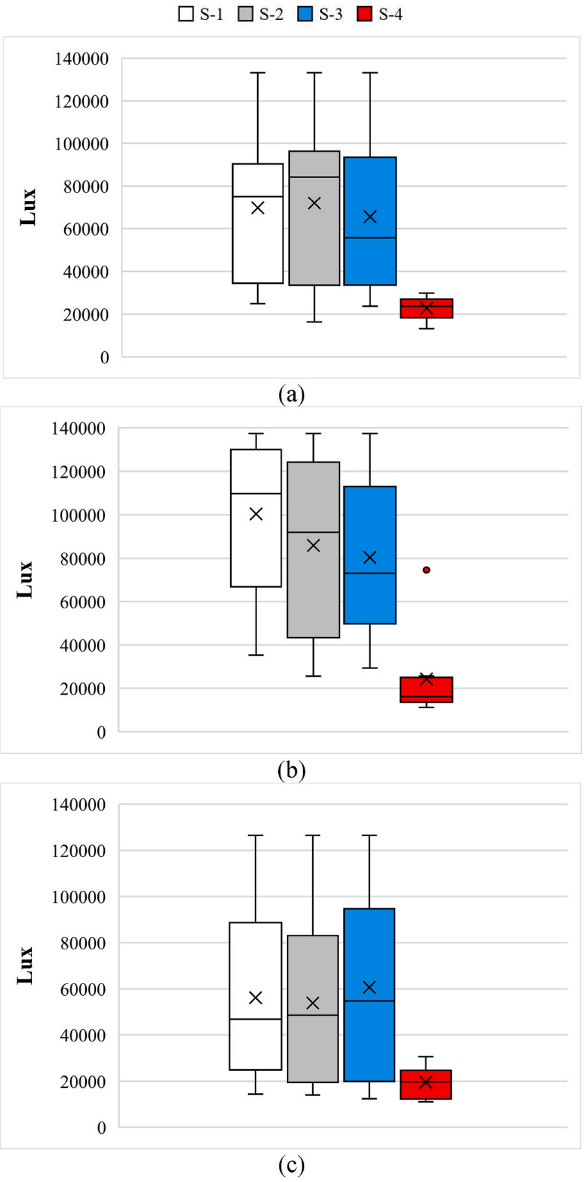


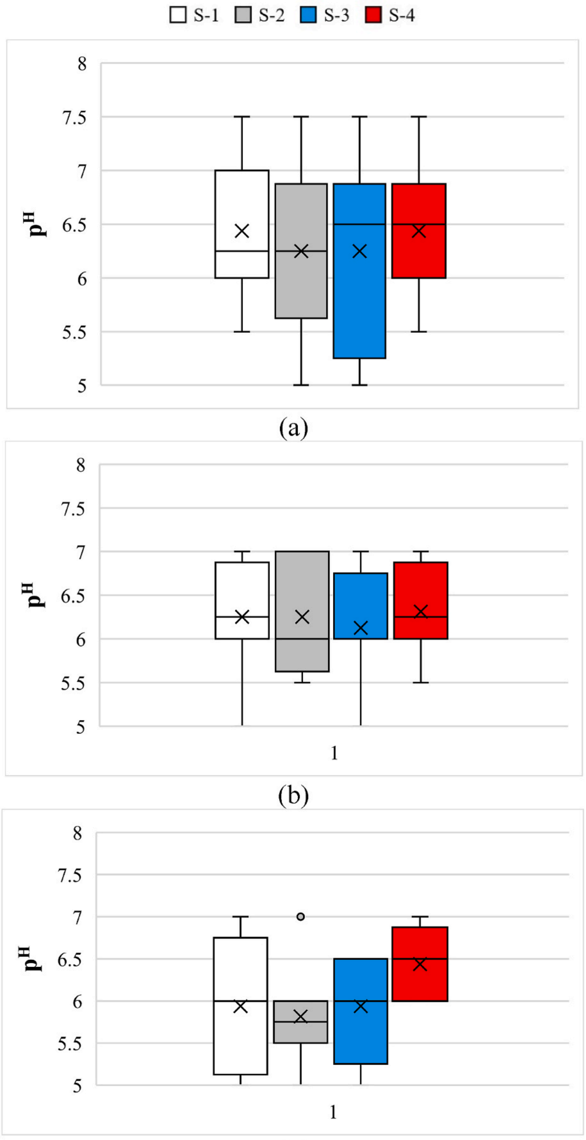
Fig. 5. Light intensity at 9 a.m., 12 p.m., and 3 p.m. for (a) area-1, (b) area-2, and (c) area-3. S-1 indicates section-1 and so on, where section-4 is the shaded zone due to APV installation. Within each box, the cross represents the average value, the horizontal line is the median value, and the box's lower (and upper) edges are the 25th (75th) percentile. Whiskers represent the upper and lower ranges. The dots (if any) represent outliers.

