Renewable and Sustainable Energy Reviews 200 (2024) 114515

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A multidisciplinary view on agrivoltaics: Future of energy and agriculture

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ARTICLE INFO

Keywords:
Agrivoltaics
Photovoltaic modules
Modelling
Land use efficiency
Crop shading
Crop yield
Microclimate

ABSTRACT

The increasing global population amplifies the demand for food and energy. Meeting these demands should be a priority and aligned with the Sustainable Development Goals (SDGs). Photovoltaic (PV) systems are one of the key technologies for a sustainable energy transition. However, PV farms are space-intensive, conflicting with other land-uses such as agriculture. Agrivoltaics (AV) offers a dual-land-use solution by combining solar energy and crop cultivation. Some pioneering AV production systems have been implemented in practice. However, optimizing the PV technology and -array design as well as understanding the impact of PV panels on crop selection and performance remains challenging. Determining the best PV technology and minimizing shading's negative effects on crops can make or break an AV system. This multidisciplinary review combines the latest findings in AV research, PV array designs and module technologies. This review also compares the agronomic potential of various crops for AV and presents a meta-analysis of crop performance under varying shading conditions. Findings from this review indicate that (1) AV systems mainly rely on crystalline silicon (c-Si) cell technology, however, wavelength selective, or spectral shifting PV technologies and diffusion coatings or H_2 panels provide future opportunities. (2) AV systems can boost land use efficiency. (3) Shading of crops in AV systems can lead to crop losses but can also provide shelter and enhance crop yield or quality in select climates. (4) Site-specific AV system design is essential to guarantee profitable operation.

1. Introduction

It has been estimated that the world population will increase to 9.8 billion by 2050 [1]. The food and agriculture organization (FAO) of the United Nations has estimated that global food production needs to increase by 70% to feed the world population in 2050 [2]. Population growth and human activities are the main drivers of climate change. Climate change affects the planet's temperature as global average temperatures are 0.95–1.2 °C higher now than at the end of the 19th century [3]. Furthermore, extreme, and unpredictable weather events contribute to global disasters [4]. The changing climate puts the agricultural sector under pressure, threatening the global food and water supply [4]. To overcome these changes, renewable energies are part of the solution. However, this should not come to the detriment of food security.

Solar energy systems are a suitable option to replace fossil fuels [5,6]. The costs of Photovoltaic (PV) panel systems have continuously decreased, leading to a rapid rise in the globally installed capacity since 2000, reaching 773.2 GW in 2020 [7]. At the end of 2021, renewable energy sources had a cumulative installed capacity of 3064 GW, with solar increasing to 849 GW [8]. The current cumulative installed global PV capacity has exceeded 1 TWp [9,10]. However, the installation of PV, especially at a commercial scale, requires huge areas of land [11]. This leads to competition for land use between agriculture and renewable

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https://doi.org/10.1016/j.rser.2024.114515
Received 7 August 2023; Received in revised form 16 April 2024; Accepted 1 May 2024
Available online 17 May 2024
1364-0321/

Nomenclature

APSIM	Agricultural Production Systems sIMulator
a-Si	Amorphous silicon
AV	Agrivoltaics
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
CO_2	Carbon dioxide
CPV	Concentrating photovoltaic
c-Si	Crystalline silicon
DSSCs	Dye-sensitized solar cells
E-W	East-west
g/m^2	Grams per meter squared
GHI	Global horizontal irradiance
GWp	Gigawatt peak
H_2	Hydrogen
ha	Hectare
kWp	Kilowatt peak
LER	Land equivalent ratio
LSC	Luminescent solar concentrator
MJ/ha	Megajoule per hectare
MWp	Megawatt peak
N–S	North-south
OPV	Organic photovoltaic
P	P-value of model fit
PAR	Photosynthetically active radiation
PSCs	Perovskite solar cells
PV	Photovoltaic
R^2	Coefficient of determination of model fit
RT	Ray tracing
SDGs	Sustainable Development Goals
TWp	Terawatt peak

energy, especially in regions with limited arable land. The installation of smaller PV systems in or on buildings and along roads preserves agricultural land. However, expansion in these applications alone would not suffice to drive forward the green energy transition. Therefore, new systems which enable dual land use are providing a solution to combine renewable energy and food production.

Agrivoltaics (AV) aims to achieve an optimized dual land use for solar energy and crops. The concept of agrivoltaics was introduced in 1981 by Goetzberger and Zastrow [12] who showed that beneath PV modules that are spaced, there can be sufficient sunlight to grow certain crops. Furthermore, crops in between PV module rows can utilize uncaptured solar irradiation. There exist several AV systems with various module layouts and associated crops [11,13–15]. The cultivation of crops under PV modules provides several economic benefits [16] such as increased revenue and higher land-use productivity [17,18]. For example, the AV test site in Heggelbach (Germany) by the Fraunhofer Institute for Solar Energy Systems ISE reported a land-use efficiency of 160% in 2017 and 186% in 2018, compared to separate crop and ground-mounted PV systems [11]. In arid and semi-arid regions, many crops underperform due to intense solar irradiation, heat, and drought. Therefore, AV has the potential to shade crops, which would mitigate these stressors, increasing crop yields [19–21]. Also, crops that are vulnerable to sunburn (UV-damage), hail, snow, wind, or rain could be cultivated underneath the protection of an AV system [11]. Water productivity can sometimes increase underneath AV systems [13,19,20] as the panels can reduce evapotranspiration by 14–29% and save up to 20% on irrigation water [22]. AV farms also generate electricity which could supplement farmers' income [16]. Improved PV module efficiency due to better convective cooling can be realized in AV systems [11], while up to 10 °C reduction in PV module temperature has been reported [23]. This proves vital as PV panels decrease in efficiency by up to 0.6%/°C above standard test conditions [24,25].

