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MINI-REVIEW

Shading effect of photovoltaic panels on horticulture crops production: a mini review

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Abstract Agrivoltaics (APV) combine crops with solar photovoltaics (PV) on the same land area to provide sustainability benefits across land, energy and water systems (Parkinson and Hunt in Environ Sci Technol Lett 7:525–531, 2020). This innovative system is among the most developing techniques in agriculture that attract significant researches attention in the past ten years. The objective of this mini review is to present and summarize the recent studies on the effect of PV shading on crop cultivation (open field system and greenhouses integrated PV panels), with the aim to identify a correlation between the growth indicators, crop quality (antioxidant activity, sugar content, etc.) and the characteristics of PV installation (shading degree). The alteration of microclimate parameters such as solar radiation, air temperature, humidity and soil temperature under the PV panels was highlighted. Moreover, impact of APV shading on irrigation and water saving and economic feasibility of APV was further discussed. Our main findings are that (1) the reduction in solar radiation is the main changed factor underneath the APV canopy where a reduction of more than 40% the solar radiation due to the presence of the PV panels was observed. (2) Agrivoltaic systems (PV greenhouse or ground) with cover ratio equal or lower than 25% did not show significant effects on plant growth and quality. (3) Inhibitory effects on crops growth was observed with coverage ratio of 50 to 100% except for strawberry and spinach. (4) Water use efficiency for some crops species in dry land climate was greater in the APV system. Given the findings, the research seems promising enough to support APV practices that limit PV panel shading to be lower than 25% to avoid affecting crop growth, assumed to be the priority of an agricultural operation.

Keywords Agrivoltaic system · Photovoltaic panels · Horticulture crops · Shading · Microclimate

1 Introduction

Population and economic expansion has increased global energy demand, which is expected to double by mid-century (Hassanpour Adeh et al. (2018); Pandey

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et al. 2016). Renewable and environmental-friendly energies which simultaneously replace fossil fuels will play an essential role to meet this demand (Weselek et al. 2019). On the other hand, moving toward cleaner energy production is the key challenge that faces researchers to solve climate change crisis (Ayop et al. 2020). Among all cleaner and renewable energies, solar power is the most plentiful and available source (Moreira et al. 2020; Malu et al. 2017). The photovoltaic (PV) panel is a device that generates energy by converting the solar energy to electrical energy (Li et al. 2020; Nonhebel 2005). Photovoltaics (PV) solar energy is an attractive renewable energy strategy due to the following reasons: (1) significant carbon emissions is avoided by using PV; (2) solar panels have a long useful life span (20–30 years); (3) it is stable, low cost and abundant energy resource; (4) they are efficient in capturing sunlight energy than photosynthesis (Kolaly et al. 2020). Installation of PV systems on agricultural land results in a land-use conflict between energy and food production which is a major concern especially in regions with limited land area or a dense population (Weselek et al. 2019). Associating food crops and solar PVon the same land area which is referred as agrivoltaic systems (also denoted as Agrophotovoltaics, APV) (Dinesh and Pearce 2016; Santra et al. 2017) is among the most developing techniques in agriculture that attract significant researches attention in the past ten years (Fig. 1a).

Agrivoltaic systems offer a solution to the increasing demand for food and energy, while also decreasing water consumption (Barron-Gafford et al. 2019). For example, photovoltaics mounted on greenhouses could be effectively used to cover energy needs for electricity and heat. Consequently, various reports in China (Hassanien and Ming (2017)), Spain (Aroca-Delgado et al. 2019), Italy (Buttaro et al. 2016), USA (Barron-Gafford et al. 2019), France (Marrou et al. 2013a), Germany (Trommsdorff et al. 2021) and India (Malu et al. 2017) have been conducted by integrating PV modules on certain areas of the agricultural greenhouses roofs or ground to protect plants by diminishing the solar radiation, light intensity and air temperature inside the greenhouses as well as reduce, or partially replace the energy consumption (Aroca-Delgado et al. 2018; Allardyce et al. 2017). Based on the potato yield that has been cultivated in 2018 in Germany, the land use efficiency rose to 186 percent per hectare with the Agrophotovoltaic system (Fig. 1b) (Trommsdorff et al. 2021). However, in these innovative systems, PV panels partially shelter the crop growing below (Marrou et al. 2013b). Therefore, the shading created under PV panels may reduce the average available light for the crop (Hassanien and Ming 2017; Hassanien et al. 2018). Consequently, several studies has experimentally investigated the effect of PV shading on crop cultivation (Table 1), with the aim to identify a correlation between the growth parameters (dry and fresh weight, yield, size, colour, etc.), crop quality (antioxidant activity, sugar content, etc.) and the characteristics of PV installation (shading degree) (Friman-Peretz et al. 2020; Ureña-Sánchez et al. 2012). It is worth mentioning that compared to PV greenhouse, there are few studies (only 27%) investigated the shading effect of ground mounted PV (open field system) on the crop performance (Fig. 2). The agrivoltaic concept has proven successful in numerous systems including solar PV and lettuce (Kavga et al. 2018), and tomatoes (Ezzaeri et al. 2018) due to their short cycle cultivation. Furthermore, it can be seen that tomato is studied more in PV greenhouse than in open field (Table 1) because it tends to be easier to get a good crop when grown in greenhouses. To the best of our knowledge, there is no specialized review discussing the shading effect of PV panels on horticultural crop performance in term of growth, yield and quality in both open field system and greenhouse. In this min review, the results of recent research that investigated the shading effect of static or mobile PV modules mounted greenhouses or ground (open field system) on crops production in different seasons were reviewed and summarized. The alteration of microclimate parameters such as solar radiation, air temperature, humidity and soil moisture under the PV panels was highlighted. Furthermore, impact of APV on water saving was further discussed (Fig. 3).

