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Agrivoltaics shading enhanced the microclimate, photosynthesis, growth and yields of vigna radiata genotypes in tropical Nigeria

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In recent years, more agricultural lands are been converted to photovoltaic (PV) power plants for better return on investment. However, prioritizing energy generation over food production poses a significant threat to the well-being of the rapidly growing global population. Agro-photovoltaics (APV) provide an opportunity to integrate crop production under PV panels. The objective of this study was to investigate the effect of APV system on microclimate, photosynthesis, and agronomic performance of mungbean in a tropical environment. Five mungbean genotypes, Tvr18, Tvr28, Tvr65, Tvr79 and Tvr83 were assessed under three APV micro environments, East-west facing PV (WPV), West-east facing PV (EPV), and no PV (NPV) in a split plot design with 5 replications. Results obtained showed significant reduction ($p < 0.05$) in photosynthetic active radiation (5–47%), leaf temperature (3–9%), and in the proportion of potentially harmful unregulated energy reaching the reaction centers (19–23%) under the PV (% reduction in WPV > EPV). Relative humidity, photochemical energy conversion, plant height, number of leaves, pods, and seeds were increased significantly ($p < 0.05$) underneath the EPV compared to NPV. Seed weight also increased non-significantly under EPV while flowering and podding behaviour, leaf area and stem diameter were comparable ($p > 0.05$) in NPV and EPV. We report for the first time that microclimate, growth, photochemistry and yield performances of mungbean were improved under APV system in a tropical environment. The improved performances of mungbean under EPV compared to WPV suggest that PV orientation is important and should not be overlooked in APV system designs.

Keywords Agrivoltaic system, Growth and yield, Photochemical efficiency, Photovoltaic shading, photosynthetic active radiation, Photosynthetic efficiency

In recent times, there has been an upward shift in the use of green energy sources such as photovoltaics (PV) as against fossil fuels due to climate change effect which has predisposed scarce agricultural lands to unhealthy competition[1]resulting in land use conflicts between food production and energy generation[2,3]. While PV systems generate clean energy, they inhibit agricultural practices or if not, the panels cast shadows that reduce sunlight availability for crops grown underneath (PV shading). As PV installations expand to meet renewable energy targets, more farmlands are being utilized to install ground-mounted PV systems.

Food security is threatened by the increased conversion of agricultural lands to the more profitable photovoltaic power plants[1,4–6] By the year 2030, the international energy agency (IEA) aims to achieve a net-zero CO_2emission in the energy sector by increasing solar and wind energy production, which could imply further encroachment into agricultural lands due to the large land area requirement of PV panels installations. Consequently, there is an urgent need to seek viable means of improving land use efficiency (LUE) if the goal to completely eradicate hunger by 2030[7] is to be achieved.

Agro-photovoltaics or agrivoltaics (APV) is a promising technology that simultaneously generates electricity from photovoltaic panels while growing crops underneath (Fig. 1). It has the potential to balance future food and energy needs[21], increase efficiency of land use[9], reduce the potential for photodamage by about 40%[10,11], and increase efficiency of light use for photochemistry[8,12]. APV can also limit the proportion of potentially harmful

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Fig. 1. APV facility (**a**) with mungbean crops growing (**b**) flowering (**c**) and podding (**d**) underneath. The facility was set up within the framework of the YESPVNIGBEN project and is situated at the Center for Energy Research and Development, University of Nigeria, Nsukka.

reactive oxygen species (ROS) reaching the photosystem II (PSII) reaction centers, power farm structures and home appliances, and conserve water during shortages[12].

Mungbean (*Vigna radiata*) is an important short-season legume crop grown in tropical and subtropical regions for its edible seeds which are high in protein. It is widely cultivated in Asia where it serves as a dietary staple and a source of income for smallholder farmers. Mungbean requires adequate sunlight throughout its growth period to maximize photosynthesis, biomass accumulation and ultimately seed yield. Although a few studies have shown that shading can negatively influence various physiological growth processes including photosynthesis, respiration and nutrient assimilation, the extent of these effects depend on the degree and duration of shading. Unfortunately, most reports on the assessment of APV systems on crop performance were concentrated in the temperate regions with cooler climate in contrast to tropical regions with hotter climate. Virtually all of the studies have reported yield reduction under PV shade with greater than 25% PV cover ratio. About 16%, 31%, and 52% reduction in yields of *Phaseolus vulgaris* grown under 25, 50, and 100% PV cover ratios, respectively was reported in Italy[13]. In a related study, significant yield reductions in sesame (19%), soybean (18–20%), and rice (13–30%) under PV ratios 25–32% was also reported in Korea[14]. Interestingly, the first reported significant increase in yield of winter wheat and potato grown underneath PV was achieved during the summer in Germany[15]. In Africa, several PV projects are been initiated such as the APV Maga project in Mali, the YESPVNIGBEN project in Nigeria and Benin. However, this paper presents the first report on assessment of APV systems on microclimate, photosynthesis, growth and yield performance of *Vigna radiata* in Africa.

This study hypothesized that in the hotter tropics, plants grown underneath the PV could photosynthesize more efficiently and yield comparably to full sun due to the higher solar radiation. The objective was to investigate the effect of an APV system on microclimate, photosynthesis, growth and yield of mungbean in a tropical climate. Results could optimize APV design to minimize crop losses from shading and guide farmers on suitable varieties and management under PV shading.

Materials and methods
Experimental site
The experiment was conducted at the Center for Energy Research and Development, University of Nigeria, Nsukka, Enugu State, Nigeria (6°51’57”N 7°24’57”E) between December 2022 and March 2023. Nsukka has mean annual rainfall of 1276 ± 706 mm, solar radiation of 1452 ± 269 w m^{-2}, and temperature of 32 ± 5°C[16]. Relative humidity varies due to seasonal variations during the rainy and dry seasons. The upper limit (about 89%) is usually experienced during the peak rainy season (July to August) while the lower limits (39–41%) occurs during dry spells (December and January).

Materials

Five mungbean genotypes namely, Tvr18, Tvr28, Tvr65, Tvr79 and Tvr83 were grown under three APV treatments [East-west facing PV (WPV), West-east facing PV (EPV) and the full sunlight or no-PV (NPV)] at the Agri-PV facility situated at the Center for Energy Research and Development, University of Nigeria, Nsukka. Mini-PAM II Photosynthetic Yield Analyzer (WALZ, Germany) was used for determination of leaf temperature, relative humidity, photosynthetic active radiation (PAR), and photosynthesis variables.

Experimental design

The experimental design was a split plot design with the three APV treatments (WPV, EPV and NPV) as the main plot treatment and five genotypes of mungbean as the sub-plot treatment replicated five times.

APV installation and layout

A 20 kWp APV facility was installed in June 2022 with dimensions 21 × 9.8 m in length and width by SUNFARMING. The height of the APV facility ranged from its lowest point 2.65 m to an elevated apex 3.15 m high, with a roof slope of 20°. The APV facility was partitioned into 3 main plots (EPV, NPV, WPV), with the two main plots at the extreme fully covered with bifacial PV modules while the middle plot was covered with a transparent acrylic glass material (for unrestricted solar transmittance or full sunlight) to serve as the control (Fig. 1).

Crop establishment

Seeds were sown in 10 *l* pots prefilled with inert coconut fiber dust and placed at a spacing of 40 × 40 cm. Two seeds were sown per pot and later thinned down to one-seed at 1 week after planting (WAP). Universal orange fertilizer (N-16%, P_2O_5–5%, K_2O-25%, MgO-3.4%, Fe-0.10%, Mn-0.04%, B-0.01%, Cu-0.01%, Mo-0.001%, Zn-0.01%) was applied at the rate of 2 *g*/*l* or 20 *g* per pot. Watering was done once daily according to the ET_C(3–5 mm)[17].