The implementation of AV systems is expected to affect crop yield due to changes in microclimatic conditions. For an AV research plant in Germany, in which the microclimate was studied, a 30% reduction in photosynthetically active radiation (PAR) under the PV panels was reported. Under this AV setup, reduced soil moisture and air temperature and altered rainwater distribution were also reported [26]. Mean daily soil temperature was on average lower by 1.2–1.4 °C while the air humidity was on average higher. The lower air and soil temperature reduced heat stress for the plants resulting in higher yields compared to the open system. The microclimate under an AV system is also significantly affected by the cultivated crop [26]. Lower mean daily irradiance and soil temperatures were recorded for wheat and lettuces grown in an AV setup [20]. However, the air temperature and humidity below the PV panels were like full sun conditions. On days with high irradiation or low wind speed, the air temperature in the AV setup was lower than in full sun [27].

While AV can help in protecting crops, reduced light might also negatively impact yields [28]. For example, Fraunhofer ISE reported losses in winter wheat, potatoes, celery, and grass/clover yield under AV for certain years [11]. A reduction in rice yield [28], lettuce [14] and tomatoes was similarly reported [29]. Despite these constraints, the potential of AV is high when implemented in an appropriate way, as converting less than 1% of the global croplands to AV, could offset the global energy demand [30].

This study provides a multidisciplinary review on the suitable PV technologies, as well as crop physiology and performance for AV systems. First, this research provides an extensive inventory of existing experimental and commercial AV sites based on different PV system designs and farming practices, and reports findings on system yields. Second, this review analyzes the suitability of different solar cell technologies. Emphasis is put on emerging PV cell technologies and what changes to the AV landscape they could facilitate once they become more cost-effective. This review then reflects on the state of the art of energy and crop modelling approaches and offers a unique overview of tools for AV simulation. The strengths and limitations of the different tools regarding proper AV design are defined. Furthermore, this study showcases a large meta-analysis of existing literature on crop performance under shading conditions, and provides agronomic insights related to crop selection for AV systems. Finally, this review concludes with the worldwide impact of AV and current research gaps, major challenges, and future opportunities of AV.

2. Agrivoltaics: technology, system composition and current implementations

2.1. Increased land use potential of agrivoltaic systems

Fig. 1 illustrates the main principle of AV land use. AV systems can theoretically achieve an increase in land use efficiency over separate production systems. Lower PV density and additional shade levels generally lead to a decrease of relative yields in energy and biomass respectively. However, if crop yield due to shading, minus farmland losses due to the AV constructions, and PV yield does not drop below 50% on average, the total AV system yield will outperform separate crop and ground-mounted PV systems.

One key performance indicator used to compare AV systems is the land equivalent ratio (LER). The LER determines the efficacy of dual land use for crop and energy production in an AV system, compared to separate crop production and PV energy generations [31]. Mathematically, the LER is defined as:

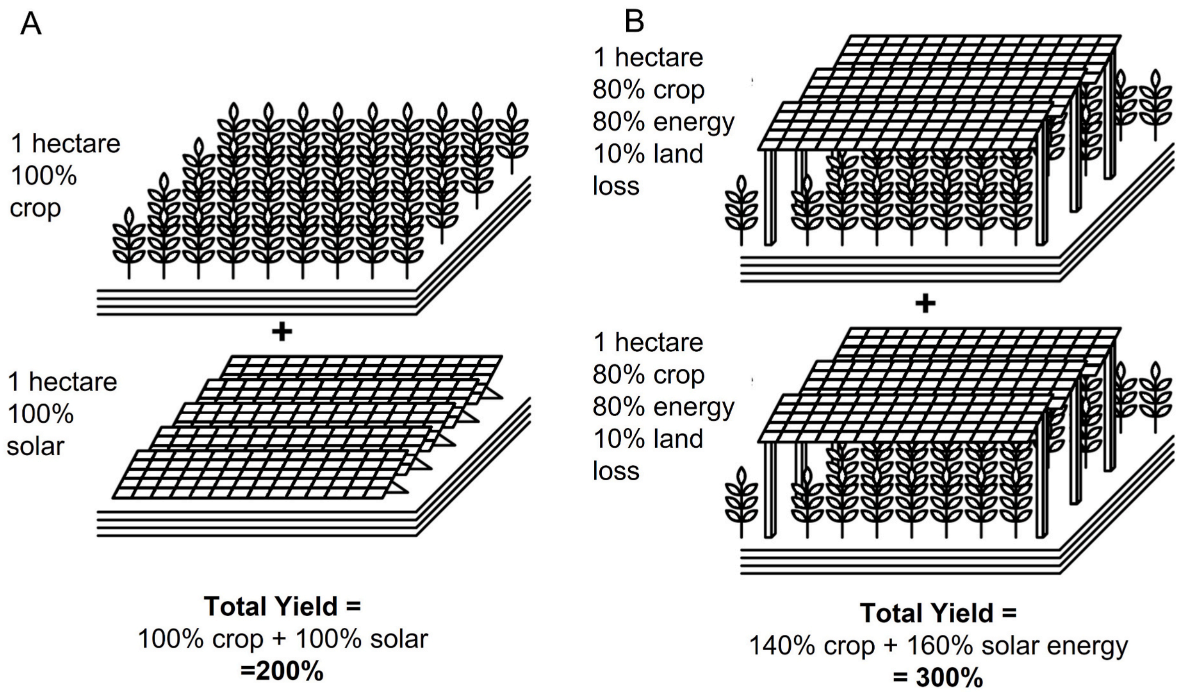

Fig. 1. Theoretical example of a separate system of farming and ground-mounted PV (A) and the combined use of land for crop and PV energy production by means of agrivoltaics (B). AV can increase the land use efficiency by 50% in this example, compared to two separate production systems alone. Values shown reflect hypothetical yield values.