Fig. 8 (a-c) depict the plant growth comparison between shaded and unshaded areas (for data, see Table A4 in the Appendix). The average growth of the plants in the shaded area is between 23.12 and 21.62 inches. On the other hand, in the unshaded areas, the average height varied between 19.68 and 22.37 inches. Therefore, the growth or height of the plant in the shaded area was found to be higher than the plants in the unshaded areas.

3.2. *Chlorophyll contents*

The leaf samples were collected from the field during the flag leaf initiation time. When the samples were tested, the results of the chlorophyll content were found high in the plants in the shaded area (Fig. 9 (a)), and their physical appearance was also indicating the same. For instance, in Fig. 9 (c), the light green (unshaded) leaf at the left and the deep green (shaded) ones at the right indicate the physical appearance of lower and higher chlorophyll contents, respectively.

According to their physical appearance, the test also verifies the same. More than 45 mg/mL average chlorophyll content was found in the shaded sections' samples, which was higher than any other unshaded sections (see Fig. 9 (b)). It can also be seen from sample



(a)

(b)

(c)

Fig. 6. p^H level at (a) area-1, (b) area-2, and (c) area-3. S-1 indicates section-1 and so on, where section-4 is the shaded zone due to APV installation. Within each box, the cross represents the average value, the horizontal line is the median value, and the box's lower (and upper) edges are the 25th (75th) percentile. Whiskers represent the upper and lower ranges. The dots (if any) represent outliers.

number 11 in the shaded area (i.e., S-4) (see Fig. 9 (b)).

3.3. *Rice yield*

Six hills in one section were selected for the yield assessment. Plot-4 (S-4) is the shaded area, and plots-1 to 3 are the unshaded areas. To calculate the yield per plot, 100 grains were collected from each hill separately, and the obtained results are presented in Fig. 10. Notably, for the 100 units of grains, the average weight was found to be 1.45% lower in the shaded area compared to the maximum in the unshaded area. In contrast, 4.82% more weight was obtained in the shaded area compared to the minimum weight found in the unshaded area. Hence, the 100 grains' yield variation was between 1.45 and 4.82%, which is insignificant.

3.4. *Biomass yield*

Plants grown in the shade were much taller than those grown in the unshaded area because of the different edaphic environmental conditions (see Fig. 11). When a canopy is shaded, it grows faster than the non-shadowed plant, allowing the plants in the shaded areas