Microclimate and photosynthesis parameters

Data were collected on microclimate indices including leaf temperature, relative humidity, photosynthetic active radiation (PAR) and absolute fluorescence variables such as minimum and maximum fluorescence of dark acclimated leaves (F_o, Fm), minimum and maximum fluorescence of illuminated leaves (F_o', Fm'), and transient fluorescence level (F') which were used to compute photosynthetic parameters including maximum photochemical yield in dark-acclimated state (Fv/Fm), effective photochemical yield of photosystem II [Y(II)], quantum yield of protective non-photochemical energy losses via heat dissipation at the antenna [Y(NPQ)], quantum yield of potentially harmful non-photochemical energy losses via heat dissipation and fluorescence at the reaction centers [Y(NO)], and electron transport rate (ETR). Both microclimate and photosynthesis data were collected simultaneously using the portable pulse amplitude modulated chlorophyll Fluorometer (Mini-PAM II, WALZ, Germany) between 9 am – 12 noon weekly. Data were taken from the flag leaf (uppermost leaf) of two sample plants per plot and averaged. Measurements were done under natural light conditions at a measuring light intensity of about 0.04 µmol m^{-2} s^{-1} and a saturating light pulse of about 5000 µmol m^{-2} s^{-1} [12]. All microclimate variables and light acclimated photosynthetic parameters such as F', Fo', and Fm' were measured between 9 am – 12 noon weekly, while plants were dark adapted pre-dawn to measure Fo and Fm. Other photosynthetic traits such as Y(II), Y(NPQ), Y(NO) and ETR were computed following the procedures[12]:

"Y(II) = (Fm' – F')/Fm', Y(NO) = F'/Fm, Y(NPQ) = (F'/Fm') – (F'/Fm), ETR = PAR × ETR factor × (P_{PS2}/P_{PS1+2}) × Y(II). Where PAR is photosynthetic active radiation, ETR factor and (P_{PS2}/P_{PS1+2}) are constants with values of 0.84 and 0.5, respectively".

Growth and yield traits

Growth traits such as number of days to emergence, plant height, leaf number, leaf area, stem diameter, canopy diameter, and yield traits such as number of days to flower initiation, number of days to 50% flowering, number of days to podding, pod length, pod width, number of pods per plant, number of seeds per pod, number of seeds per plant, pod weight per plant, and seed weight were quantified. The number of days to emergence was determined by counting the days from seed sowing to the day of first seedling emergence. The number of days to flower onset was obtained by recording the days from the date of sowing to when the first flower opens. Number of days to podding was recorded by counting the days from sowing to when at least the first pod is formed. Leaf number per plant was obtained by counting the number of fully expanded leaves per plant. Plant height was recorded as the distance between the plant's base and the peak of the terminal leaf bud using a measuring tape[18–21]. Leaf area was estimated non-destructively according to the regression equation, $Y = 0.1686 + 1.017LW$[22]. Stem diameter was determined with a measuring tape at 5 cm above ground level of each plant. Canopy diameter was taken as the distance of the widest canopy width. Pod length was determined as the average length of 10 pods while pod width was determined as the average diameter of 10 pods measured for length. Number of seeds per pod was determined as the average number of seeds in the 10 pods measured for length. Pod weight was computed as the total weight of pods harvested per plant. Seed yield was recorded as the total weight of dry seeds per plant.

Statistical analysis

All data were subjected to analysis of variance (ANOVA), using GenStat Discovery 10.3 DE and significant means were separated using F-LSD at $p \leq 0.05$. Charts were constructed using GraphPad Prism 6.

Results

Effects of PV-shading and genotype on microclimate of mungbean

PV shading significantly influenced ($p < 0.05$) PAR of mungbean plants grown underneath. PAR was consistently reduced under PV shading compared to no-shading, with WPV recording the least PAR values throughout the study duration. At instances when instantaneous solar radiation was high (6, 7 WAP) PAR was significantly higher in NPV than EPV and WPV respectively, however, at other times when solar radiation was low, both EPV and NPV recorded comparable PAR (4, 5, and 8 WAP). PV-shading decreased PAR values by 22–47% in WPV and by 5–42% in EPV. In general, PAR ranked NPV > EPV > WPV (Fig. 2a). Variation in PAR interception among the five genotypes was negligible under the present investigation ($P > 0.05$). All genotypes demonstrated equal ability to intercept solar radiation under each PV level. However, across PV treatments, the genotypes varied significantly. For instance, at 9 WAP Tvr79 grown in NPV recorded significantly higher PAR (174.20 μmol photons m^{-2} s^{-1}) than Tvr79 grown under WPV (110.10 μmol photons m^{-2} s^{-1}) and under EPV (114.70 μmol photons m^{-2} s^{-1}). The trend showed that the genotypes recorded higher PAR interception in the control (NPV) than underneath the corresponding EPV and WPV treatments (Fig. 2b).

Leaf temperature of mungbean was reduced ($p < 0.05$) by 6–9% underneath WPV and by 3–5% underneath EPV. The least temperatures were recorded in plants grown under the WPV throughout the study duration (Fig. 2c). This was followed by EPV, while NPV recorded the highest leaf temperature across the PV treatments. Leaf temperature was comparable ($p > 0.05$) across all genotypes at 4–8 WAP. However at 9 WAP, Tvr65 and Tvr79 recorded significantly higher leaf temperatures (27.20 and 27.18 °C) than the other genotypes (Fig. 2d). Leaf temperature was unaffected ($p > 0.05$) by the interaction of PV shading and genotype. The responses of the genotypes were similar across the PV treatments, recording higher leaf temperatures at NPV, EPV and WPV respectively. Notably, two genotypes Tvr79 and Tvr28 recorded numerically higher leaf temperatures in the NPV plot than the EPV and WPV plots, consistently throughout the study duration.

The effect of PV-shading on leaf relative humidity was significant ($P < 0.05$). PV-shading significantly increased relative humidity by 3–6% and 3–8% underneath the EPV and WPV respectively throughout the study duration compared to the NPV (Fig. 2e). The interaction effect of PV-shading and genotype on relative humidity was significant ($p < 0.05$). Higher relative humidity was recorded in all mungbean genotypes under PV-shaded (WPV > EPV) conditions than under the control. Notably, at 9 WAP, the interaction effect of PV-shading and genotype showed that the genotypes Tvr18 and Tvr28 grown under the WPV shading recorded higher relative humidity values compared to Tvr83 grown in NPV which was the least (Fig. 2f).

Effects of PV-shading and genotype on photosynthesis of mungbean

PV-shading significantly increased maximum photochemical efficiency in mungbean plants in contrast to NPV-shading ($p < 0.05$). The highest significant maximum photochemical efficiency values were recorded under the WPV and EPV treatments respectively while plants in the NPV-shading recorded the least values (Fig. 3a). The effect of genotype on maximum photochemical efficiency was also significant. Two genotypes, Tvr18 and Tvr65 consistently influenced higher values than the other genotypes (Fig. 3b). The interaction of PV-shading and genotype on maximum photochemical efficiency also showed significant variation. Higher maximum photochemical efficiency values were recorded when genotypes were grown under the WPV and EPV treatments respectively, compared to NPV-shading (Table 1).

Effective quantum yield of PSII photochemistry [Y(II)] was also significantly increased ($p < 0.05$) by PV-shading. Higher [Y(II)] values were recorded for plants under PV-shaded conditions than in NPV-shading, with plants under the WPV expressing higher Y(II) values than its counterparts under the EPV throughout the study duration (Fig. 3c). Y(II) was unaffected by genotype as all genotypes showed statistical similarity ($p > 0.05$). The response of the genotypes followed a trend, with higher values underneath the WPV than the EPV while plants in the NPV-shading had the least values. Notably, the interaction of the WPV and Tvr28 genotype recorded significantly ($p < 0.05$) higher Y(II) (0.740) than the interaction between the NPV-shading and other genotypes, with NPV-shading by Tvr28 interaction recording the least value (0.435) (Fig. 3d).

Contrary to its effects on maximum and effective photochemical efficiencies, PV-shading significantly decreased ($p < 0.05$) ETR of mungbean. Higher ETR values were recorded consistently under NPV shading than under EPV and WPV shadings respectively (Fig. 3e). Percentage decrease in ETR values for plants grown under PV-shaded conditions ranged from 18 to 67% underneath WPV, and from 8 to 47% underneath EPV. Genotype did not affect ETR for majority of the study duration (4–8 WAP). However, at 9 WAP, Tvr18 recorded significantly higher ETR (47.44) than Tvr65 (38.55) which was the least (Fig. 3f). Interestingly, the interaction effect of PV-shading and genotype was also significant at 9 WAP. The genotypes showed a peculiar trend, recording higher ETR values in the NPV-shading than underneath the EPV and WPV shadings respectively. PAR and Y(II) are components of ETR, hence, a higher PAR implies a higher ETR and vice versa. Genotypic variation across PV treatments was evident. Tvr83 grown in NPV (54.01) was significantly different from Tvr83 under the WPV (30.92) which was the least.