$$LER = \frac{Y_{cr,AV}}{Y_{cr,ref}} * (1 - \mathrm{LL}) + \frac{Y_{e,AV}}{Y_{e,ref}} \quad (1)$$

where $Y_{cr,AV}$ is the crop yield under AV, and $Y_{cr,ref}$ is the crop yield in an open reference field (full sun). LL figures in the land loss due to the AV system. $Y_{e,AV}$ is the energy yield for an AV system, and $Y_{e,ref}$ is the energy yield for a conventional ground-mounted PV system. Energy and crop yields are expressed per unit area. Most AV systems have reported an increased LER. For example, an average LER of 1.64 for various vegetables was reported [13]. Another report stated that AV systems could increase global land productivity by 35–73% [31]. An optimization model for vertical bifacial AV modules reported a LER above 1.2 [32]. Blueberries under east-west (E-W) modules achieved an improved productivity of 50% [33]. LERs of 1, 1.25 and 1.5 for two lettuce varieties under static, controlled tracking and solar tracking respectively were also achieved [17]. Another study showed a LER of 1.21 for lettuce [34]. To summarize, while not all-encompassing, the LER can serve as a good indicator for an AV system's practical potential.

2.2. Variations in agrivoltaics system layout allow fine-tuned designs

In recent years, AV systems have been classified based on the type of system (open or closed), type of support structures (overhead, interspace, and PV greenhouses), module mobility (one-axis tracking, two-

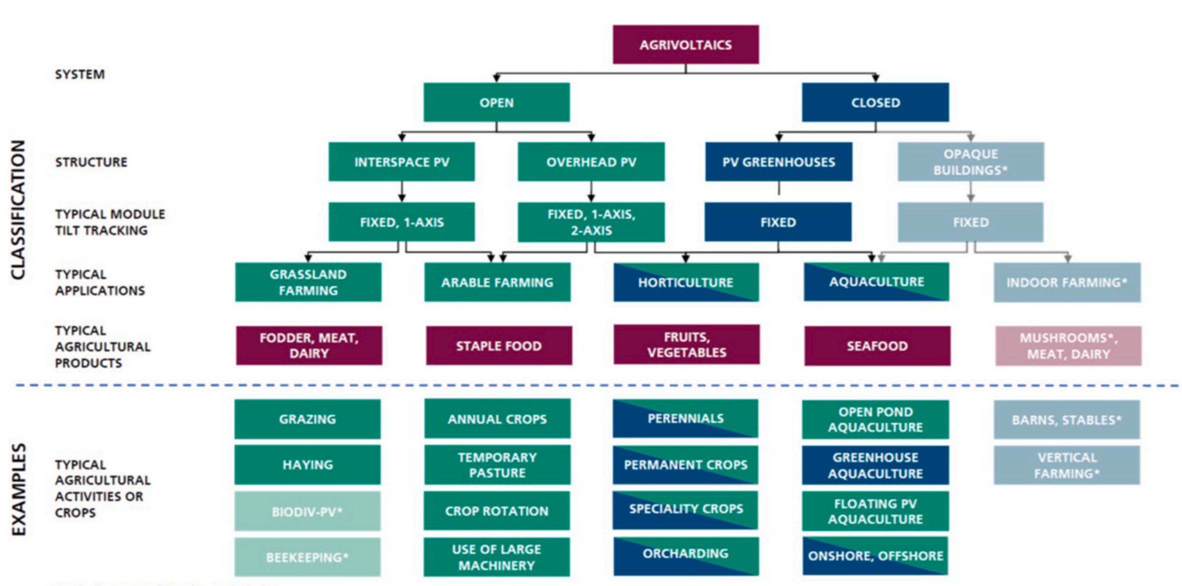

Fig. 2. Broad classification of agrivoltaic systems with suitable examples of the farming systems employed [35].

axis tracking, and fixed), and the type of farming application (arable, grassland, horticulture, and aquaculture) [35]. Fig. 2 shows these main classification of AV systems [35]. While no exclusive relation between PV and crop configuration exists, closed systems have a greater influence on the crop microclimate than open systems. Closed AV either receives protection from foil or glass cover or has specific climate control systems. Open AV systems do not rely on these additional measures or inputs and may show more variable microclimatic conditions as a result.

2.2.1. PV array designs for AV systems

Different AV module orientations have been proposed [11]. Vertical agrivoltaic systems are principally E-W facing while open overhead systems could have any orientation. In vertical AV systems, the PV modules are usually installed close to the ground, and the power curve has two peaks: one in the morning and one in the evening. Next2Sun GmbH has implemented several E-W vertical bifacial AV systems, mainly used for fodder cultivation [11,36]. In Ireland, 'solar energy fences' have been developed for cow grazing [36,37]. In Sweden, Ref. [32] investigated potatoes and oats in a vertical bifacial AV system and reported 50% reduction in crop yields as the row distance decreased from 20 m to 5 m. When the panel density was half or lower than that of ground-mounted PV systems, E-W vertical bifacial modules and north-south (N–S) tilted monofacial farms showed a similar energy yield and PAR at crop level [21]. In Boston (USA), Ref. [33] carried out simulations to find the optimum array topology for fixed medium to large-scale bifacial module arrays by using E-W vertical, E-W wings, and N–S facing PV systems and reported a specific yield increase of 13%, 18% and 39% respectively. They suggested that E-W vertical systems amplified the light penetration during winter months and are therefore more suitable for permanent crops. E-W vertical bifacial AV systems could offer much better daytime irradiance distribution compared to fixed-tilt south facing AV systems [38]. However, commercially deployed arable farming in vertical AV systems is, for the moment, rare.