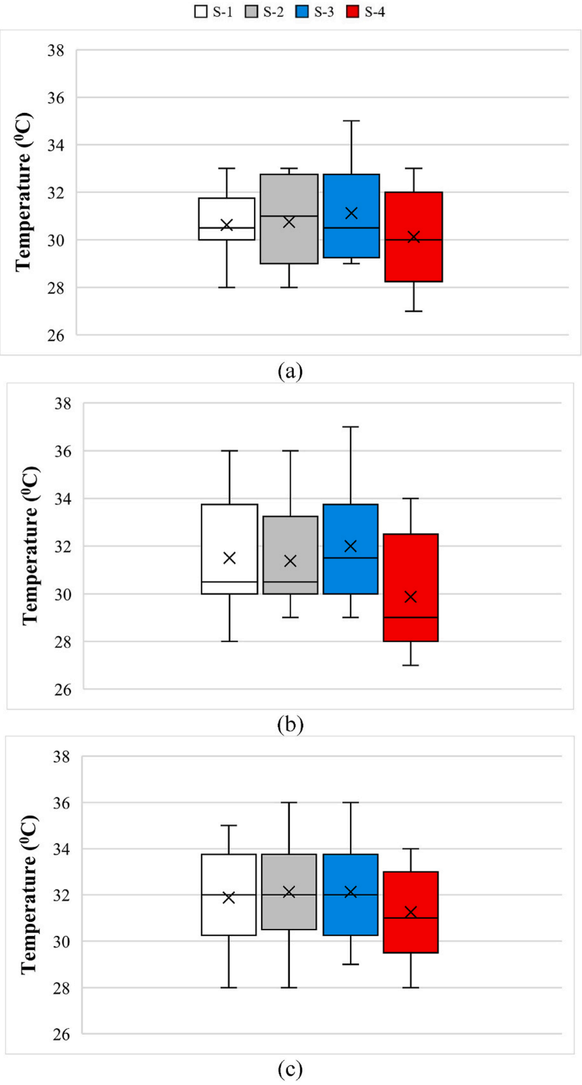


Fig. 7. Soil temperature at 9 a.m., 12 p.m., and 3 p.m. for (a) area-1, (b) area-2, and (c) area-3. S-1 indicates section-1 and so on, where section-4 is the shaded zone due to APV installation. Within each box, the cross represents the average value, the horizontal line is the median value, and the box's lower (and upper) edges are the 25th (75th) percentile. Whiskers represent the upper and lower ranges. The dots (if any) represent outliers.

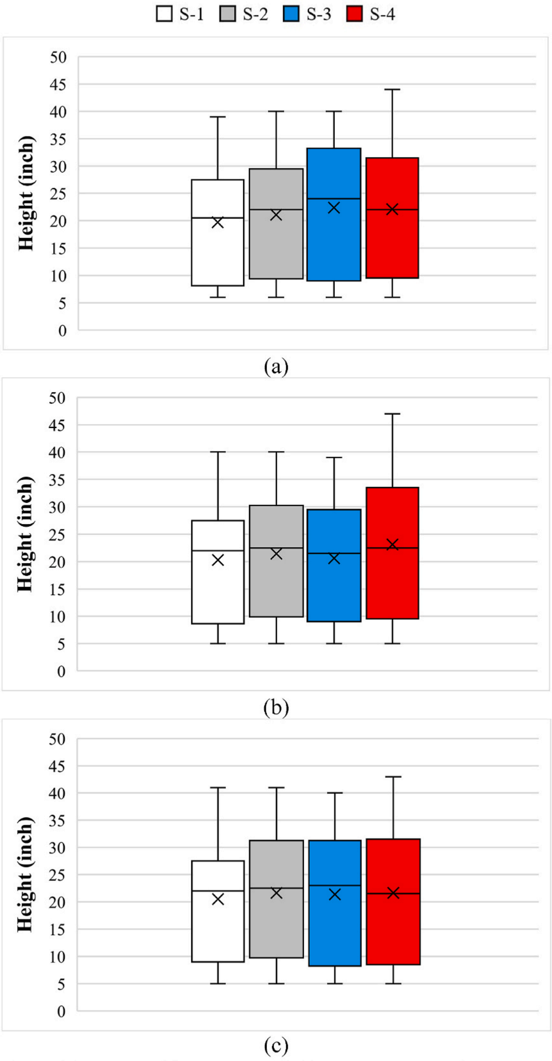
could receive more effective light and form the necessary food for their growth. So, there is a possibility to get more biomass from the plants in the shade than in a regular, non-shaded field.

4. Discussion

Previous studies found that light intensity has a significant impact on crops such as rice [38,39], and wheat [40]. It was reported that the decrease in light intensity during rice filling is one of the direct causes of reduced yield, and the change in light quality may be the key factor behind the decline in grain quality [39]. In an early study, Venkateswarlu et al. (1977) found that as light intensity decreased over the various stages of growth, yields decreased, particularly in the ripening phase [38]. Importantly, these results were obtained with consistent shading. Whereas for the APV, the shading is not consistent; that is, the plants under the APV receive sunlight for certain hours depending on the sun's rotating position.