2 Microclimate change under PV panels

The variation of microclimate factors is one of the most vital issues for agricultural practice underneath an APV array. The reduction in solar radiation is the main changed factor underneath the APV canopy (Cossu et al. 2020). However, several other microclimate factors may also be altered i.e. air temperature

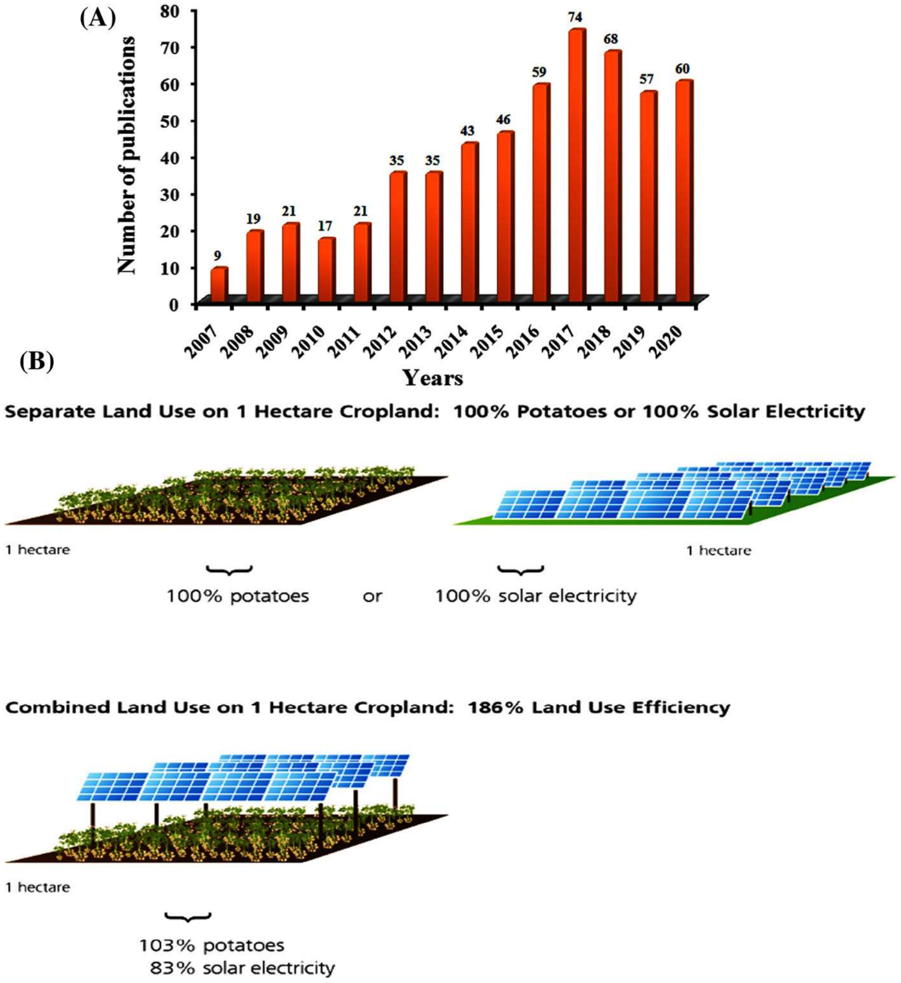

Fig. 1 **a** Number of research articles per years about agrivoltaic system cited by web of science (data analysis on 29th September 2020) and **b** through the combined land use, the land use efficiency with the APV system is 186%. *Source*: © Fraunhofer ISE

and humidity. As proof of concept, in summer period, the global radiation was found to be $\sim$ 400 Wm^2 under the shaded area of the organic PV tunnel (23% shade) which is lower than inside the control tunnel and under the unshaded area in the organic PV tunnel (650–680 Wm^2). In this system, no significant changes were observed in mean air temperatures and humidity between PV and control plot. Whereas, soil temperature was found to be increased to maximum values of 33.5 and 32.8 °C in the organic PV and control plots from 8:00 to 16:00 (Fig. 4) (Friman-Peretz et al. 2020).

A reduction of 50.50% and 41% of the solar radiation due to the presence of the PV panels (covering 40% roof area) compared to the control greenhouse was observed in summer and winter period, respectively. Air temperature was also affected by the presence or absence of PV panels, with the unshaded greenhouse exhibiting an increase in air temperature of 8% compared to the shaded greenhouse. However, in winter season it was at the same level for both tunnels. The differences in the relative humidity between the two systems in sunny and cold period were 7.74% and 2%, respectively (Ezzaeri et al. 2020). Ezzaeri et al. find that 10% of shade during warm month April does not have any significant effect on the microclimate (Ezzaeri et al. 2018). In another study, Cossu et al. assessed the climate conditions inside an east–west oriented greenhouse with 50% of the roof area covered by PV panels, studying the solar radiation distribution and the temperature and humidity variability, with tomatoes crop for the test. It was

Table 1 Studies on the shading effect of PV panels on crops performance

Crops	Location	APV system	Geometrical arrangements	Cover ratio (%)	Energy production	Remarks	References
Tomato	Almería, Spain	PV greenhouse	Checkerboard pattern	9.8%	2766 kW h crop/cycle	No significant affect on yield and negative effect on fruit size and color. The generated energy is higher than the consumed energy by the greenhouse (768 kwh crop/cycle)	Ureña-Sánchez et al. (2012)
	South Eastern Spain	PV greenhouse	Checkerboard pattern	9.79%	8.25 kW h/m^2	Blocking effect of photosynthetically active radiation is not significant for plants growing	Pérez-Alonso et al. (2012)
	Sardinia, Italy	PV greenhouse	Straight lines	50%	107,885 kWh (112 kWh/m^2)	Reduction of crop yield	Cossu et al. (2014)
	Merlino, Italy	PV greenhouse	–	50%	–	Quantitative and qualitative reduction of crop production	Bulgari et al. (2015)
	Sardinia, Italy	PV greenhouse	Straight lines	50%	–	Reduction of crop yield	Cossu et al. (1170)
	Kunming, China	PV greenhouse	Straight lines	20%	637 kWh (24.5 kWh/m^2)	No significant affect of crop growth was observed	Hassanien et al. (2018)
	South-eastern Spain	PV greenhouse	Straight lines	9.8%	6.40 kW h/m^2	The fruit diameter was decreased, without affecting the yield	Aroca-Delgado et al. (2019)
	Agadir, Marroco	PV greenhouse	Checkerboard pattern	10%	–	No significant affect of crop growth and quality	Ezzaeri et al. (2018)
	Sardinia (Italy)	PV greenhouse	Straight lines	25%	–	No significant affect on crop growth	Cossu et al. (2020)
				50%		Yield reduction of 39%	
				60% and 100%		Not compatible for crop cultivation	
	Southern Agadir, Marroco	PV greenhouse	Checkerboard pattern	40%	–	No significant affect on crop yield	Ezzaeri et al. (2020)
	South–East Spain	PV greenhouse	Straight lines	15%, 30% and 50%	–	Over 30% shading affect fruit quality and yield	López-Díaz et al. (2020)
	North of Tucson, AZ, USA	Open field system	Straight lines	–	–	Increase in fruit production	Barron-Gafford et al. (2019)