The proportion of non-photochemical energy lost at the antenna was significantly decreased ($p < 0.05$) by PV-shading (WPV and EPV) by 47–60% (Fig. 3g). This observation was consistent throughout the duration of the study. The magnitude of losses was in the order NPV > EPV > WPV. The WPV also significantly decreased the proportion of non-photochemical energy that reached the reaction centers which was eventually dissipated either as heat or fluorescence by 19–23% (Fig. 3h). The magnitude of energy dissipation followed the same trend as in Y(NPQ) with NPV > EPV > WPV. The effect of genotype on Y(NPQ) was not clearly shown until at 9 WAP where significant effect was recorded. Y(NPQ) was higher in Tvr83 and Tvr65 in contrast to Tvr28 which recorded the least (Fig. 3i). The effect of genotype on Y(NO) was not clearly shown across the weeks of observation except at 7 WAP where Tvr18 recorded higher Y(NO) mean value (0.197) than Tvr65 (0.173) but was comparable to Tvr28, Tvr79 and Tvr83 (Fig. 3j). Significant interaction effect of PV-shading and genotype on

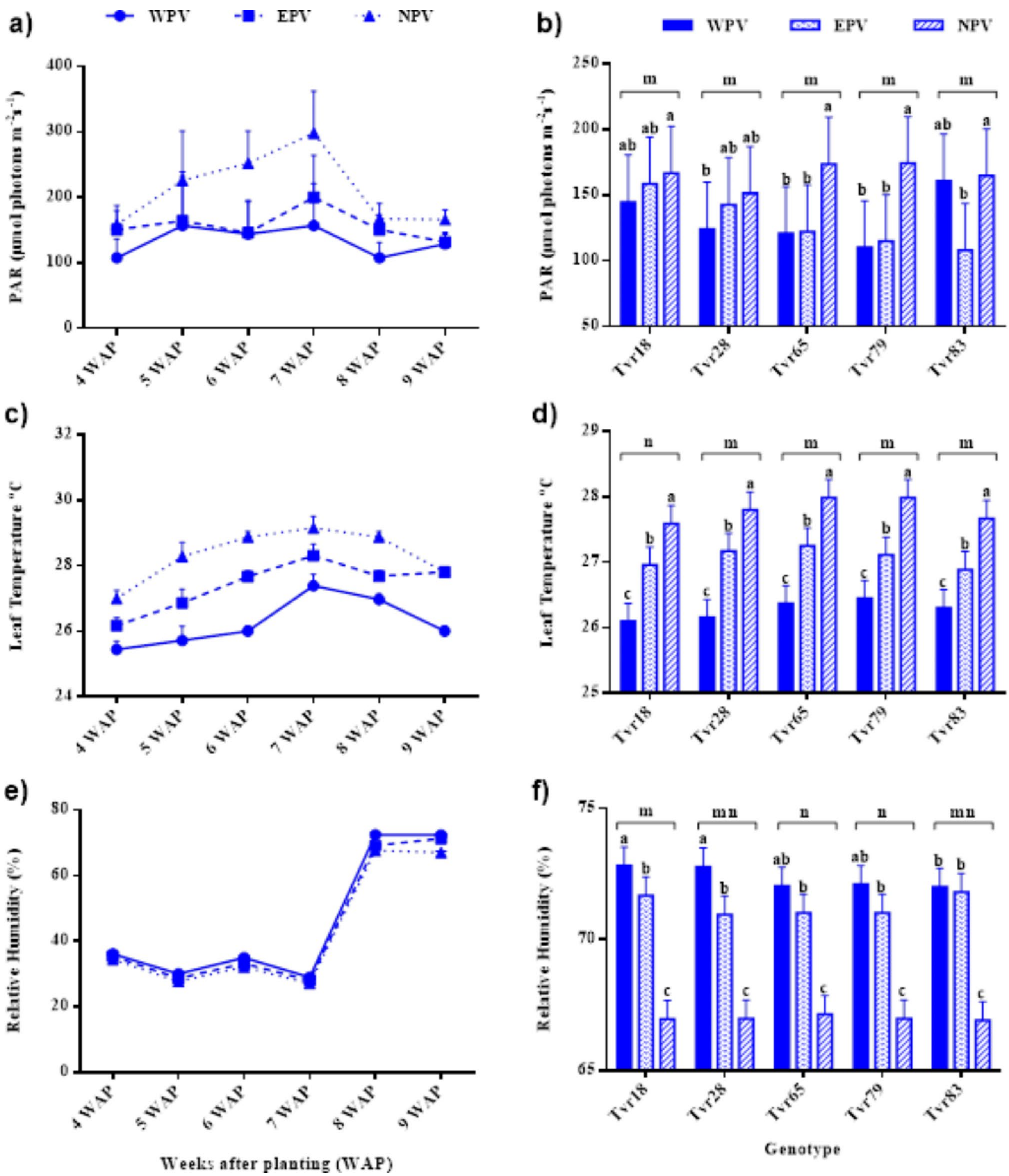

Fig. 2. Mean weekly PAR (**a**), leaf temperature (**c**), and relative humidity (**e**) underneath the different APV partitions; and genotypic variation in PAR (**b**), leaf temperature (**d**), and relative humidity (**f**) underneath the different APV partitions at 9 WAP. WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV; Bars with different letters are significantly different at $p < 0.05$.

Y(NPQ) and Y(NO) was also recorded. The genotypes responded differently across the PV-shading treatments. NPV-shading recorded higher Y(NPQ) values across all genotypes compared to the EPV and WPV, respectively. However, the specific effect of each genotype across the PV-shading treatments did not follow any specific trend (Fig. 3i and j).

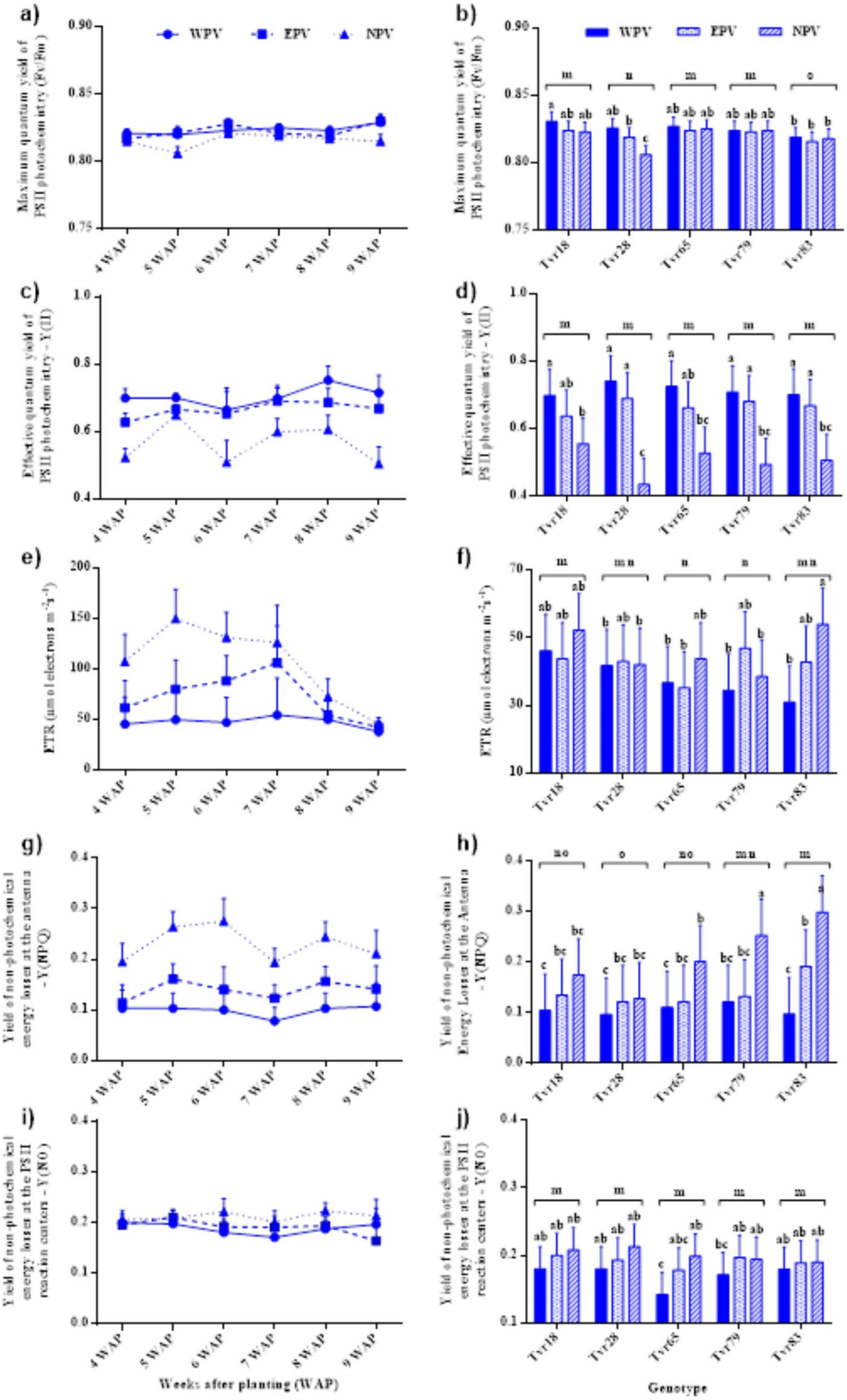

Fig. 3. Effect of APV system on mean weekly maximum photochemical efficiency (**a**), effective photochemical efficiency (**c**), electron transport rate (**e**), non-photochemical energy losses at the antenna (**g**) non-photochemical energy losses at reaction centers (**i**), and genotypic responses in: maximum photochemical efficiency (**b**), effective photochemical efficiency (**d**), electron transport rate (**f**), non-photochemical energy losses at the antenna (**h**) non-photochemical energy losses at reaction centers (**j**) underneath the different APV partitions at 9 WAP. WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV; Bars with different letters are significantly different at $p < 0.05$.