The light saturation point varies from one plant to another. "*The light saturation point is a crucial criterion for defining the shading ratio of an agrivoltaic system or, once the system is installed, for determining the suitability of crops to be cultivated in the system. The lower the light saturation point the more shade can be given to a crop without experiencing yield losses*." [30].

The soil temperature was found to be lower in shaded plots compared to unshaded; thus, soil temperature positively influences yield, yield components, grain filling, and quality of rice [41]. An earlier study found that shading due to APV underpins a good soil water balance [42]. A more stable p^H was also obtained for the soil in the shaded regions than the unshaded ones. This clarifies that the



(a)

(b)

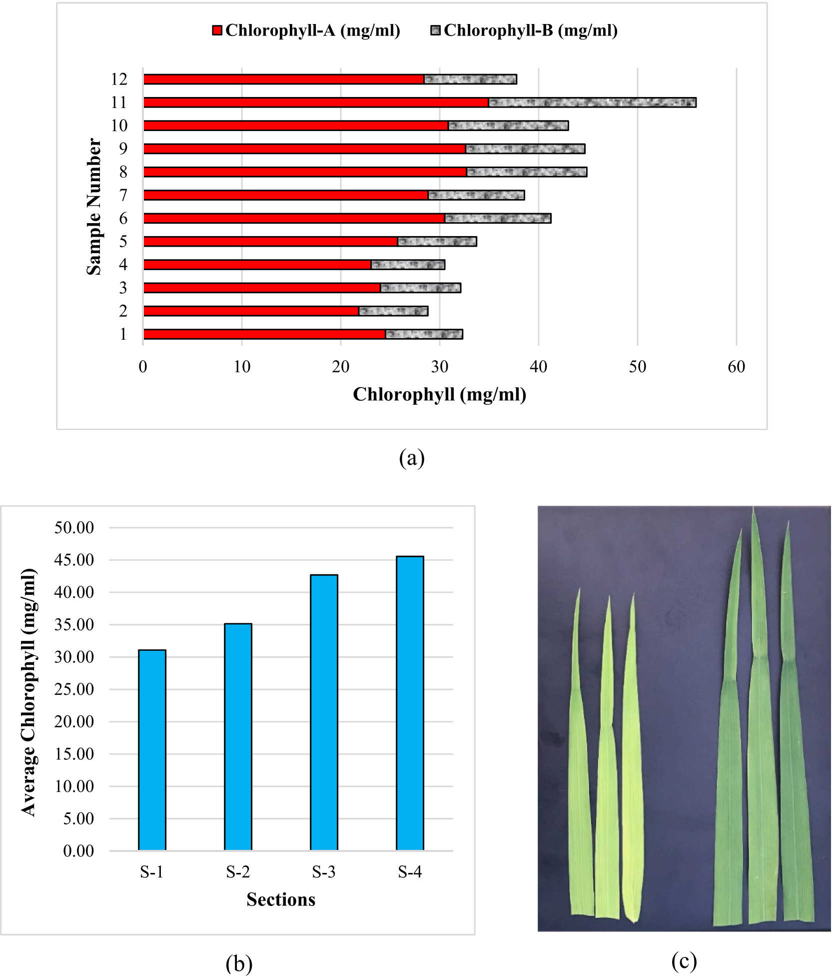
(c)

Fig. 8. Plant height at (a) area-1, (b) area-2, and (c) area-3. S-1 indicates section-1 and so on, where section-4 is the shaded zone due to APV installation. Within each box, the cross represents the average value, the horizontal line is the median value, and the box's lower (and upper) edges are the 25th (75th) percentile. Whiskers represent the upper and lower ranges. The dots (if any) represent outliers.

proposed APV installation does not negatively impact soil p^H. Consequently, it helps to increase the production as the p^H is within the favorable range for the good growth of the BRRI-33 rice. This pH trend improves soil physico-chemical and biological properties, improving yield [43].