Table 1 continued

Crops	Location	APV system	Geometrical arrangements	Cover ratio (%)	Energy production	Remarks	References
Lettuce	Montpellier, France	Open field system	Straight lines	50% 30%	6.5 to18 kWhm^2	Significant affect on crop yield No significant affect on crop yield	Marrou et al. (2013a), Marrou et al. (2013b), Valle et al. (2017)
	South–West Greece	PV greenhouse	Straight lines	20%	50.83 kWhm^2	No significant reduction effect to plant growing. The system covers the 38% of the yearly total greenhouse energy demand	Trypanagnostopoulos et al. (2017)
	Lat, Japan	PV greenhouse	Checkerboard pattern	50%	–	Significant effect on growth of crop (lower dry weight)	Tani et al. (2014)
	South–West Greece	PV greenhouse	Straight lines	20%	–	No significant affect on crop growth	Kavga et al. (2018)
	Kunming, China	PV greenhouse	Straight lines	20%	637 KWh	No significant affect on crop growth The system covers the 20% of the annual energy demand	Hassanien and Ming (2017)
	Sardinia (Italy)	PV greenhouse	Straight lines	25 50 60% and 100%	–	Compatible for cultivation.Yield reduction higher than 25% Incompatible for cultivation	Cossu et al. (2020)
Peppers	T.Thessaloniki, Greece	PV greenhouse	Straight lines	22%	–	Improved crop yield	Zisis et al. (2019)
	western Greece	PV greenhouse	Straight lines	20%	–	No affect on plant growth and quality	Kavga et al. (2019)
	Sardinia (Italy)	PV greenhouse	Straight lines	25% 50%, 60 and 100%	–	No significant yield reduction of 25% Incompatible for cultivation (Low yield)	Cossu et al. (2020)
Cucumber	Montpellier, France	Open field system	Straight lines	50% and 30%	–	Total number of leaves was more affected and reduced growth rates at the beginning of the plant life cycle	Marrou et al. (2013b)
	Sardinia (Italy)	PV greenhouse	Straight lines	25% 50% 60% and 100%	–	No significant affect on crop growth Significant yield reduction Incompatible for cultivation	Cossu et al. (2020)

Table 1 continued

Crops	Location	APV system	Geometrical arrangements	Cover ratio (%)	Energy production	Remarks	References
Rocket	Apulia, Southern Italy	PV greenhouse	Straight lines	25%	–	No significant affect on crop growth and dry weight	Buttaro et al. (2016)
	South–West Greece	PV greenhouse	Straight lines	20%	–	Rocket cultivation was less productive and showed lower photosynthetic rate	Kavga et al. (2018)
Onion	Japan	PV Greenhouse	Straight lines Checkerboard pattern	12.9%		Significant effect on crop quality and production No significant effect	Kadowaki et al. (2012)
Strawberry	Apulia, Southern Italy	PV Greenhouse	Straight	25%	–	Increase in antioxidant capacity and phenol content	Blando et al. (2018)
	Sardinia (Italy)	PV greenhouse	Straight lines	25% and 50% 60% and 100%	–	No significant affect on crop yield Significant affect on crop yield	Cossu et al. (2020)
	Kunming, China	PV greenhouse	Straight lines	25.9%	–	Strawberry crops shaded were superior to unshaded strawberry in terms of growth, quality and yield	Tang et al. (2020)
Potatoes	Belgium	Open field system	Checkerboard pattern	50%	2447 kWh	The total leaf area for potatoes below the PV modules was larger than the reference area	Willockx et al. (2020)
	Germany	Open field system	Straight lines	–	246 MWh	Equal crops yield compared to unshaded condition	Trommsdorff et al. (2021)

found that the PV modules reduced the availability of solar radiation inside the greenhouse by 64%, compared to the greenhouse without PV modules (Cossu et al. 2014). Considering north–south orientation, increasing the roof shading from 15 to 50%, the percentage reduction of PAR compared to the control greenhouse changed from 28.8 to 66.3%; with PV shading also effectively reducing indoor air temperature (López-Díaz et al. 2020).

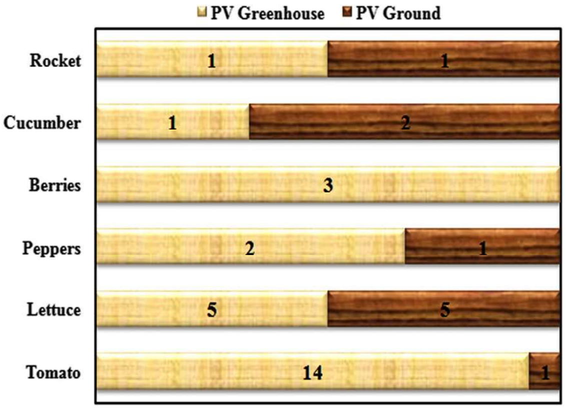

Fig. 2 Number of studies on the effects of PV shading on crop growth, depending on type of crop and agrivoltaic system (ground or greenhouse mounted PV)

Reda Hassanienet et al. found that the reduction of solar radiation under the semi-transparent building integrated photovoltaics (BIPV) mounted on top of a greenhouse (20% of shade) was 35–40% more than the control plot on clear days. This system decreases the air temperature by (1–3 °C) on clear days and has no effect on relative humidity (Hassanien and Ming 2017; Hassanien et al. 2018). Zervoudakis et al. find that the PV installation with 20% shading induced 2.2 °C and 7.2% of temperature and Photosynthetically Active Radiation (PAR) decrease during the studied crops cultivation periods(Feb–April) (Kavga et al. 2018). The effects of a six-acre agrivoltaic solar farm on the microclimatology and soil moisture was investigated by Hassanpour Adeh et al. where significant differences in mean air temperature, relative humidity, wind speed, wind direction, and soil moisture were observed. Moreover, areas under PV panels were significantly more water efficient (328% more efficient) (Hassanpour Adeh et al. 2018). It was noted that the APV have great influence on soil moisture. Barron-Gafford found that soil moisture levels in the agrivoltaic system (elevated ground mounted PV)