PV-Shading	Genotype	Maximum photochemical efficiency (Fv/Fm)	Effective photochemical efficiency Y(II)	Electron transport rate (µmol electrons $m^{-2} s^{-1}$)	Non-photochemical losses at the antenna Y(NPQ)	Non-photochemical energy losses at reaction centers Y(NO)
WPV	Tvr18	0.832	0.699	46.22	0.105	0.197
	Tvr28	0.827	0.740	41.78	0.097	0.188
	Tvr65	0.839	0.725	36.73	0.111	0.196
	Tvr79	0.825	0.709	34.41	0.122	0.195
	Tvr83	0.820	0.701	30.92	0.098	0.210
EPV	Tvr18	0.833	0.637	43.78	0.135	0.166
	Tvr28	0.827	0.690	43.05	0.122	0.149
	Tvr65	0.835	0.662	35.18	0.122	0.169
	Tvr79	0.832	0.681	46.91	0.133	0.173
	Tvr83	0.825	0.668	42.78	0.192	0.163
NPV	Tvr18	0.821	0.555	52.33	0.175	0.208
	Tvr28	0.812	0.435	42.12	0.128	0.205
	Tvr65	0.828	0.527	43.75	0.201	0.236
	Tvr79	0.823	0.494	38.60	0.253	0.190
	Tvr83	0.803	0.506	54.01	0.299	0.229
$F\_LSD_{0.05}$		0.010	0.077	10.804	0.072	0.050

Table 1. Genotypic variation in photosynthesis traits underneath three APV partitions at 9 WAP. WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV; Bars with different letters are significantly different at $p < 0.05$. Any two interaction means with a difference ≥ the F_LSD value for each trait are significantly different at $p < 0.05$.

Effects of PV-shading and genotype on phenology of mungbean

Phenological attributes of mungbean such as days to 1% flowering, days to 50% flowering, and days to podding were significantly affected (p<0.05) by PV-shading. Days to emergence did not vary significantly (p<0.05) with PV-shading (Fig. 4a). PV-shading delayed flowering onset in WPV by 10 days and EPV by 6 days (Fig. 4b). Days to 50% flowering was delayed by 9 and 4 days in WPV and EPV respectively (Fig. 4c), while podding was delayed by 11 and 9 days in WPV and EPV respectively (Fig. 4d). Days to emergence did not show any particular trend, however, days to 1% flowering and days to podding were earliest in the control (No-PV shading) than WPV and EPV shading treatments. PV-shading and genotype interaction had a significant effect (p<0.05) on days to 50% flowering. Longer days to 50% flowering and podding were recorded for all genotypes underneath the WPV and EPV shadings, respectively in contrast to NPV-shading. The interaction of NPV-shading and Tvr83 had the shortest days to 50% flowering in contrast to the interaction of WPV-shading by Tvr65 which took the longest (48.00).

Effects of PV-shading and genotype on growth performance of mungbean

PV-shading significantly enhanced ($p < 0.05$) taller mungbean plants. Plant height increased significantly ($p < 0.05$) by 3–14% under the WPV, and non-significantly by 2–9% underneath the EPV (Fig. 5a). The trend was consistent throughout the duration of the study; however, significant effect of PV-shading was evident after 8 weeks of sowing. For instance at 9 WAS, plant height was higher underneath the WPV (69.60 cm) and EPV (63.90 cm) plots than the un-shaded control (61.22 cm) plot. The genotypes expressed significant variation in plant height ($p < 0.05$), responding differently underneath the APV treatments (Fig. 5b). Tvr28 produced consistently taller plants compared to Tvr83 which recorded the shortest plants. Except for Tvr18 where plants in the NPV were taller than the plants underneath the EPV and WPV by 7% and 15% respectively, the other four genotypes grew taller underneath the WPV and EPV respectively. Increase in plant height was in the magnitude of 9% and 22% in Tvr28, 8% and 15% in Tvr65, 3% and 20% in Tvr79, and by 19% and 34% in Tvr28 underneath the EPV and WPV, respectively compared to NPV (Fig. 5b). The interaction of WPV-shading and Tvr28 exerted the greatest increase on plant height, and was consistently the tallest in contrast to the interaction of NPV-shading and Tvr83 which was consistent in influencing shorter plants. In general, the genotypes recorded taller plants underneath the WPV and EPV treatments than in the NPV-shading.

Leaf number in mungbean was significantly increased ($p < 0.05$) by PV-shading. Higher leaf number was recorded underneath the WPV than the NPV-shading. This trend was consistent throughout the study duration (Fig. 5c). Except at 5, 6, and 8 WAP where leaf number was significantly higher in the EPV than NPV-shading, leaf number was comparable under the EPV and NPV treatments at 3, 4, 7 and 9 WAP. Notably, leaf number increased by 21–42% and by 10–13% under the WPV and EPV treatments, respectively compared to the NPV-shading. The genotypes also varied significantly in leaf number ($p < 0.05$). More leaves were recorded in Tvr83 throughout the study duration (Fig. 5d). Interestingly also, leaf number was significantly affected ($p < 0.05$) by the interaction of PV-shading and genotype for majority of the study duration and at 9 WAP. Leaf number increased by 6% and 35% in Tvr18, 30% and 35% in Tvr65, and by 28% and 47% in Tvr79 underneath the EPV