At the same time, the shadow due to the APV also underpins to keep the soil temperature comparatively lower than the unshaded areas. Thus, these shaded areas can keep biologically available water for longer, which positively impacts rice plant growth, development, and yield. This study observed no significant impact of shading on the rice yield due to the new non-traditional APV installation type for the BRRI-33 paddy field. Evidently, no significant difference between the average yield obtained from the shaded and unshaded areas was found (see Fig. 10). A recent simulation study also found that APV on rice fields is profitable [44], which is in line with our practical field experiment results. The chlorophyll contents of the plants in the shaded area were found to be higher than the unshaded area. This also justifies the good yield quantity of the plants in the shaded areas. The rice canopy grows more when it is under shade. So, the plants that receive shade due to the APV grow more than the unshaded plants. Hence, the plant height in the shade was higher than the plants in the unshaded areas. This results in more biomass, which can be used for bioenergy generation [45,46] and could be potential future research.

Therefore, the proposed APV installation does not hamper the production of the BRRI-33 rice, a major rice variety in Bangladesh. Rather discontinuous light intensity may have a positive impact on overall rice yield, as it was observed in the present study that more grain weight and biomass were yielded in shaded plots. This positive impact on rice yield could be due to the effects that arose from the simultaneous synchronization of various factors, such as the edaphic, topological, physical, and molecular physiological status of the



(a)

(b)

(c)

Fig. 9. Chlorophyll contents in the sample: (a) Chlorophyll A and B in the collected samples. Samples 1–3, 4–6, 7–9, and 10–12 are from sections 1, 2, 3, and 4, respectively. (b) Average chlorophyll (A & B) contents in the tested samples from four sections. S-1, 2, and 3 are unshaded, and S-4 is shaded; (c) Physical appearance of chlorophyll in the leaf: unshaded (left) and shaded (right).

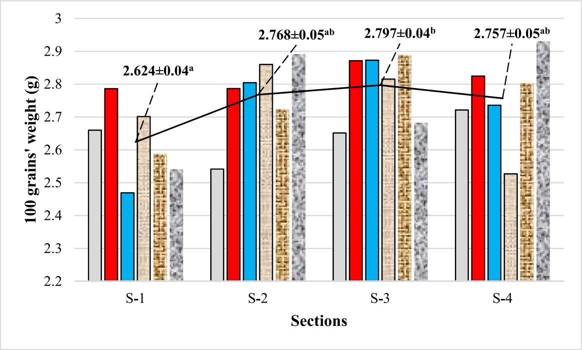


Fig. 10. Bar diagram showing the grain weights of the rice hills. There were four plots, and each section contained six hills. Sections 1 to 3 are unshaded, and section 4 is shaded due to APV. Each bar presents the weight of 100 grains from each hill, and the solid line represents the mean ± standard error (SE) of six rice hills. The same letters included in the vaues are not significantly different from each other at $P \leq 0.05$ level according to Duncan's multiple range test as analyzed using IBM SPSS v.21 software.

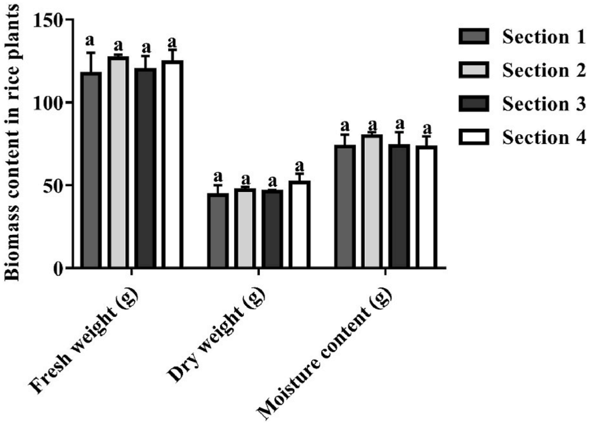


Fig. 11. Biomass contents in rice plants. Each value represents three rice hills' mean ± standard error (SE). The same letters above in the bar are not significantly different from each other at $P \leq 0.05$ level according to Duncan's multiple range test as analyzed using IBM SPSS v.21 software. Sections 1 to 3 are unshaded, and plot four is shaded due to APV.

rice plant, that was ensured by the typical inconsistent light conditions. However, further research is needed to confirm the hypothesis, which creates room for extensive research in the area studied. In addition, the sustainability aspects of the proposed APV installation in terms of social, economic, and environment were not assessed and left for future studies.