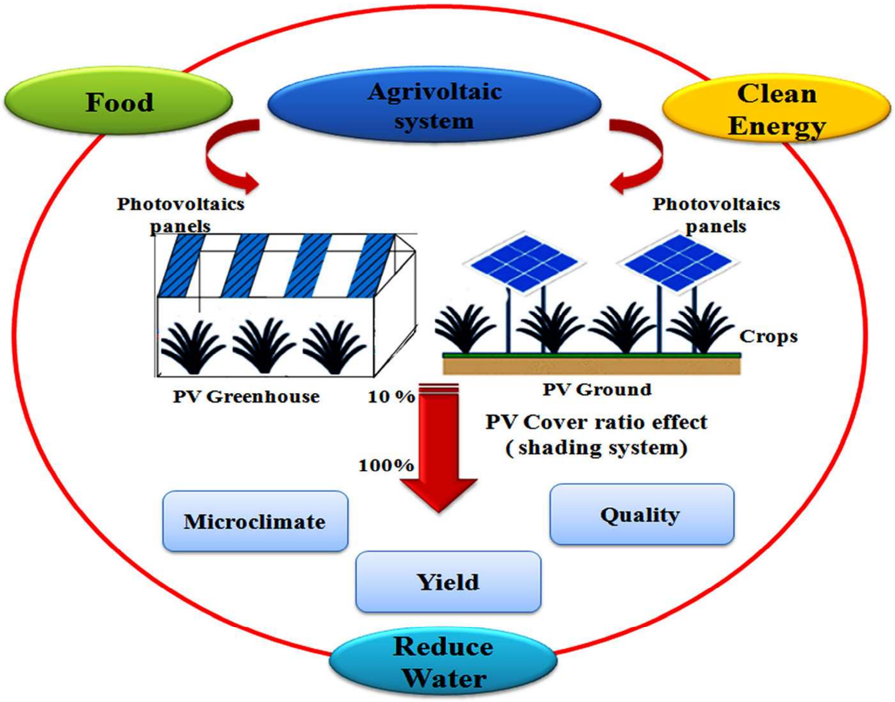

Fig. 3 General discussed point in this review

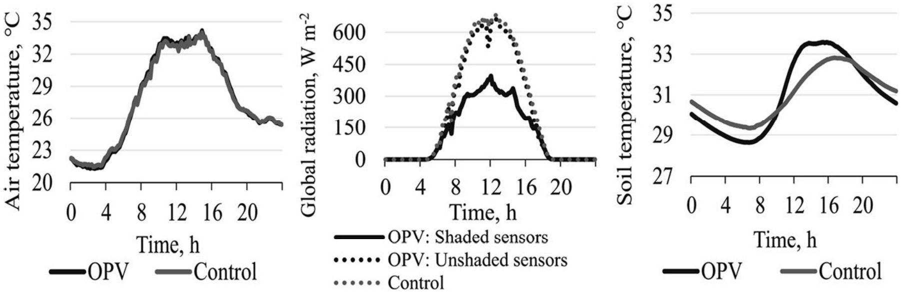

Fig. 4 Diurnal changes of different microclimate parameters measured in PV and control tunnels in mid of July. (Modified from Ref (Friman-Peretz et al. 2020))

after 2 days irrigation remained above the driest points seen in the control plot after daily irrigation events, concluding the possibility of reduce irrigation in APV systems (Barron-Gafford et al. 2019) (see Sect. 4).

3 Case studies on shading effect of PV panels on crop production

The solar radiation received by the plants may decrease crop yields and reduce fruit sizes (Marrou et al. 2013a). Consequently, the impact that solar panels could have on crop yield and fruit quality has attracted great attention of researchers. Tomato, lettuce, pepper, cucumbers and strawberries are the most studied crops under PV panels (Fig. 5). The recent literatures for applications of selective shading systems on the aforementioned crops and others plants are reviewed in the following sections.

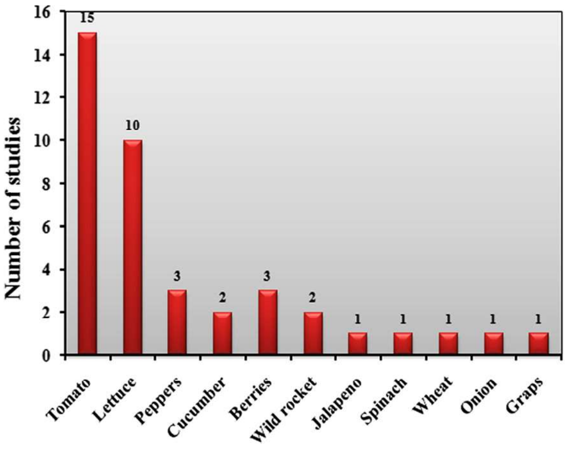

Fig. 5 Number of research articles depending on type of horticulture crops growth under PV modules (data analysis on 6th October 2020)

3.1 Tomato cultivation underneath PV

In this section, we will discuss the influence of APV on tomato productivity in greenhouse and in open field system. In this regards, Meir Teitel et al. showed that 23% of organic PV shading in greenhouse has no negative effect on the tomato yield and it has been found that the cumulative number of tomatoes, their mass, and average tomato mass were higher, by 9, 36, and 21%. respectively, than in the unshaded tunnel due to a much lower canopy temperature. Similar results were obtained by applying 25% black shading system on the roof of the greenhouse tunnel (Friman-Peretz et al. 2020). In a recent study by Ezzaeri et al. in Marocc, Agadir. It was found that 10% of PV shading arranged in a checkerboard pattern, during warm month April, did not have any significant effect on the microclimate or on the tomato yield. Neither did it result in any significant effects on other agronomy parameters such as height and stem diameter. In addition, the population of *Tuta absoluta (pest)* caused yield reduction was inhibited by PV panels (Ezzaeri et al. 2018). The same results of 9.8% shading by checkerboard pattern PV on tomato yield have been reported by Carreno-Ortega et al. However, it showed negative effect on fruit size and colour (Ureña-Sánchez et al. 2012). The effect of 9.8% shading rate, by applying PV, on the morphology and fruit quality of tomato during two growing period (2010–11 and 2011–12) in south-eastern Spain has been studied recently by Ángel Jesús et al. The test results indicated that solar panels caused small reduction in PAR. However, it did not affect the total and marketable yield; plant morphology; number of flowers per branch; and fruit colour, firmness and pH despite their negative effect on the fruit diameter (Aroca-

Delgado et al. 2019). By the installation of the aforementioned system, the yearly electricity production was found to be 8.25 kW h/m^2 (Pérez-Alonso et al. 2012).