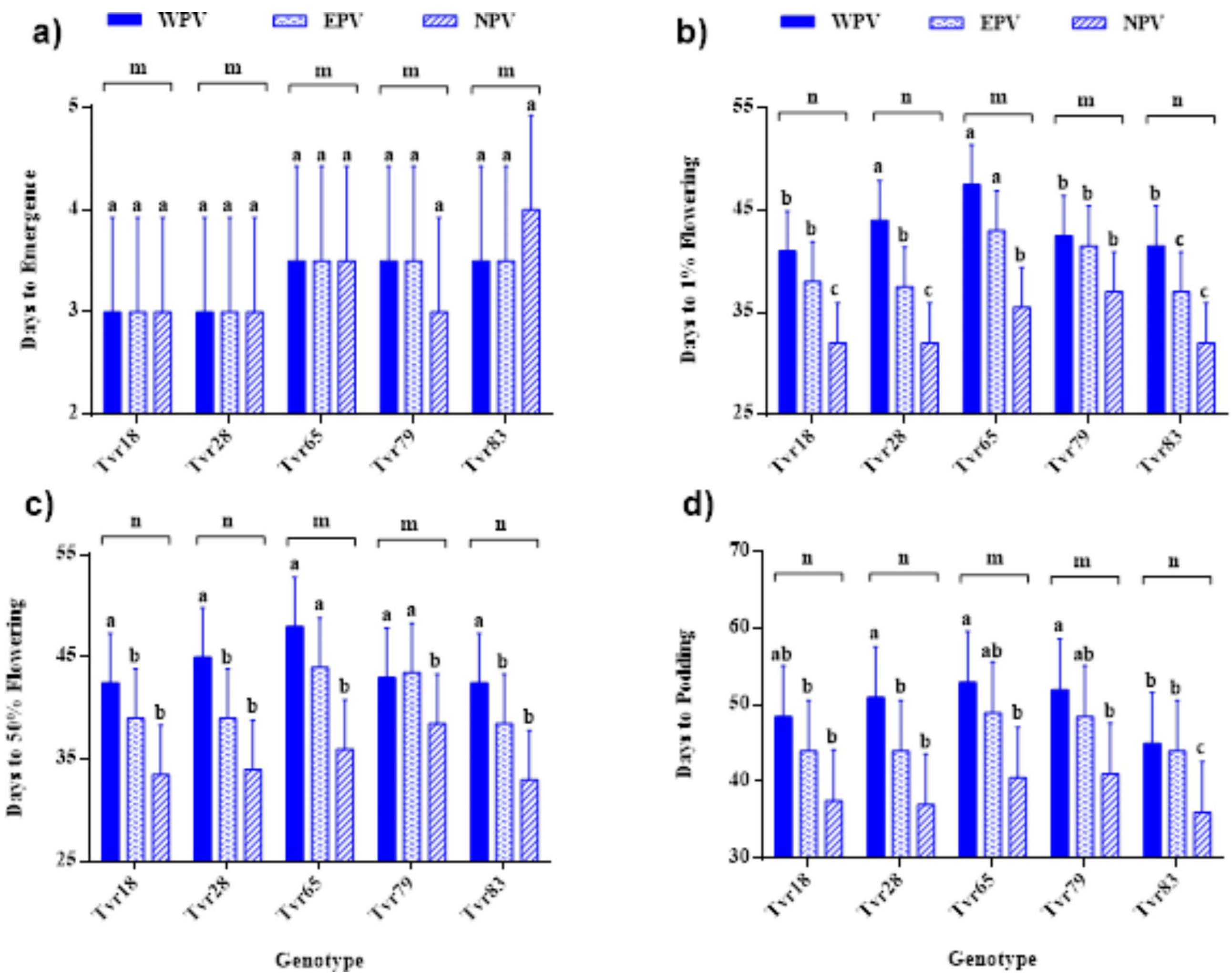

Fig. 4. Effect of APV system on mean number of days to: emergence (**a**), flowering onset (**b**), 50% flowering (**c**), and podding (**d**). WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV; Bars with different letters are significantly different at $p < 0.05$.

and WPV respectively compared to the NPV. Leaf number in Tvr28 and Tvr83 was not significantly affected by PV shading. However, the interaction of WPV-shading and Tvr83 produced the highest leaf number (93.30) in contrast to the interaction of NPV-shading by Tvr18 which had the least (39.20) at 9 WAP.

Significant variation ($p < 0.05$) in leaf area was recorded among the APV-treatments. The WPV influenced smaller leaf sizes than the NPV-shading (Fig. 5e). However, there was no significant difference ($p > 0.05$) in leaf area between the EPV and NPV treatments. Leaf Area also varied significantly with genotype. Tvr65 genotype had broader and larger leaves compared to Tvr83 which had smaller leaves (Fig. 5f). Leaf area was also significantly affected ($p < 0.05$) by the interaction of PV-shading and genotype. Smaller leaf area was observed across all genotypes under the WPV-shading but the response of the genotypes were similar underneath the EPV and NPV ($p > 0.05$). Notably, the interaction of the NPV-shading and Tvr65 produced the largest leaf area at 9 WAP (114.00 cm^2) in contrast to the interaction of the WPV-shading by Tvr83, which recorded the least (62.00 cm^2) (Table 2).

The main effect of PV-shading on stem diameter showed significant variability ($p < 0.05$). Stem diameter was significantly reduced (11–12% less) under the WPV-shading compared to the NPV-shading (Fig. 6a). In contrast, underneath the EPV, stem diameter increased by 8–24% compared to the NPV-shading. The genotypes showed significant variability ($p < 0.05$) in stem diameter. Tvr28 had bigger stems compared to Tvr83 which produced smaller stems (Fig. 6b). The effect of PV-shading and genotype interaction on stem diameter was not clearly shown ($p > 0.05$) until at 7–9 WAP where significant interaction effect became evident (Fig. 6b). The genotypes recorded comparably larger stems underneath the EPV and NPV treatments, respectively than underneath the WPV. Remarkably, at 9 WAP, the interaction of the EPV by Tvr79 recorded the largest stem diameter (0.81 cm) in contrast to the interaction of the WPV by Tvr83 which recorded the smallest stem diameter (0.62 cm).

In a similar trend, PV-shading also significantly influenced ($p < 0.05$) canopy diameter of mungbean (Fig. 6c). Canopy diameter was wider underneath the EPV than underneath the WPV, although was comparable to the NPV for most part of the study duration except at 6 and 7 WAP where the EPV treatment gave superior canopy

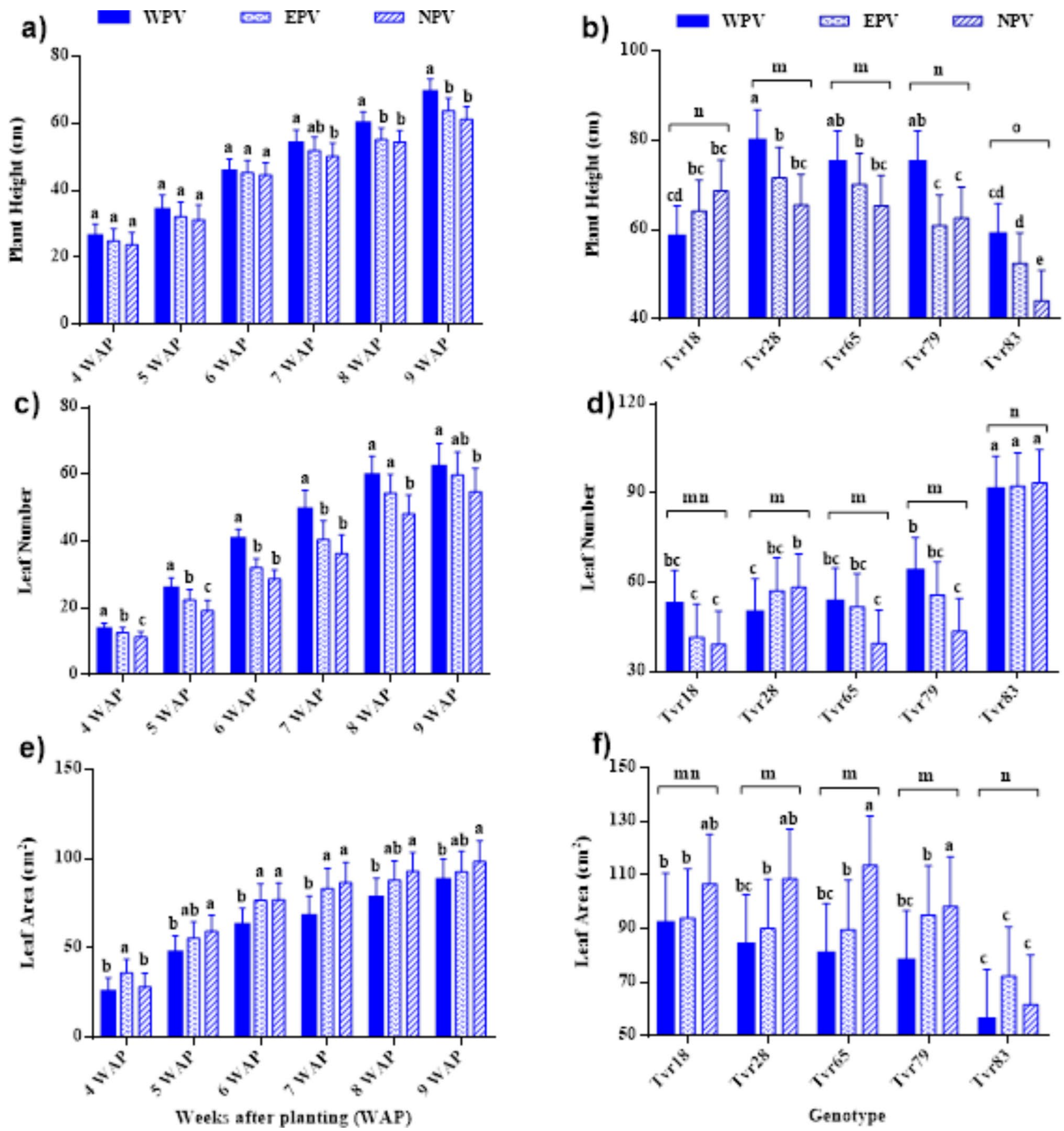

Fig. 5. Effect of APV system on mean weekly plant height (**a**), leaf number (**c**) and leaf area (e); and genotypic variation in plant height (**b**), leaf number (**d**) and leaf area (**f**) underneath APV at 9 WAP. WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV; Bars with different letters are significantly different at $p < 0.05$.

diameter than the NPV shading. Percentage decrease in canopy diameter underneath the WPV was in the range of 7–16%. The genotypes also expressed variability in canopy diameter ($p < 0.05$). Canopy diameter was wider in Tvr79 than in Tvr83 (Fig. 6d). The response of the genotypes under the different PV-treatments was variable (Fig. 6d). Conspicuously, at 9 WAP, the interaction of the NPV and Tvr79 had the largest canopy diameter (56.70 cm) in contrast to the interaction of the EPV and Tvr83 which recorded the least value (40.80 cm). Tvr79 genotype also showed consistency under the EPV and WPV by recording higher mean canopy diameter than other interaction effects.