In open overhead systems, the land underneath the PV modules is used for crop growth. A review of existing systems reports that the PV modules are installed at between 4 m and 7 m above the ground [39]. Typical design considerations for open overhead systems include the row-row distances, the clearance height, PV array design and the use of tracking systems. N–S facing AV systems prioritize energy generation while E-W wing AV system provided a more homogeneous light distribution at crop level [33]. Concerns on the spatial heterogeneity of sunlight distribution at crop level under fixed tilted N–S monofacial PV array in AV have been expressed [40]. While comparing this spatial heterogeneity with the light distribution under vertical bifacial E-W PV arrays, they found similar relative yields for both energy and crops, provided the panel density was reduced by 50%. Spatial distribution of sunlight at crop level under bifacial vertical E-W systems was more homogeneous compared to monofacial N–S fix tilt counterparts [40]. It was also reported that E-W vertical bifacial solar farms showed the least seasonal crop yield variations compared to N–S solar farms [39].

Vertical bifacial PV systems offer specific advantages such as higher resilience to soiling, Ref. [40] reduced land loss, and lower construction costs [41,42]. They also have less visual impact on the landscape and mitigate wind at crop level [11]. Overhead systems offer greater protection of crops from adverse solar radiation, precipitation, and temperatures. However, the amount of land required by overhead AV systems for the same energy production is about 20–40% more than that for a ground-mounted PV system [11]. Even when co-located with agricultural production systems, the energy density of agrivoltaics is significant. While the energy density of utility scale PV in the USA is on average 0.87 MWp/ha [43], agrivoltaic systems can easily reach 0.6 MWp/ha [44] (except for grassland and meadows which have lower coverage). Onshore wind typically reaches 0.2 MWp/ha, Ref. [45] indicating that on the same land area, agrivoltaics can produce 50% more renewable energy than wind energy, considering the different capacity factor.

2.2.2. Tracking PV creates opportunities in AV systems

Tracking PV systems can help optimize energy yield while ensuring sufficient crop growth by improving light availability at crop level. The LER for an olive grove AV system with N–S horizontal trackers increased between 28.9% and 47.2% [46]. Increased LER in tracked AV systems has also been reported [47] (potato cultivation) and [17] (lettuce). Experiments also suggested that dynamic AV systems could mitigate climate change related seasonal yield variability and could increase spatial uniformity of crop production while reducing crop water demands [34]. A simulated fixed, one-, and two-axis tracking AV systems in Lanna (Sweden) reported highest light homogeneity and lowest PAR reduction for the two-axis tracker [48]. However, PV systems with trackers are usually more expensive to build and design, and the development of tracking algorithms that combine energy and crop needs can be challenging.

2.3. Global AV state and realizations

Global AV capacity exceeded 14 GWp in 2021 [49]. A compound annual growth rate of 38% is forecast between 2022 and 2027 for the global AV market [50]. The Asia-Pacific region dominates, owing to the high PV module production capacity and PV favorable policies. The Baofeng Group has built a 1 GW agrivoltaic solar park in the Ningxia Province (China), for goji berry production [51]. REM Tec has also developed 'Agrovoltaico" plants in Piacenza (Italy) with flax and maize [52]. In France, AV plants have been installed over vineyards to protect grapes from intense heatwaves [53]. In the Netherlands, BayWa r.e. has developed 1.2 MWp redcurrant [54] and 2.67 MWp raspberry AV farms [55]. In Germany, some MW projects have been developed by Next2Sun GmbH, including the 4.1 MWp solar park in Donaueschingen-Aasen for hay and silage [36] and the 2 MWp solar park in Eppelborn-Dirmingen for hay [11]. Fig. 3 shows a range of different AV systems including tracking (Fig. 3A, B, D), fixed tilt (Fig. 3C, E, F), vertical interspace (Fig. 3E) and overhead (all but Fig. 3E) systems. Note how different farming systems are compatible with multiple configurations. Nevertheless, a trend towards specific PV design and crop integrations is apparent. Findings from various AV commercial, research pilot and test sites across the world are summarized in Table 1.

Table 1 shows an overview of some existing commercial, pilot and research AV systems across the world. The technical specifications and crop types including animal farming are also indicated in these findings. Results on crop and animal growth and yields and the microclimatic conditions in these systems are reported where available.

2.4. Suitability of emerging solar cell technologies for agrivoltaics

The selection of PV module technology and topology for AV differs subtly from traditional ground-mounted PV. Fig. 4A shows the exponential developments in the global installed PV capacity. PV modules are characterized based on their solar cell technology including wafer-based c-Si or thin films such as amorphous silicon, Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). Wafer-based c-Si still accounted for nearly 95% of the total production in 2022 [11] and leads the share of PV technologies (Fig. 4B). The market share of bifacial PV modules increases steadily (Fig. 4C). Finally, Fig. 4D represents the evolution of PV system end-use. Whereas rooftop PV remains relatively steady, it is noteworthy how 'power plant' PV is decreasing in favor of dual-use systems.