In a study conducted by Li et al. it was noted that semi-transparent building integrated photovoltaics (BIPV) mounted on top of a tomato greenhouse with 20% of shade produce 637 kWh of annual electric energy generation where the system did not affect the growth of tomato (Hassanien et al. 2018). In measurements with a tomato crop, covering 40% roof area of greenhouse with PV panels in the checkerboard pattern did not have a significant impact on the overall yield of tomatoes during summer period. However, in winter season, PV resulted in delay of tomato maturity due to the reduction of solar radiation inside the photovoltaic greenhouse (Ezzaeri et al. 2020). The delay of maturity during this period could be solved by using LED supplemental lighting (Wojciechowska et al. 2015). An attempt to investigate the shading effect from a PV array and of integrating the natural radiation with supplementary lighting powered by PV energy was presented by Cossu et al. The supplementary lighting with 50% of shade with a total rated power of 68 KWp did not affect the tomato crop production and the annual yields under the plastic roofs were higher than under the PV roofs (Cossu et al. 2014). In order to achieve and find the best PV cover ratio (shading) for high energy and crop yield production, Ledda et al. analyzed the yield of numerous greenhouse horticultural and floricultural crops inside PV greenhouse spread in southern Europe, with PV cover ration ranging from 25 to 100% and it was found that the structures with a 25% of shade were compatible with the cultivation of tomato (with the average yield reduction around 20%) and other high light demanding crops species such as cucumber and sweet pepper with limited yield reduction (below 25%) (Cossu et al. 2020). These results were consistent with that found by L´opez-Díaz et al. increasing the roof shading from 15 to 50% negatively affected the total tomato yield and fruit color, reducing from a minimum of 10% (16.9 kg/m^2) up to approximately 40% (11.5 kg/m^2) (Fig. 6) (López-Díaz et al. 2020). It can be concluded from the above studies that restrictions on tomato growth and yield occurred when shading ratio increased from 50 to 100% (Fig. 7). Recently, the impact of agrivoltaic system on food production, water savings, and energy generation have been investigated by Barron-Gafford et al. In this study, tomatos are grown in the partial shade of the solar infrastructure in dryland environement (south USA). The results indicated that total fruit production of tomato doubled in the APV system (open field system) (Barron-Gafford et al. 2019).

3.2 Lettuce cultivation underneath PV

The effect of shading on the growth of lettuce has been studied by various researches in different projects. As proof of concept, H. Marrou et al. assessed the growth rate (crop temperature and number of leaves) of lettuce cultivated under 25% and 50% PV shading (ground mounted PV) during different weather period (spring and summer). The results showed that daily crop temperature remained close to the one in the full sun and the growth rates (leaf apparition rate) were reduced under PV at the beginning of the plant life cycle due to the reduction of ground temperature in the shade of the solar panels caused by fluctuating irradiance. In addition, lettuce cultivated under 25% and 50% PV cover ratio showed an average yield factor of respectively 99 and 79% of the control crop (Marrou et al. 2013b). In attempt to improve lettuce growth, light diffusion films under roof-mounted PV modules with 50% of shade were suggested by Makio Hayash and his coworkers. The results showed that dry weight and relative growth rate were low in fluctuating conditions where diffusion light conditions improved growth rate (wide leaves) in summer and spring seasons. In additions, the ratio of leaf width to length was close to that in control. However, the relative growth rate in winter period is reduced due to the reduction of photosynthetic photon flux density (PPFD) (Tani et al. 2014). The reduction of PPFD could be solved by using lightweight PV film (Eberspacher et al. 2001). PV greenhouse with low covering ratio of greenhouse roof (20%) in South–West Greece gave satisfactory results regarding lettuce grow indicators i.e. fresh and dry weight, the length and the surface of the leaves (Fig. 8) and it was found that PV panels produced 50.83 kWh/m^2 for the studied cultivation period of Feb–Mar–Apr which is effective to energy contribution in electricity and heat. However, it was lower compared to sun tracking PV panels mode (mobile PV) (Trypanagnostopoulos et al. 2017). In china, the integration of semi-transparent photovoltaic panels with greenhouses which occupied

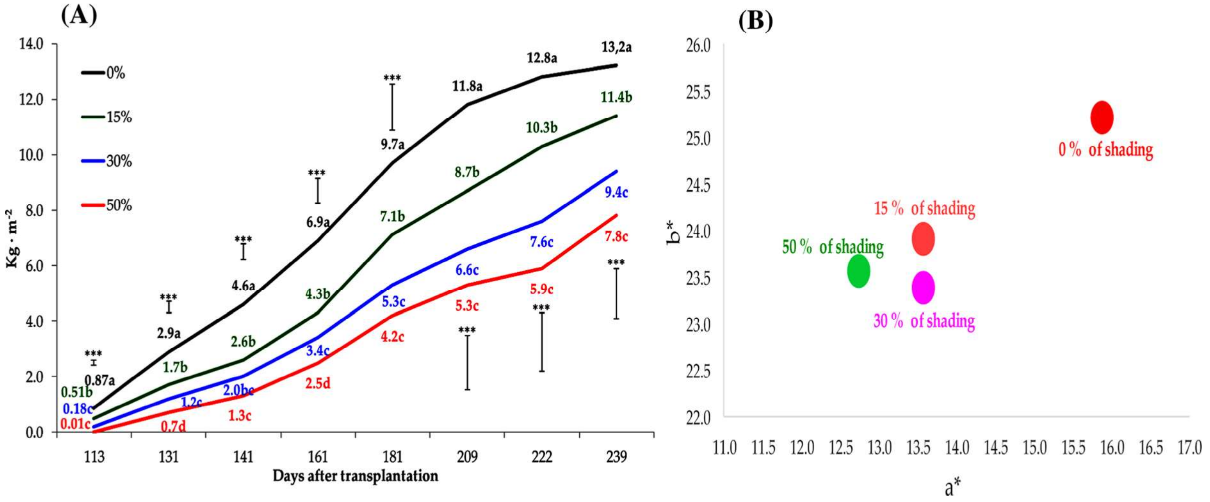

Fig. 6 **a** Shading effects on the temporal evolution of accumulated marketable yield (kg/m^2); **b** shading effect on fruit color. Adapted from López-Díaz et al. (2020)

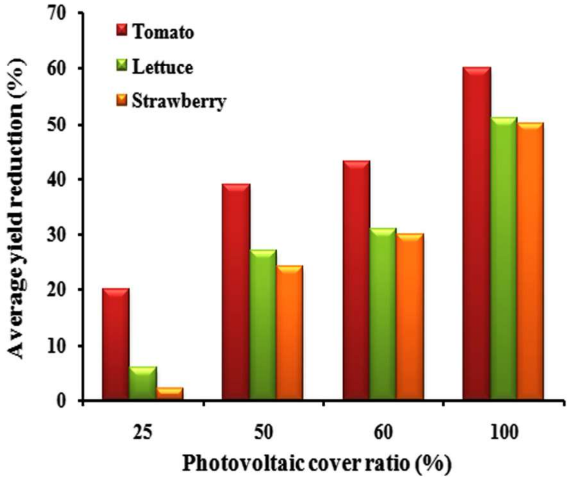

Fig. 7 The average yield reduction of crops depending of different PV greenhouse cover ratio located in Syrdinia, Italy. (Data reproduced from Ref Cossu et al. 2020)