PV-Shading	Geno-type	Plant height (cm)	Number of leaves	Leaf area (cm^2)	Stem diameter (cm)	Canopy diameter
WPV	Tvr18	58.50	52.90	98.70	0.64	49.60
	Tvr28	80.00	50.00	93.10	0.72	49.50
	Tvr65	75.20	53.60	103.20	0.67	49.40
	Tvr79	75.20	63.90	83.20	0.62	48.10
	Tvr83	59.00	91.30	63.30	0.62	45.70
EPV	Tvr18	64.20	41.60	99.60	0.76	46.00
	Tvr28	71.60	57.20	95.80	0.68	44.30
	Tvr65	70.20	51.80	98.70	0.73	45.30
	Tvr79	60.90	55.80	97.00	0.81	52.90
	Tvr83	52.40	92.30	72.70	0.66	40.80
NPV	Tvr18	68.70	39.20	106.80	0.68	46.40
	Tvr28	65.50	58.30	107.70	0.76	50.70
	Tvr65	65.30	39.60	114.00	0.75	55.10
	Tvr79	62.60	43.50	107.80	0.77	56.70
	Tvr83	44.00	93.50	57.00	0.66	48.90
$F\_LSD_{(0.05)}$		6.857	11.170	19.450	0.077	6.522

Table 2. Genotypic variation in growth traits of mungbean underneath three APV partitions at 9 WAP. WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV. Any two interaction means with a difference ≥ the F_LSD value under each column are significantly different at $p < 0.05$.

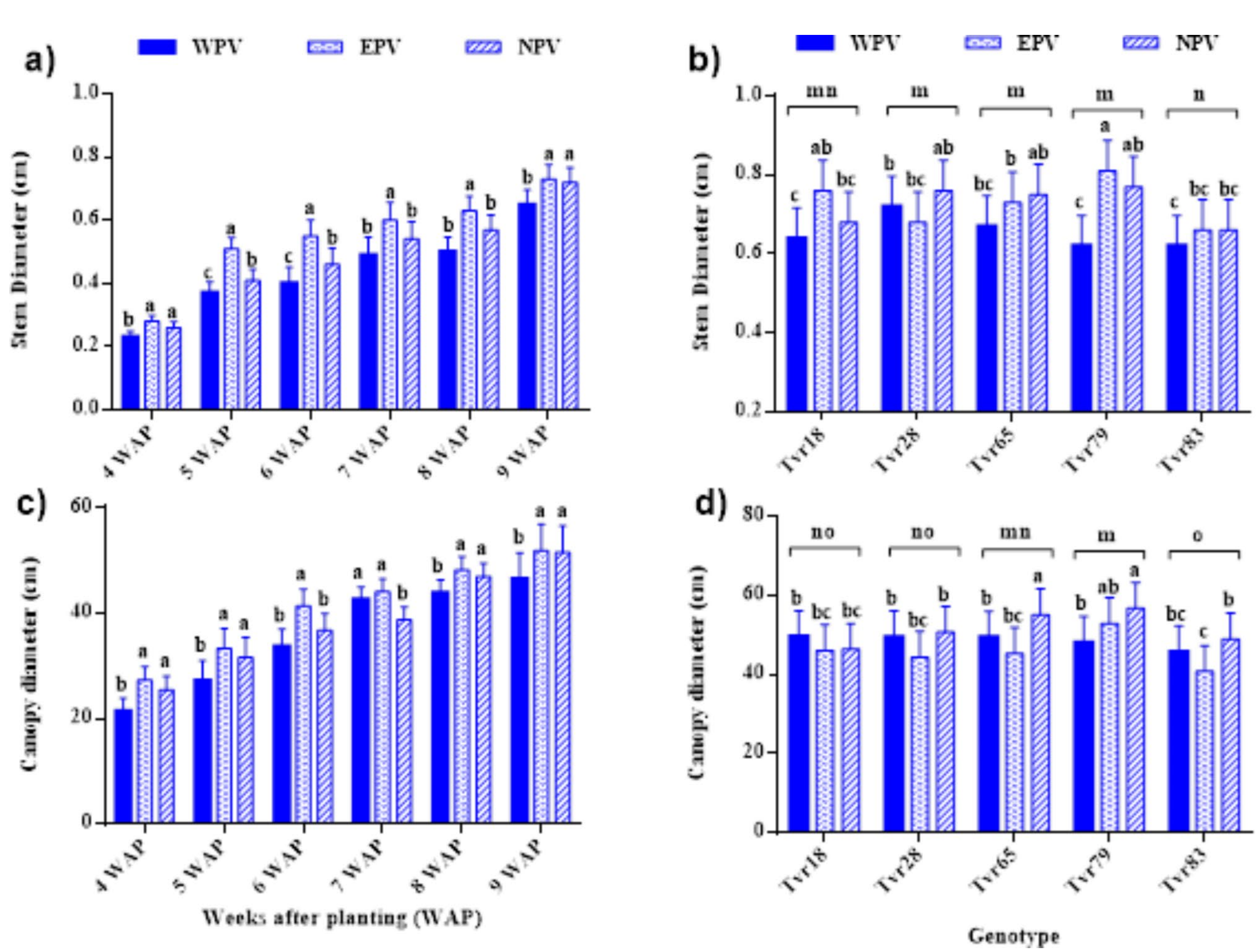

Fig. 6. Effect of APV system on mean weekly stem diameter (**a**), canopy diameter (**c**); and genotypic variation in stem diameter (**b**) and canopy diameter (**d**) underneath APV at 9 WAP. WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV; Bars with different letters are significantly different at $p < 0.05$.

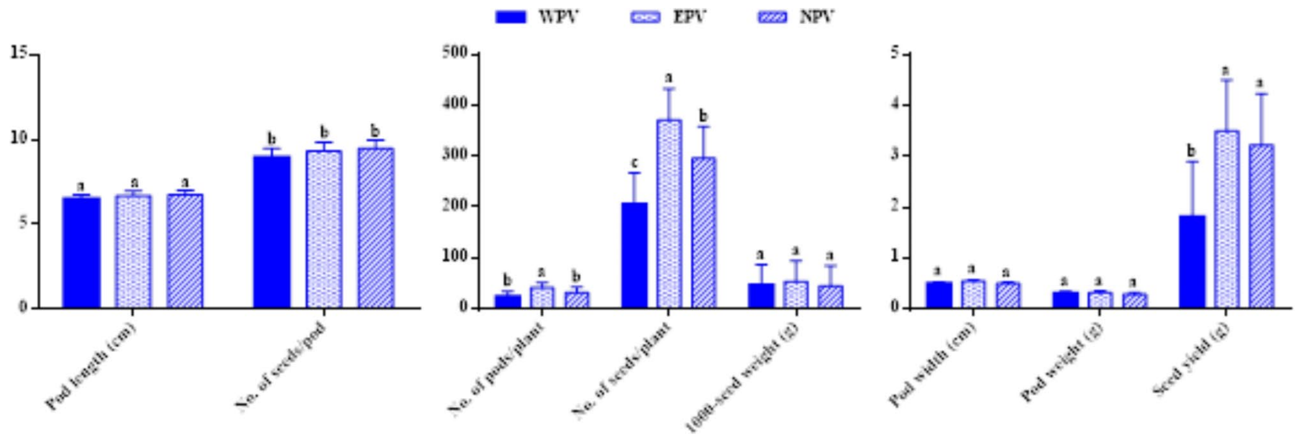

Fig. 7. Effect of APV system on yield and yield components of mungbean at maturity. WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV; Bars with different letters are significantly different at $p < 0.05$.

PV-Shading	Genotype	Number of pods / plant	Pod length (cm)	Pod width (cm)	Number of seeds / pod	Number of seeds / plant	Pod weight (g)	1000seed weight (g)	Seed weight (g)
WPV	Tvr18	22.80	6.25	0.53	7.39	171.60	0.35	69.00	1.98
	Tvr28	22.80	7.19	0.54	9.48	204.70	0.36	44.00	2.04
	Tvr65	17.40	7.00	0.51	9.48	165.20	0.27	34.00	0.70
	Tvr79	16.80	7.93	0.49	11.98	206.00	0.31	35.00	1.81
	Tvr83	42.30	4.18	0.43	6.60	278.80	0.25	54.00	2.54
EPV	Tvr18	22.80	6.91	0.59	7.94	181.40	0.34	68.00	1.94
	Tvr28	47.40	7.49	0.60	9.37	436.70	0.34	68.00	4.12
	Tvr65	22.80	7.56	0.51	12.38lePara>	282.70	0.36	34.00	3.78
	Tvr79	52.80	7.27	0.55	10.03	531.00	0.28	48.00	3.27
	Tvr83	61.20	4.30	0.49	6.93	422.50	0.28	52.00	4.40
NPV	Tvr18	29.40	7.33	0.55	9.76	288.40	0.31	56.00	2.36
	Tvr28	42.60	7.87	0.50	10.90	463.40	0.36	54.00	3.76
	Tvr65	19.20	7.22	0.51	10.69	203.80	0.30	34.00	3.11
	Tvr79	24.60	7.31	0.49	10.05	247.20	0.26	35.00	3.06
	Tvr83	45.00	3.99	0.46	6.06	278.70	0.23	46.00	3.64
$F\_LSD_{(0.05)}$		14.690	0.618	0.040	1.274	112.111	0.071	34.982	1.739

Table 3. Genotypic variation in yield components traits of mungbean underneath three APV partitions at 9 WAP. WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV; ns: not significantly different at $p < 0.05$. Any two interaction means with a difference ≥ the F_LSD value for each trait are significantly different at $p < 0.05$.