While in principle all PV module technologies are applicable in AV systems, semitransparent PV offer advantages to the crops. Thin-film semi-transparent modules such as CIGS, CdTe, a-Si, and micro a-Si have a low mass per unit area (about 500 g/m^2) [11], good aesthetics, homogeneous transparency, and a better temperature coefficient compared to wafer-based c-Si [35]. However, thin film technologies have rarely been used in open AV systems, due to their relatively higher cost and lower performance [35]. Tinted semitransparent a-Si PV panels

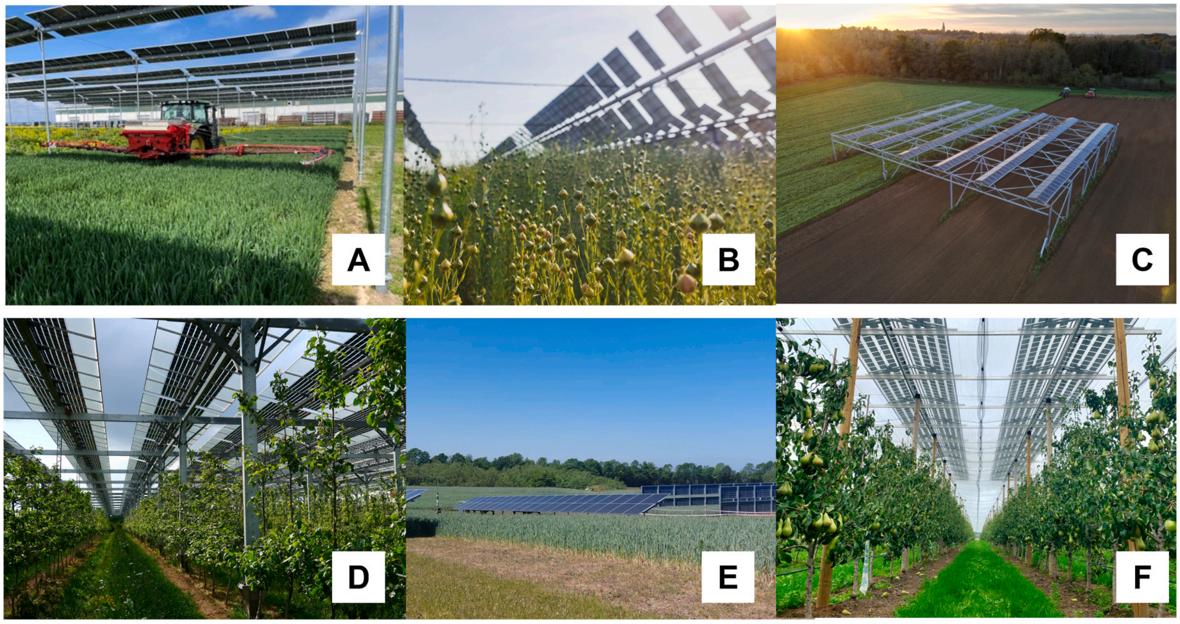

Fig. 3. (A) Single axis tracking PV panels above wheat, Krinner Solar pilot site, summer 2023, Straβkirchen, Germany. (B) Two axis tracking agrivoltaic plant (Agrivoltaico) above Flax, summer 2022, Piacenza, Italy. (C) An elevated arable agrivoltaic pilot above yellow mustard, fall 2022 in Lovenjoel, Belgium. (D) 258 kWp agrivoltaic apple orchard above 8 cultivars, static and single axis tracking in Geldsdorf, Rhineland-Palatinate, Germany [56]. (E) Interspaced and vertical bifacial module pilot site with winter wheat, summer 2023, Foulum, Denmark. and (F) A small scale elevated E-W 13.32 kWp agrivoltaic pear orchard in Bierbeek, Belgium, summer 2021 [57].

were tested for the growth of basil and spinach [91]. The marketable biomass yield for basil was not affected while that of spinach was lower. Sun-loving plants grown in a semitransparent a-Si greenhouse exhibited lower biomass production and increased elongation [92].

Organic PV (OPV) modules offer wavelength selective transparency [93]. However, OPV modules typically face scalability challenges and have a low resilience to factors such as heat, water, oxygen, high irradiation, and mechanical stress [94]. OPV modules installed inside a polytunnel greenhouse however had longer lifespans compared to those installed outside [95]. This was due to dust and harsh weather on the OPV modules. An OPV tomato greenhouse tunnel with 37% roof cover ratio showed higher leaf area index, cumulative yield and average fruit mass compared to a control tunnel [72]. Simulation results for tomato in an OPV greenhouse resulted in a 46% increase in tomato dry mass compared to a c-Si greenhouse [96].

Dye-sensitized solar cells (DSSCs) are defined by their dye color. Like OPV, DSSCs also offer wavelength selective transparency, flexibility, and light weight [35]. Enhanced DSSCs with transmittance in red (625–675 nm) and blue (425–475 nm) have been developed [97]. A DSSC module with transparency in the wavelength range 600–900 nm was implemented in Greece [98]. Compared to a conventional greenhouse, the tomatoes in the DSSC greenhouse had better growth and less pest pressure. DSSC greenhouses could enhance the thermal stability of the greenhouse, partially blocking IR radiation while increasing biomass yields compared to conventional greenhouse glazing and opaque PV greenhouses [99]. Additionally, the performance of DSSCs is independent of the light incidence angle [35]. However, like OPVs, DSSCs are limited by their stability and efficiency.

Perovskite solar cells (PSCs) also can be tuned to provide semi-transparency or absorption of different wavelengths. The latter feature makes PSCs and OPV suitable in tandem with c-Si solar cells, to utilize the solar spectrum more efficiently. PSCs have shown great improvements in efficiency in recent years. Despite efficiencies >25% [100,101], they are limited by their long-term reliability, their scalability and there are concerns about the toxicity of lead (Pb) used in their fabrication. However, Ref. [102] showed that a transparent titanium dioxide (TiO_2) sponge can be used to prevent lead leakage in PSCs.