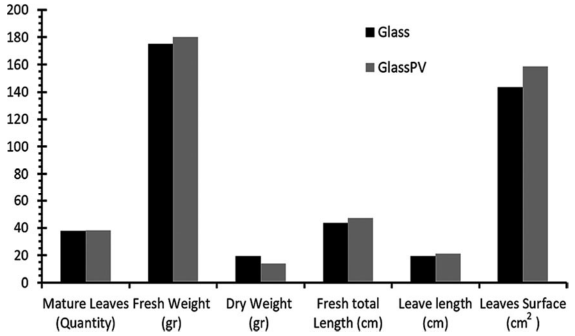

Fig. 8 Average values of lettuce grow indicators. Adapted from Trypanagnostopoulos et al. (2017)

20% of the roof area and its influence on lettuce growth was evaluated by Hassanien et al. It is noted that agrivoltaic system can decrease the solar irradiation and the internal air temperatures as well as generate electric energy for environmental control systems without significant influence on the growth of lettuce plants. Meanwhile, it can decrease the water consumption by decreasing the evapotranspiration rate (Hassanien and Ming 2017).

It seems that the solar intensity demand for maximum plant growth differs between species. For example, rocket plants were cultivated from May to Jun under same shading condition as lettuce in the aformontioned report (Trypanagnostopoulos et al. 2017). However, the rocket growth was affected by PV panels and showed lower photosynthetic rate than in the reference greenhouse (Kavga et al. 2018). It was found that 30% and 50% of shade with sun tracking PV panels which were elevated to 4 m above ground did not show any significant effect on lettuce production (Valle et al. 2017). Same results were obtained under fixed panels with same covering ratio (Marrou et al. 2013a). Despite this solar tracking PV systems showed good results in terms of energy production without competing with food and permits dual food/energy production. However, high cost hindered their application.

More recently, Ledda et al. proved that lettuce as medium light demanding crop can be grown inside PV greenhouse with 25–50% PV cover ratio with an average yield factor of 94–73% (6–27% yield reduction), respectively (Fig. 7) (Cossu et al. 2020). It can be seen that these results were comparable with experimental trials inside the open field system (99 and 79%) carried out by Marrou et al. (Marrou et al. 2013b) due to the microclimates differences between greenhouses and ground mounted PV panels. Limiting PAR compensation ability of lettuce limited its yield reduction by increasing the radiation interception efficiency (RIE) with physiological adjustments (different leaf arrangement, a decrease of the leaf number coupled to a higher total leaf area and head diameter) (Marrou et al. 2013a).

3.3 Pepper cultivation underneath PV

Organic photovoltaics (OPVs) are constantly gaining ground among other PV technologies due to their low weight, tunable optical transmittance, flexibility and high conformability. S. Logothetidis et al. found that under 22% of shade by semitransparent OPVs based on P3HT:PCBM photoactive layer, the pepper plants showed better performance and produced 20.2% more fruit mass compared to the control ones. In addition, at the end of the growing season, the height of the shaded plants was 21.8% larger than the control and outdoor plants due to their protection from UV radiation (Zisis et al. 2019). More recently, P Zoumpoulakis et al. reported no significant effects of 20% shading roof coverage by polycrystalline silicon (pc-Si) PV panels on the growth, yield and quality of pepper (phytochemical profile) in western Greece greenhouse where the pepper fruit extracts in terms of total phenolic content, antioxidant and antiradical activities indicated non-statistically significant differences between PV greenhouses and control (Kavga et al. 2019). In Italy, it was found that sweet pepper species were compatible inside PV greenhouses with a PV cover ratio of 25% with limited yield reduction below 25%. However, the heterogeneous light distribution on the greenhouse area with a PV cover ratio of 50% caused a low yield (31%). In addition, PV cover ratio of 60% and 100% were incompatible for sweet pepper growth (high yield losses was found to be up to 75%) (Cossu et al. 2020).

3.4 Berry cultivation underneath PV

The possibilities to combine berries (wild strawberry, blackberry and red rasp-berry) and energy production were reported by Federica Blando and his team. The aforementioned crops inside PV greenhouses with 32 and 100% PV cover ratio (semi transparent and non transparent PV modules) resulted in an increase of the antioxidant activity of the fresh produce, including total anthocyanins, citric and fumaric acid. In addition, it was found that shading has a negative effect on sugar content of the studied crops (Blando et al. 2018). More recently, opaque PV modules covering 25.9% of the greenhouse roof with solar combined air source heat pump system showed satisfactory results for strawberry cultivation (Fig. 9). The chlorophyll content of the shaded strawberry crops was 1.3 times higher than that of the unshaded crops in hot climate and the soluble solids content of the shaded strawberry fruit was 16.4%, which was higher than that of the unshaded strawberry samples. Moreover, the yield of the shaded samples was 1.2 times that of the unshaded samples (Tang et al. 2020). Strawberries species can be grown under 25% and 50% shade with limited yield losses (less than 25%). However, it can not be cultivated under 60% or 100% of shade (Fig. 7) (Cossu et al. 2020).

3.5 Other crops cultivation underneath PV

Kadowaki et al. evaluated the influence of PV shading mounted greenhouse on the growth of the onion (*Alliumfistulosum* L). Two types of the photovoltaic panel distribution, checkerboard and straight-line were tested, each one covering 12.9% of the roof area. Study results indicated that the electricity generated by the PV array for checkerboard and straight-line was similar. Moreover, the straight-line arranged PV-array decreased dry matter weight (DW) and fresh weight (FW) of Welsh onion compared to the checkerboard PV-array and control. Conversely, the solar radiation inside the checkerboard PV greenhouse was more uniform than in the straight-line PV greenhouse because the former layout improved the unbalanced spatial distribution of solar radiation received in the greenhouse (Kadowaki et al. 2012). In an Italian greenhouse, where semi transparent PV modules covered 32% roof area with a stripe formation along a north–south orientation and east–west