Effects of PV-shading and genotype on yield components and seed weight of mungbean

Yield components of mungbean such as number of pods per plant, number of seeds per plant and seed weight were significantly affected by PV-shading, whereas, yield components such as pod length, pod width, number of seeds per pod, average pod weight and 1000-seed weight were not significantly affected by PV-shading (Fig. 7). Pod number, seed number and seed weight were significantly higher underneath the EPV compared to NPV and WPV. Pod number increased by 28% under the EPV and decreased by 24% under the WPV. Likewise, seed number and seed weight increased under EPV-shading by 25% and 38% respectively, but decreased under WPV-shading by 31% and 28%, respectively (Fig. 7).

Genotype also had significant effect on yield components of mungbean. For instance, Tvr28 showed superiority in pod length (7.52 cm), seed number (368.30), pod weight (0.35 g), and seed weight (3.31 g); Tvr83 was significantly higher in pod number; Tvr65 recorded higher seed number per pod (10.85) while Tvr18 had larger pod width (0.56) and 1000 seed weight (64.33 g) (Table 3). The genotypes responded differently to the APV shading treatments. Notably, the interaction of the NPV-shading and Tvr83 influenced higher pod number (61.20) and seed weight (4.40 g) than did the WPV and Tvr65 interaction (17.40 and 0.70 g, respectively) which recorded the least (Fig. 8). The NPV-shading and Tvr79 interaction recorded higher seed number per plant (531.00) than did the WPV and Tvr65 interaction (165.20) which recorded the least. In addition, the WPV and Tvr79 interaction recorded higher pod length (7.93 cm) and seed number per pod (11.98) than did the

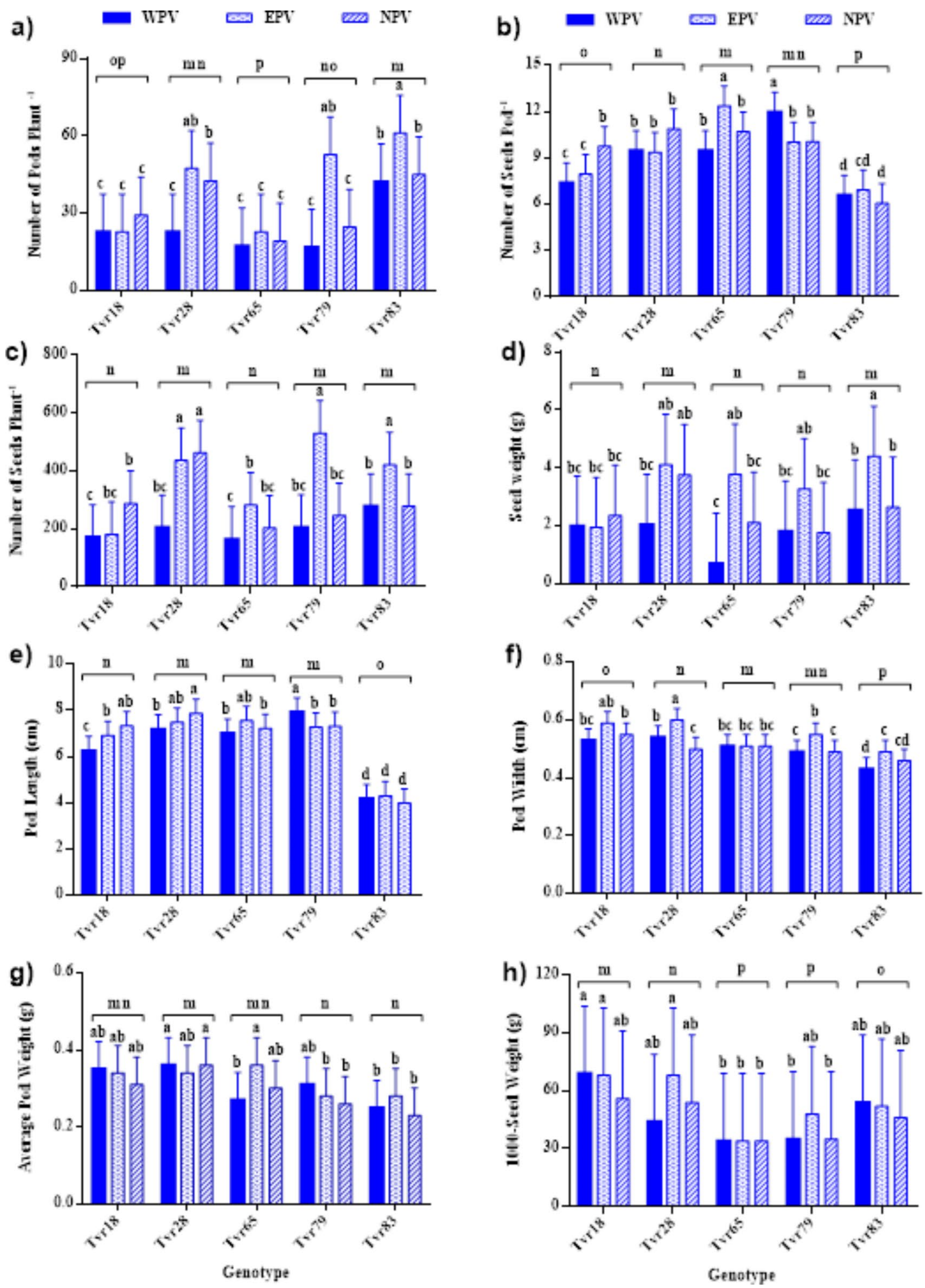

Fig. 8. Effect of APV system and genotype on the yield and yield components of mungbean at maturity. WPV: East-west facing PV; EPV: West-east facing PV; NPV: No-PV; Bars with different letters are significantly different at $p<0.05$.

NPV-shading and Tvr83 interaction (3.99 cm and 6.06, respectively) which was the least. The most conspicuous increases in 1000 seed weight were obtained in the interaction of the WPV and Tvr18 (69.00 g); and also in the interaction of the EPV with Tvr18 (68.00 g) and Tvr28 (68.00 g). The genotype Tvr65 recorded the least 1000 seed weight (34.00 g) across the PV-shading treatments.

Discussion

Microclimate indices of a plant such as PAR, temperature, and relative humidity exert considerable influence on crop growth and development. Crops perform optimally under specific climatic conditions, and any sharp deviation from the optimal requirement could greatly affect crop productivity. This study recorded significant reduction in PAR and leaf temperature with a corresponding increase in relative humidity as a consequence of PV-shading in contrast to NPV-shading for most part of the study duration, which could be attributed to the effect of the opaque PV-modules in shading-off between 5 and 47% of incident radiation thereby exerting a cooling effect on the plants consequently resulting in reduced temperature (3–9%), and increased air humidity (3–8%) arising from reduced evapo-transpiration underneath the WPV and EPV treatments. In addition, dust particles on roof tops and the angle of incidence of the sun rays also play vital roles in impacting the microclimate of the plant. Significant decreases in PAR and temperature under APV in contrast to control has previously been reported[15]. This report is also consistent with findings of other researchers[23,24]. The variation between the shaded treatments, WPV and EPV, arising from the orientation of the PV panels even though the same PV panels were used, is indicative that panel orientation is a very important factor to consider during installation of an APV facility. This study recorded higher PAR and temperature values with lower relative humidity under the EPV compared to the WPV which could be implicated on the rising of the sun from the East and setting at the West.