In summary, the impacts of the proposed non-traditional APV installation can be pointed out as-

- Continuous sunlight may not be required for rice, at least not in the case of BRRI-33, and APV might be installed in the cultivating area for irrigation purposes.
- The APV does not have a negative impact on soil p^H level.
- The APV shadow helps to keep the soil temperature low and ensures less irrigation under the APV system.
- More plant height ensures increased biomass, which might be used for bioenergy generation.
- The proposed non-traditional APV installation has almost zero negative impact on yield.
- The APV shadow helps to increase the chlorophyll content in the plants.

5. Conclusion

Agrophotovoltaic (APV) is one of the technologies that enable the dual use of land, crop production, and energy generation. The application of this technology is familiar in developed countries. However, in developing countries, this is yet to be familiarized. In Bangladesh, this APV is becoming popular in terms of solar irrigation pump (SIP). Unfortunately, the farmers or the concerned authorities are using traditional installation procedures for this system.

Consequently, a vast amount of agricultural land is getting wasted. Therefore, in this study, a new (in Bangladesh) installation type of APV or SIP has been tested for the BRRI-33 rice, one of the major rice varieties in Bangladesh. Results show that the new APV installation type has no significant negative impact on crop production. Additionally, it helps to produce more biomass that could be used for bioenergy, charcoal, biomanure feedstock, and cattle feed. Hence, the new APV installation type was found to be effective, at least for BRRI-33 rice in Bangladesh.

Although this study found positive results from using APV in Bangladesh for BRRI-33 rice, there are a few limitations. First, this study did not investigate the impact of soil types, as different soil types have diverse effects on crops. Second, although rice is a major cereal crop in Bangladesh, only the BRRI-33 rice variety was studied. Nevertheless, future studies need to focus on other major crops in Bangladesh to check the year-round crop production feasibility on the same land in APV condition. Third, the impacts of seasons on crops were not studied. Finally, as this is a pilot study, small sample sizes are considered. Hence, the obtained result should not be generalized. Although this is true, it is the first study of its kind in Bangladesh and could be used as a reference for future research.

Author contribution statement

Shourov Sarker Joy: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Imran Khan: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

A.M. Swaraz: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supp. material/referenced in article.

Additional information

No additional information is available for this paper.

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.

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Appendix

Table A1
Illuminance variations under shaded and unshaded sections.

Date	Parameter (unit)	Unshaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)	Shaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)
25-Aug-2022	Illuminance (lx)	1	133200	137400	126500	4	17420	74600	25020
		2	133200	137400	126500				
		3	133200	137400	126500				
01-Sep-2022		1	60210	35180	57400	4	27310	14050	15410
		2	98080	25550	60590				
		3	51310	46810	47170				
08-Sep-2022		1	90060	128800	20560	4	25160	17710	11270
		2	90990	117900	18170				
		3	60180	112100	13750				
15-Sep-2022		1	34820	57650	43430	4	22210	25610	30600
		2	32710	58090	42540				
		3	23740	58940	38440				
21-Sep-2022		1	24900	130400	14490	4	26280	14530	11110
		2	16380	38470	14120				
		3	29380	29270	12450				
29-Sep-2022		1	90030	94260	50330	4	29860	23210	20710
		2	83470	96590	54710				
		3	83690	87140	62440				
04-Oct-2022		1	34310	124500	37830	4	13230	13420	23830
		2	36070	126300	23780				
		3	46240	113300	88240				
16-Oct-2022		1	90490	95020	99120	4	21160	11180	18850
		2	84980	87340	90490				
		3	96780	58700	96850				

Note: A-1, A-2, and A-3 indicate Area-1, Area-2, and Area-3, respectively (referring to Fig. 3).

Table A2
p^H variations under shaded and unshaded sections.