Luminescent solar concentrators (LSCs) also have potential in AV systems. Most LSCs consist either of a polymer blended into a luminescent material [103] or thin films doped with a fluorescent compound which absorbs a given spectrum of light and re-emits photons of a different spectrum which are propagated by total internal reflection and captured by solar cells at the edge of the film [104]. Greenhouses have been equipped with LSCs [105] and showed extremely limited degradation [106]. Also, positive crop growth [107] and increased solar conversion efficiency was demonstrated (3.8% compared to the reference at 2.9%) [106]. However, organic dye LSCs suffer from photo-stability issues and reabsorption losses [105]. LSCs based on rare-earth complexes demonstrate excellent optical properties, photo-stability and high absorption coefficient [105]. They can utilize radiation in the non-photosynthetic range for energy generation while radiation in the photosynthesis spectrum can be transmitted to the crops. Nevertheless, the optical properties of the luminescent dyes or complexes must be further investigated and adapted to the crop needs.

Concentrating PV uses optics to focus light on solar cells. The concentration of light reduces the PV area needed, therefore enabling the use of highly efficient III-V multi-junction solar cells [35]. Semi-transparent concentrating PV systems can allow diffuse light to pass through, while those with curved mirrors can use dichroic materials to reach wavelength-selective transparency [108]. A parabolic concentrator with dichroic film which transmits red and blue light and reflects the rest to c-Si solar cells was implemented in an AV test setup [109,110]. Lettuce, cucumber, and water spinach showed a better growth rate and higher soluble sugar content under this concentrating PV setup compared to full sun. Despite this promise, concentrating AV systems require tracking, adding to their cost.

An alternative solar energy technology that can potentially pair well with AV is the production of solar hydrogen (H_2). This provides a cost-effective catalytic method for converting solar energy and ambient water vapor (prominent above transpiring crops) into H_2 fuel [5,6]. Efficiency values of 15.1% for solar to H_2 conversion have been reported [5,6]. These H_2 panels open the doorway to efficient, low cost, autonomous and safe solar H_2 generation. This technology offers an alternative for electricity storage or density problems by providing fuel for e.g.,

Table 1
Selection of AV realizations, their characteristics, and summary of their performances.

Location	Crop type	PV description	AV plant description	Summary of findings	Source type	Ref
Australia, Victoria	*Blush pear*	*Monofacial c-Si modules*	*52 kWp AV system with 4.5 m row spacing.*	- Larger fruit in control compared to AV system. - Fruit weight, number and yield higher in control field.	Website	[58, 59]
Austria, Guntramsdorf	*Field crops (Potatoes)*	*380 Wp n-PERT (passivated emitter and rear totally diffused) c-Si bifacial modules*	*22.5 kWp installed capacity with E-W vertical glass-glass bifacial PV modules.*	*N/A*	Website	[36]
Belgium, Bierbeek	*Pear*	*72 PV of 185 Wp c-SI panels with glass-backsheet and 21% efficiency*	*13.3 kWp capacity double inclined (E-W) AV system. 40% module transparency with 4.6 m clearance.*	- *Decrease in total pear yield by 16.4% under* AV system. Mainly due to the reduction in fruit size and numbers. - Pear quality (firmness, color, brix, and ethylene production) was similar for both AV and open field systems. - LER of 1*.236 in 2021.*	Peer reviewed journal paper	[60]
Belgium, Grembergen	*Beetroot*	*72 bifacial half-cut c-Si passivated emitter and rear cell (PERC) cells with 0.7 bifaciality factor*	*AV setup consisting of: 450 kWp/ha of three fixed rows each consisting of 12 double stacked vertical PV modules (0.6 m elevation) and a second single axis tracking AV system (2.3 m elevation) with similar module layout and capacity as the vertical one.*	- *In 2021 (rain fed season) compared to* open field, root biomass of sugar beet was 26% lower in vertical set up and 22% lower in tracking set up. - Lower biomass reduction of 17% in vertical system and 12% in tracking system compare*d to open field.* - *In 2022 (dry year), root biomass was equal in both vertical system and open field but was lower by 10% in solar tracking.*	Peer reviewed journal paper	[61]
Belgium, Lovenjoel	*Wheat*	*Bifacial 340 Wp PV modules with 0.7 bifaciality factor*	*81.6 KWp AV system with six rows (40 modules per row) of double inclined PV modules with ground cover ratio of 30%, 5 m clearance height and 12° tilt angle*	- *A 34% reduction in wheat yield in AV system compared to open field. Mainly due to reduction in number of grains (not individual weight of grains).*	Peer reviewed journal paper	[62]
Chile, Curacavi	*Cauliflower*	*48 polycrystalline silicon modules*	*12.48 KWp capacity. Fixed mounted and inclined at 27° with 27% cover ratio*	- *Reduction of 19.7% up to 25.2% in the monthly sum of irradiation* compared *to open field.* - *Lower air temperature and higher air humidity in AV setup.*	Peer reviewed conference proceeding	[63]
China, Ningxia Province	*Goji berries*	*c-Si PV modules*	1 *GW overhead AV system installed at 2.9 m above ground.*	- *Improved ecosystem, 30–40% reduction in evaporation, and 85% increase in vegetation coverage.*	Website	[51, 64]
China, Anhui region, Jinzhai	*N/A*	*330 Wp poly-crystalline modules*	*2 axes tracking 544 kWp overhead AV plant, with PV modules 4.5 m above ground and 20% cover ratio.*	*N/A*	Website	[65]
France, Montpellier	*Lettuce (Kiribati and Madelona)*	*Monocrystalline PV modules*	*Stationary full-density and half-density AV systems south-east facing and controlled and solar tracking systems. Mounted 4 m above ground.*	- *Increased leaf area in spring for all AV systems compared to full sun.* - *Restricting tracking at midday resulted in higher biomass in spring.* - *On average, higher dry mass for full sun, followed by controlled tracking, solar tracking, and fixed modules.* - *Highest land productivity (LER of 1.5) with solar tracking compared to stationary PV modules.*	Peer reviewed journal paper	[17]
France, Piolenc	*Grapes (vineyard)*	*280 c-Si PV panels*	*84 KWp generation capacity tracking AV system. 4.5 ha AV vineyard, with a 4.2 m elevation and row-to-row distance of 2.25 m.*	- *Reduction in water demand by 12-34% under PV panels. Improved aromatic profile of grapes with 13% more anthocyanins (red pigments), and 9–14% more acidity.*	Website and peer reviewed journal	[66, 67]
France, Mallemort	*Apples*	*196 c-Si PV panels*	*61 kWp AV tracking system with 4.5 m clearance height, 4 m row distance.*	- *63% less water stress for trees in AV system compared to open fields and lower temperatures by 2–4 °C.*	Website	[68]
Germany, Büren-Steinbach, North Rhine-Westphalia	*Blueberries, raspberries, apples, and grapes.*	*116 bifacial 320 Wp c-Si PV modules*	*740 KWp installed capacity AV system with tracking*	- *High blueberry yields but lower strawberry yields in 2020.*	Website	[11]
Germany, Donaueschingen-Aasen,	*Hay and silage*	*10,960 of 380 Wp n-PERT (passivated emitter rear totally diffused) c-Si bifacial modules*	*4.1 MWp installed capacity of vertical E-W bifacial modules.*	- *Upgraded crop yield plus narrow strips under modules used to cultivate flowers.*	Website	[36]