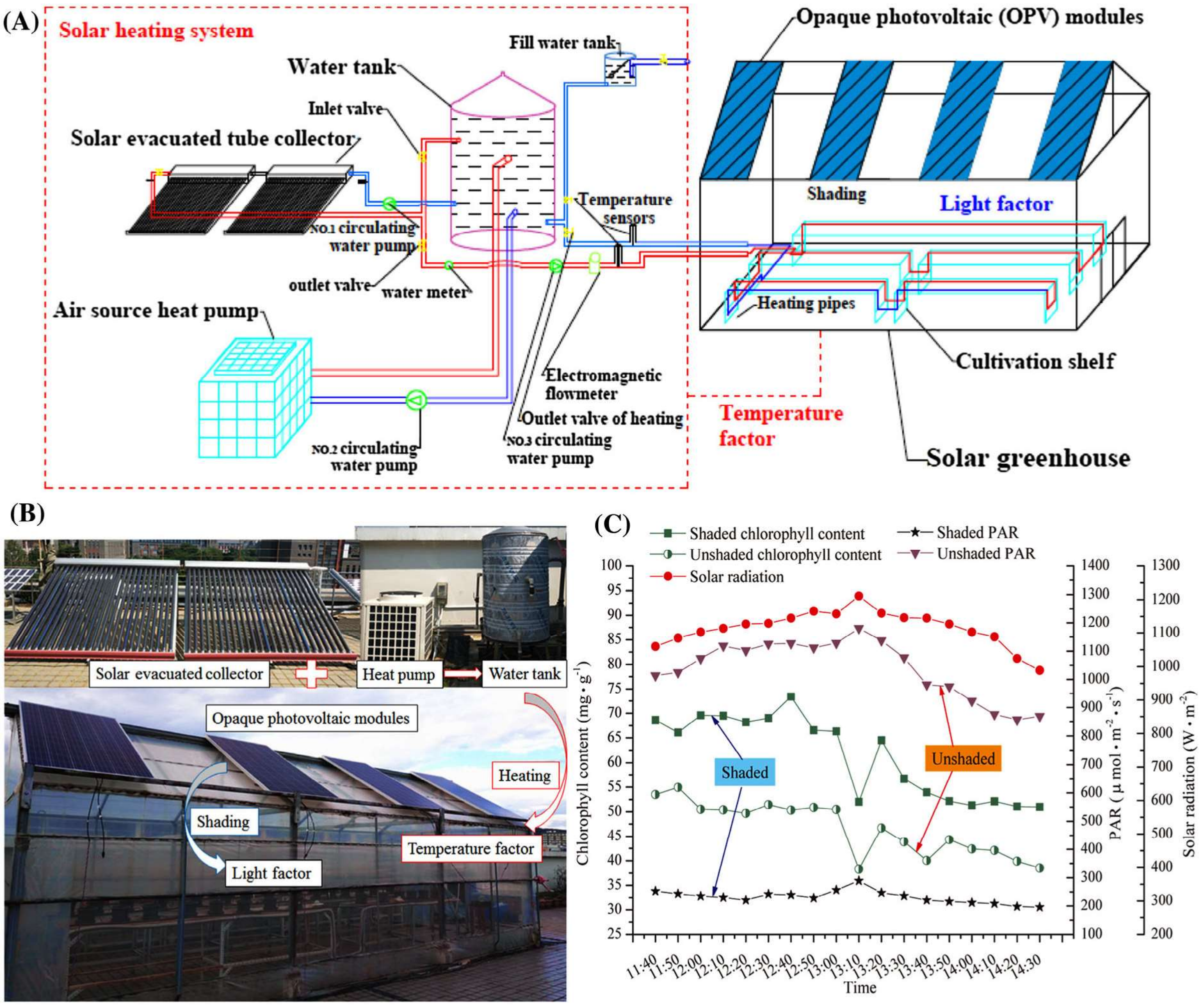

Fig. 9 Energy system and layout of the solar greenhouse: **a** principle diagram, **b** experimental platform and **c** response of the chlorophyll content in strawberry leaves to the light factor in sunny weather. Adapted from Tang et al. (2020)

spacing intervals, high-quality wild rocket yield was produced in the PV greenhouse (Buttaro et al. 2016). Agrivoltaic solar tracking system named Agrovoltaico® was examined in combination with a maize crop in a simulation study conducted by Amaducci et al. The outcomes indicated that in rainfed conditions, the average grain yield was higher and more stable under agrivoltaic than under full light (Amaducci et al. 2018). Recently, in study conducted by Barron-Gafford et al. showed that jalapenos produced a similar amount of fruit in both the agrivoltaics system and the traditional plot, but did so with 65% less transpirational water loss (Barron-Gafford et al. 2019).

Considering an experimental cultivation of cucumber, Ledda et al. found that this crop can cultivated inside PV greenhouse with covering ratio of 25% with yield reduction less than 25% compared to control. Whereas it showed an average yield factor Y_f of 59% (yield reduction higher than 35%) when half roof is covered by PV (Cossu et al. 2020). Quite different results were found out in the case of spinach cultivation, where this crop can be cultivated inside PV greenhouses with cover ratio of 60% with limited yield losses.

The effect of shading during different seasons on several species of crops (Potato, celeriac and winter wheat) was studied and compared by Trommsdorff and his team. It was found that the biomass yields of different crops categories (shaded tolerant and intolerant species) tend to rise with decreasing shading ratio in both studied seasons (winter and summer). In another hand, crop yields of winter cultivars decreased much more at higher coverage ratio as compared to summer periods due to the lower relative PAR during winter. It was also concluded that shading resulted in significant reductions of shaded intolerant crops (wheat) yield at maturity whereas it did not affect the biomass yield of potatoes (shaded tolerant crops) (Trommsdorff et al. 2021). In measurments with potatoes cultivation under PV, it has been proved that potatoes have the ability to adapt to shaded conditions and can compensate the reduction of PAR radiation by a higher light harvesting capability (Willockx et al. 2020).

4 Impact of APV on irrigation (water use efficiency)

Microclimate measurements under dry climate at crop level below PV panels suggest that APV systems could contribute to save water (Marrou et al. 2013c). The reduction in direct sunlight exposure beneath the PV panels led to cooler air temperature during the day and warmer temperatures at night, which allowed the plant under the solar arrays to retain more moisture than the control crops that grew in open field planting area. Studies conducted in dryland environment declared that water use efficiency (WUE) for the jalapeno was 157% greater in the APV system while for tomato, WUE was 65% greater. In terms of irrigation, it was found that soil moisture remained approximately 15% greater in APV system when irrigation was every 2 days. By contrast, when irrigating daily, soil moisture remained 5% greater before the next watering (Fig. 10) (Barron-Gafford et al. 2019). For lettuce, it was found that WUE was increased by 12% in half densities (30% shading). However, for cucumbers, WUE was reduced, in the shade it was 49% of that in the full sun in full densities (50% shading) and 86% in half densities because cucumbers are more sensitive to shade (Marrou et al. 2013c). A simulation study carried out by Elamri et al. showed that the mean overall effects of the tested artificial shading conditions for lettuce cultivation were a reduction of plant water demands by – 20% (Elamri et al. 2018). It is worth mentioning that the above crops were cultivated under an agrivoltaic system with PV module 4 m above the ground.