Date	Parameter	Unshaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)	Shaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)
25-Aug-2022	p^H	1	7.5	7	6	4	7.5	7	6
		2	7.5	7	6				
		3	7.5	7	6				
01-Sep-2022		1	7	7	7	4	6	7	7
		2	5	7	5.5				
		3	5	5	5				
08-Sep-2022		1	5.5	5	5	4	6	6.5	6
		2	6	6	5.5				
		3	5	6	5				

(*continued on next page*)

Table A2 (*continued*)

Date	Parameter	Unshaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)	Shaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)
15-Sep-2022		1	6	6.5	5	4	5.5	6	7
		2	6	7	5				
		3	7	7	6.5				
21-Sep-2022		1	6	6	6	4	6.5	5.5	6.5
		2	5.5	6	6				
		3	6.5	6	6.5				
29-Sep-2022		1	7	6.5	7	4	7	6	6
		2	7	6	7				
		3	6.5	6	6.5				
04-Oct-2022		1	6.5	6	6	4	6.5	6	6.5
		2	6.5	5.5	5.5				
		3	6	6	6				
16-Oct-2022		1	6	6	5.5	4	6.5	6.5	6.5
		2	6.5	5.5	6				
		3	6.5	6	6				

Note: A-1, A-2, and A-3 indicate Area-1, Area-2, and Area-3, respectively (referring to Fig. 3).

Table A3
Soil temperature variations under shaded and unshaded sections.

Date	Parameter (unit)	Unshaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)	Shaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)
25-Aug-2022	Soil Temperature (^{o}C)	1	33	34	34	4	33	34	34
		2	33	34	34				
		3	33	34	34				
01-Sep-2022		1	31	31	35	4	32	31	33
		2	33	31	36				
		3	32	32	36				
08-Sep-2022		1	32	36	30	4	32	33	33
		2	32	36	33				
		3	35	37	33				
15-Sep-2022		1	30	30	32	4	30	28	31
		2	30	30	32				
		3	30	31	32				
21-Sep-2022		1	31	33	32	4	30	30	31
		2	32	31	32				
		3	31	33	31				
29-Sep-2022		1	30	30	33	4	28	28	31
		2	29	30	32				
		3	29	30	32				
04-Oct-2022		1	30	30	31	4	29	28	29
		2	29	30	30				
		3	29	30	30				
16-Oct-2022		1	28	28	28	4	27	27	28
		2	28	29	28				
		3	30	29	29				

Note: A-1, A-2, and A-3 indicate Area-1, Area-2, and Area-3, respectively (referring to Fig. 3).

Table A4
Plant height variations under shaded and unshaded sections.

Date	Parameter (unit)	Unshaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)	Shaded Section No.	A-1 (9 a.m.)	A-2 (12 p.m.)	A-3 (3 p.m.)
25-Aug-2022	Plant Height (inch)	1	6	5	5	4	6	5	5
		2	6	5	5				
		3	6	5	5				
01-Sep-2022		1	7.5	7.5	8	4	8.7	8	7
		2	8.5	8.5	9				
		3	8	8	7				
08-Sep-2022		1	10	12	12	4	12	14	13
		2	12	14	12				
		3	12	12	12				
15-Sep-2022		1	19	21	21	4	20	21	20
		2	20	21	21				
		3	23	20	22				
21-Sep-2022		1	22	23	23	4	24	24	23
		2	24	24	24				
		3	25	23	24				

(*continued on next page*)

Table A4 (*continued*)

Date	Parameter (unit)	Unshaded Section No.	A-1 (9 a. m.)	A-2 (12 p. m.)	A-3 (3 p. m.)	Shaded Section No.	A-1 (9 a. m.)	A-2 (12 p. m.)	A-3 (3 p. m.)
29-Sep-2022		1	26	26	26	4	30	32	30
		2	28	28	29				
		3	31	28	29				
04-Oct-2022		1	28	28	28	4	32	34	32
		2	30	31	32				
		3	34	30	32				
16-Oct-2022		1	39	40	41	4	44	47	43
		2	40	40	41				
		3	40	39	40				

Note: A-1, A-2, and A-3 indicate Area-1, Area-2, and Area-3, respectively (referring to Fig. 3).

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