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Table 1 (*continued*)

Location	Crop type	PV description	AV plant description	Summary of findings	Source type	Ref
Germany, Eppelborn-Dirmingen	*Hay and silage*	*n-PERT (60%) and heterojunction (40%) c-Si bifacial cells*	*2 MWp installed capacity of vertical E-W bifacial modules.*	- *Upgraded pasture yield.*	Website	[36]
Germany, Heggelbach	*Winter wheat, potato, celery, and grass/clover mixture*	*720 bifacial glass-glass PV modules of 270 Wp,*	*194.4 KWp capacity AV system in south-west alignment, with modules at a clearance height of 5 m and 9.5 m row distance.*	- *In 2017, crop yields were above the critical 80%.* - *In 2018, potato yield increased even for the hotter summer thanks to shade under PV modules.* - *LER increased between 1.6-1.8.*	Website	[11]
Greece, Agios Pavlos	*Grapes (vineyard)*	*Nanostructure-coated solar cells (nanomaterials and monocrystalline Si solar cells)*	*40 kWp AV system. Nanomaterials change solar spectrum by converting UV to visible light.*	- *Increased grape harvest owing to double harvest a year (autumn and winter).*	Websites	[69, 70]
India, Jodhpur, ICAR Central Arid Zone Research Institute (CAZRI)	*Aubergine ('Brinjal'), aloe vera, snap melon, cumin, Chickpea, bean varieties, psyllium, and spinach*	*Polycrystalline silicon PV modules of 260 Wp capacity*	*105 KWp AV system, with five AV array designs (two single rows in full and half densities, one double row in full and half densities and two triple rows in full and half densities) for rainfed and irrigated crops. PV modules inclined south with a tilt angle of 26 °. 2.96 m row spacing and 0.5 m ground clearance.*	- *Highest net returns of PV and crop for irrigated brinjal under one row full density PV array, followed by rainfed snap melon.*	Peer reviewed journal article	[71]
Ireland, Waterford	*Pasture/grass (cattle grazing)*	*380 Wp n-PERT c-Si bifacial modules*	*Two AV farms:* *−25 KWp installed capacity and -27 KWp capacity vertical E-W bifacial modules.*	- Minimal *interference with pasture growth and milk produced.*	Websites	[36, 37]
Israel, Kafr Qara	*Tomatoes*	*Organic PV modules*	*OPV (37% roof cover) greenhouse tunnel-oriented N–S also covered with polyethylene sheet.*	- *In 2018, the cumulative number of tomatoes, mass and average mass were higher by 9%, 36% and 21% respectively in OPV tunnel compared to control tunnel (with only polyethylene sheet).* - *In 2019, yields were similar in OPV and control (with polyethylene and an additional 25% black shading screen) tunnels.*	Peer reviewed journal article	[72]
Italy, Castelvetro	*Maize and winter wheat*	*280 Wp poly-crystalline modules*	*2 axes tracking 7 ha, 3.2 MWp AV plant with modules 4.5 m above ground and 13% cover ratio.*	*N/A*	Peer reviewed journal article and website	[52, 73]
Italy, Monticelli d'Ongina	*Maize and winter wheat*	*280 Wp poly-crystalline modules*	*2 axes tracking 20 ha, 1.5 MWp AV plant with modules 4.5 m above ground and 13% cover ratio.*	- *The average rainfed maize yield was higher and more stable under AV than in full sun.*	Peer reviewed journal article and website	[73, 74]
Italy, Sardinia	*N/A*	- 60 multi- c-SI PV modules each of rated power 235 Wp for cover ratios of 100%, 60% and 50%. - 48 mono- c-SI solar cells of 205 Wp rated power for 25% cover ratio.	*E-W PV greenhouses with cover ratios: 100% for mono pitched roof, 60% Venlo-type, 50% gable roof, 25% gable roof and 25% gable roof with checkerboard pattern. Greenhouses in E-W and N–S orientations.*	- *Yearly cumulated global radiation decreased by 0.8% and 0.6% for a 1% increase in cover ratio for E-W and N–S orientations, respectively.* - *Checkerboard pattern and N–S orientation increased uniformity of light distribution.*	Peer reviewed journal article	[75]
Japan, Chiba Prefecture	*Maize*	*72 c-Si PV modules*	*48 PV modules in full density, 24 PV modules in half density, mounted at 30° tilt angles, and a control system (no modules).*	- *The average fresh weight and biomass of maize stover in low PV density was higher than in full density and control systems.*	Peer reviewed journal article	[15]
Japan, Aichi Prefecture	*Citrus trees ('Dekopon')*	*600 opaque c-Si PV modules*	*50 kWp overhead AV system, with PV panels at 5 m elevation.*	- *Expected ¥2.5 million additional income.*	Website	[76]
Japan, Chiba Prefecture	*Peanuts, yams, eggplants, cucumber, tomatoes, and taros*	*348 opaque c-Si PV panels*	*34.4kWp overhead AV system with PV panels at 3 m elevation and PV rows 5 m apart.*	- *¥1.6 million additional income annually compared to only ¥100,000 from just farming.*	Website	[76]
Kenya, Kajiado	*Cabbage, eggplants, lettuce, and maize*	*180 of 345 Wp c-Si solar panels*	*56 kWp systems with opaque PV modules.*	- *Cabbages were a third larger and healthier than in open field.* - *Maize was taller and healthier.* - *Eggplants and lettuce were also better under PV shade.*	Website	[77, 78]
Netherlands, Babberich	*Raspberries*	*10,250 of 250 Wp frameless and semi-transparent c-Si modules*	*2.67 MWp structure with 35% transparency per module.*	- *The panels provided favorable* lower temperatures *and protected the crops from the weather.* - *5% lower yield under AV compared to open field in 2021.*	Website	[55, 79]
Netherlands, Wadenoijen region	*Redcurrant*	*Glass-glass semitransparent monocrystalline modules*	*1.2 MWp AV plant with 4500 plants.*	- *On* hottest *day, temperatures were 10°C lower in AV.*	Website	[54]
South Korea, Jeollanam-do Province	*Salt farm*	*270 Wp c-Si modules*	*6.48 KW capacity aquavoltaic system installed at 0° tilt.*	- *7.8% power gain due to cooling of panels by seawater.*	Peer reviewed journal article	[80]