The rate of electron transport which corresponds to CO_2 assimilation rate, non-photochemical quenching, and the yield of potentially harmful unregulated non-photochemical energy dissipation were significantly reduced under the PV treatments compared to the NPV with the WPV recording the lowest values. However, both maximum and effective quanta yields of photochemical energy were optimized underneath the WPV and EPV treatments than the control. The reduction in CO_2assimilation rate and the quantum of energy lost to heat and fluorescence through the regulated and unregulated pathways is attributable to the reduced light intensity of the PV-shaded environment in contrast to the control. Light intensity decreased under PV-shading by 22–47% and 5–42% underneath the WPV and EPV treatments respectively in contrast to the control. Although, photochemical efficiency was higher in PV-shaded plants, rate of electron transport was slower than control due to reduced PAR. The reduced photochemical efficiency of plants in the control treatment is a function of the higher proportion of excess excitation energy lost through the non-photochemical routes, Y(NPQ) and Y(NO) relative to the shaded plants. Higher photochemical efficiency and reduced non-photochemical energy dissipation of plants under reduced light conditions had previously been corroborated by several researchers[8,12,25–28]. The low Y(NO) values recorded in contrast to Y(II) is an indication that the plants were able to minimize the production of harmful reactive oxygen species and maintained low steady state fluorescence in the PSII antenna through an efficient combination of photochemical and non-photochemical quenching processes. It also suggests that energy conversion for photochemistry and protective regulatory mechanisms were efficient, and that the plants had no problems coping with the incident radiation which agrees with previous report[12]. The mungbean genotypes showed slight variation in at least one of six weeks for which data were collected in some photosynthetic traits such as ETR, Fv/Fm, and Y(NPQ) but was not significant for majority of the period under investigation (4–9 WAP). While comparable responses in photochemical conversion efficiency and in yield of non-regulated energy dissipation of PSII were recorded across all genotypes, ETR was significantly higher in Tvr18 (47.44 μmol electrons $m^{(-2}s^{(-1)}$) than Tvr65 (38.55 μmol electrons $m^{(-2}s^{(-1)}$); Fv/Fm was reduced in Tvr83 (0.816) compared to Tvr65 (0.831); and Y(NPQ) was higher in Tvr83 (0.196) compared to Tvr28 (0.116) at 9 WAP. The slight variation in some photosynthesis variables among the mungbean genotypes could suggest differences in the capacities of their light harvesting antenna complexes and chlorophyll contents. Decreased Y(NPQ), ETR and coefficient of photochemical quenching was also reported in chlorophyll deficient soybean variety in Germany in contrast to control[29]. It is also consistent with the findings of previous scientists who observed smaller PSII antenna sizes in chlorophyll deficient barley, barley-mutant, Y11y11, and Arabidopsis varieties respectively in contrast to control[30–33].

The most significant delay in phenology of mungbean was recorded under the WPV-shading. Specifically, WPV-shading prolonged flowering onset, days to 50% flowering, and podding by 30%, 26%, and 30% respectively. Except for days to flowering onset which delayed underneath the EPV by 16% compared to NPV-shading, other phenological traits showed a similar trend with the NPV-shading. The prolonged phenological periods of mungbean as a consequence of PV-shading is implicated on the variation in microclimate parameters such as PAR, temperature, and relative humidity within the PV-shaded environment in contrast to the un-shaded. This is in agreement with previous reports that shading by PV panels delayed bloom timing, phenology and development in the late season for pollinators in a dry land in the Rogue River Valley, Oregon[34,35].

Except for days to emergence (Fig. 4a), mungbean genotypes also expressed differences in phenology. Remarkably, Tvr83 was earliest (36.38) to flowering onset (Fig. 4b), 50% flowering (38.00) (Fig. 4c), and podding (41.67) (Fig. 4d) compared to Tvr65 which was the latest to flower set (42.00), 50% flowering (42.67), and podding (47.50). The observed variation in phenology among the genotypes could be attributed to a combination of inherent genotypic differences and their preference for shade environment[20,21,36].

Growth performance of mungbean was significantly impacted by APV. The thinner and taller plants recorded underneath the WPV in contrast to NPV are typical of plants behavior under shade or under reduced light conditions. Plants tend to elongate their stems to maximize exposure to sunlight for photosynthesis in a process referred to as etiolation. This also explains the higher leaf number with corresponding smaller sizes as the plants could not sufficiently adjust their leaf sizes under the limited light condition. This report is in agreement with several reports on growth performance of crops under shade. Particularly, increased plant height of tomato and potato crops underneath PV-shade than open condition[14,37,38]. In another related study, increase in leaf sizes of *Tetrastigma hemsleyanum* under PV-shading had been reported with PV cover ratio less than 75%, and a decrease in leaf sizes under more intense shading conditions (90% PV cover ratio)[39]. Furthermore, leaf area of dwarf rice plants grown underneath shade were reduced compared to control plants[−39]. Variation was also observed among the genotypes in all growth traits measured (Fig. 5). The mungbean genotypes responded differently ($P < 0.05$) across the APV treatments especially in traits such as plant height, leaf number, leaf area, stem diameter, and canopy diameter. The behavior of the genotypes followed a similar trend, recording taller plants, more leaf number, and thinner stems under the WPV except for Tvr18 that exhibited a crossover effect in plant height, with shorter plants (58.50 cm) than in the NPV (68.70 cm). The variability in the genotypes behavior under shade could be implicated on their genotypic differences in response to shade environment which corroborates earlier reports[12,20,21].

The superior number of pods, number of seed, and seed weight recorded underneath the EPV in contrast to the WPV is a function of the improved microclimate conditions provided by the West-east-oriented PV modules which allowed sufficient PAR, improved temperature and air humidity, consequently favoring higher rate of electron transport to the PSII reaction centers and eventually translating into increased photosynthetic efficiency which manifested phenotypically as higher yield contrary to the East-west oriented type. In addition, plants underneath the PV treatments had lower unregulated energy dissipation of heat, implying that the plants were less exposed to potentially harmful reactive oxygen species that may have ensued with higher levels of unregulated energy dissipation to the PSII reaction centers. Furthermore, it also implies that the PV shading reduced plant stress compared to its NPV counterpart. This study showed for the first time that contrary to widely reported reduction in yield of crops under fully covered APV system, mungbean crops grown under the west-east oriented PV in tropical Nigeria had significantly more pods and seeds per plant, and non-significantly higher seed yield compared to the un-shaded control. This is a major breakthrough in the agrivoltaics research especially as countries all over the world are striving to maintain a sustainable balance between food production and clean energy generation without having to compromise one for the other. Rather, the same piece of land is used to produce more food and energy giving a land use efficiency of over 180%. With more crop trials, there is an increased tendency that significant yield differences in favor of APV would be detected in other crops. This finding is consistent with the 11–13% increase in yields of potato and winter wheat grown underneath PV in hot summer in Germany[15]. In addition, mungbean genotypes expressed variability in growth and yield components underneath the APV treatments which emphasizes their genotypic differences and their selective preference for shade environment[35,40].

Conclusion

The study highlights the emergence of APV systems as a promising solution to the increasing food and clean energy demand of the global populace. Specifically, this paper showed for the first time how APV system regulates microclimate conditions, photosynthesis, growth, and yield of mungbean grown underneath it in a tropical climate. We showed that the altered microclimate conditions underneath the APV system influenced photosynthetic activity, phenology, growth and yield traits of mungbean. The east-west oriented PV significantly reduced incident radiation, leaf temperature, rate of electron transport, non-photochemical stresses due to down regulation and up regulation of incident radiation, leaf area, stem and canopy diameter, pod and seed number per plant, and seed weight compared to the NPV. Furthermore, phenological attributes like flowering and podding dates were prolonged. Interestingly, the west-east oriented PV showed statistical parity with the NPV for most of these traits but was superior to the NPV in number of pods, seeds, and seed weight. Two genotypes Tvr28 and Tvr83 had higher yield performance than the others, which highlights the need to select suitable cultivars to optimize productivity in agrivoltaics systems. The findings of this study confirm that APV systems could offer a sustainable approach to simultaneously harness electricity generation and food production in the Tropics. It provides tropical-specific data and insights for the first time. It highlights the importance of PV orientation when installing APV systems for tropical climates, with mungbean exhibiting improved performance under west-east oriented PV. Optimizing PV orientation could help mitigate the negative impacts of shading on crop productivity while maximizing energy generation. This knowledge can inform the development and implementation of APV systems that effectively balance energy production and food security, offering a sustainable solution to meet the needs of a growing global population. This way, solar power can be generated without fully converting agricultural fields. This study could serve as a reference for future research seeking to optimize crop yields, maximize land use efficiency, and balance food and energy security through APV systems. However, more crop trials should be carried out under APV systems in the tropics to be able to come up with a sustainable model.

Data availability

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request.

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Author contributions
UNU, OM, MM and MIU conceived and designed the research. UNU and MIU conducted experiments. UNU analyzed data. UNU, OM, MM and MIU wrote the manuscript. All authors read and approved the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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