5 Economic feasibility of APV

The economic achievement of APVs would depend on how much energy could be generated in APV along with production of good crops quality while having low operational costs (Premier 2021). One study mentioned that the generated energy from the cultivation of tomatoes under PV greenhouse is higher than the consumed energy by the greenhouse (768 kwh crop/cycle) (Ureña-Sánchez et al. 2012). In another experimental research, it was found that the APV system could covers from 20 to 38% of the yearly total lettuce PV greenhouse energy demand (Hassanien and Ming 2017; Trypanagnostopoulos et al. 2017). In study conducted by Trommsdorff et al. indicated that the total amount of electricity produced from APV system was 246 MWh where the 41% of the generated electricity was consumed locally by the farming community (Trommsdorff et al. 2021). It is worth mentioning that the electricity generation quantity in APV depends on the density of the PV panels (see Table 1). The APV system could make a profit by selling those generated energy to an energy company. More recently, Schindele et al. mentioned that, at €0.0828 kWh^{-1}, the Levelized Cost of Electricity (LCOE) of APV is 38% higher than that of conventional PV solar farms, resulting in €0.0226 kWh^{-1-} extra LCOE. Moreover, it stated that the operating expenses of APV are lower than ground-mounted PV farms because of synergetic effects and benefits from co-location (Schindele et al. 2020).

6 Concluding remarks and perspective

Energy and food demand is increased dramatically due to the population expansion. This issue led researchers to move towards a more rational use of energy and the development of renewable energies. Agrivoltaics is an emerging approach to allow the co-location of power generation from photovoltaic (PV) technologies and crops production.

This mini review has reported experimental studies about the effect of PV shading on horticulture crop cultivation and a correlation between the growth

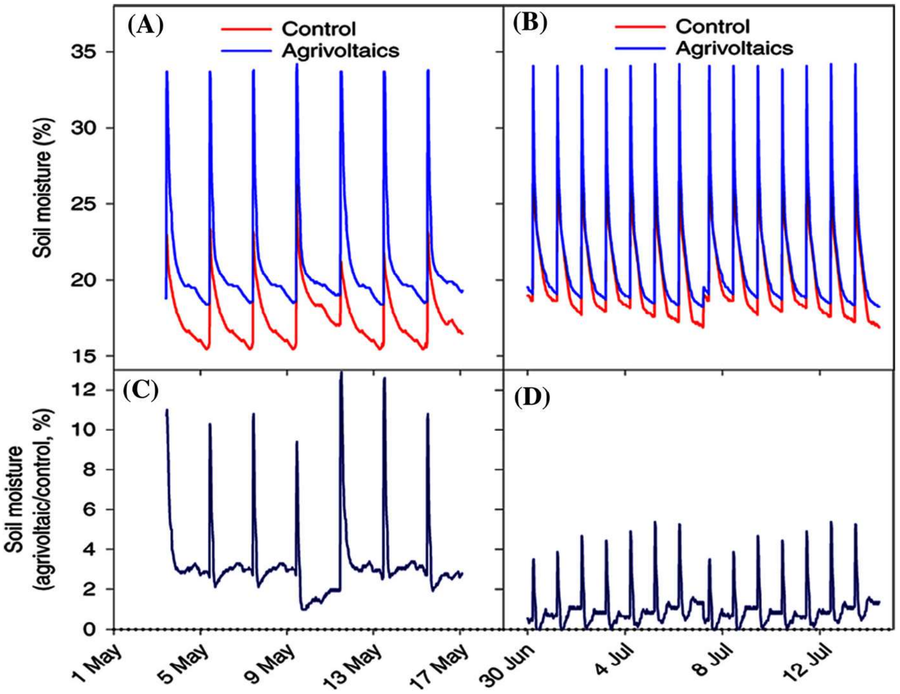

Fig. 10 Impacts of colocation of agriculture and solar PV panels (agrivoltaic) over traditional (control) installations on irrigation resources, as indicated by soil moisture. **a**, **b**, Thirty-minute average volumetric water content (soil moisture) in the top 5 cm of the soil in the agrivoltaic and control settings. **c**, **d**, Differences between soil moisture in an agrivoltaic setting and in control plots, where positive values indicate additional moisture in the agrivoltaic setting. **a**, **c**, A period when plots were watered every two days. **b**, **d**, A period when plots were watered every day. Adapted from Barron-Gafford et al. (2019)

parameters and the characteristics of PV installation, in terms of degree of roof coverage has been found. Majority of the experimental results on the APV system showed that the shading resulted from this system is a good solution to avoid excessive temperatures and reduce the amount of incident light to the crops. All studies showed that the reduction in solar radiation is the main changed factor underneath the APV canopy where a reduction of more than 40% the solar radiation due to the presence of the PV panels was observed. The air temperature found to be higher in the unshaded installation compared to the shaded plot when high coverage ratio (more than 20% of shade) was applied.

It is noted that majority of researches that studied the crop growth in both agrivoltaic system (PV greenhouse or ground) with cover ratio equal or lower than 25% did not report significant effects on plant growth and quality (average yield reduction less than 25%). Whereas, all studies reported inhibitory effects on crops growth with coverage ratio of 50–100% except for strawberry and spinach where they showed a better performance with cover ratio of 50% and 60%, respectively. Hence, APV systems can avoid impacting crop growth in systems with reduced shading, and can simultaneously improve water use, a benefit that the authors did note is worth further research. Therefore, the potential reduction in water use within agrivoltaics (ground or greenhouse mounted PV) could be substantial and warrants further research in future studies.

Despite solar tracking PV system showing good results in terms of energy production without competing with food production. However, high cost hindered their application.

In hot climate, empirical results confirmed that greenhouses can take advantage from the use of PV panels with moderate covering ratios with the aim to convert the excess of sunlight into electricity.

The highlighted researches focus more on tomato and lettuce cultivation, whereas other horticulture crops that may have improved yields when grown under agrivoltaic systems (such as potato which is highly consumed globally) have rarely studied.

Consequently, the future research needs to concentrate more on this crop to add to the existing research which has indicated that it is compatible with cultivation under PV.

In the literature, there are only few APV experimentations were studied in arid climates. Consequently, it is better to add more experiments on the effects of APV for other climates, especially in arid climates.

In terms of economic, the relationship between costs and benefits of APV systems should be analyzed and quantified in the future researches. In addition, life cycle assessment of the APV system is considered as hot-topic that needs to be comprehensively investigated and evaluated.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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