(*continued on next page*)

Table 1 (*continued*)

Location	Crop type	PV description	AV plant description	Summary of findings	Source type	Ref
				- 9% less power generation from salt (due to tilt angle of 0°) farm compared to ground mounted PV.		
South Korea, Jeollanam-do Province	*Broccoli*	*Bifacial c-Si modules*	*AV system with 30° tilt and 3.3 m elevation.*	- *Greener broccoli under AV (higher consumer preference) and yield, antioxidants and glucosinolates were like open field.*	Peer reviewed journal article	[81]
Sweden, Västerås	*Oats and potatoes*	*60 opaque bifacial c-Si PV modules.*	*22.8 kWp AV system composed of vertical E-W PV modules.*	- *For open field, maximum weight of oats and potatoes was 5 t/ha and 6.6 t/ha, respectively. No results for AV system. However, simulated results showed that crop yields doubled when row distance increased from 5 m to 20 m.*	Peer reviewed journal article	[32]
Switzerland, Luzern	*Raspberries*	*800 PERC bifacial c-Si PV modules*	*160 kWp system based on Insolagrin technology (optic micro-tracking which enables dynamic light adjustment).*	*N/A*	Website	[82]
Tanzania, Morogoro	*Spinach and sweet pepper*	*Opaque c-SI PV modules*	*36 kWp off-grid system with 50% PV density.*	- *Spinach yields were 82.1% higher under AV.* - *Sweet pepper yields were 31.5% lower under AV.*	Peer reviewed conference proceeding	[83, 84]
USA, Arizona	*Chiltepin pepper, jalapeno, and cherry tomato*	*c-SI PV panels*	*South-facing panels at 32° tilt with row distance of one m and 3.3 m elevation.*	- *Chiltepin production was three times higher under AV compared to control (open) system.* - *Jalapeno yield was slightly lower under AV while cherry tomato yield in AV setup was twice that of the open field.* - *Daily water use efficiency was also higher for all plants under the AV system.*	Peer reviewed journal article	[27]
USA, Colorado	*Lettuce, clary sage, raspberry, and grassland*	*3276 monofacial c-Si PV modules*	*1.2 MWp AV system with single axis trackers.*	- *Lower microclimate temperatures.* - *Lower irrigation water needed compared to open field.*	Website	[85, 86]
USA, Oregon State University	*Sheep grazing (pasture)*	*Polycrystalline modules*	*1.4 MW capacity with E-W PV modules and tilted at 18° southwards, elevation of 1.1 m and 6 m between rows.*	- *38% lower herbage under AV compared to open field. Heterogeneity in biomass production under AV due to heterogeneous shading from panels.*	Peer reviewed journal article	[87]

high-power agricultural machinery. When installed in proximity of the H_2 backbone infrastructure [111], agrivoltaic solar H_2 allows large-scale production and transport of renewable energy without adding load to the electrical grid infrastructure.

Despite these emerging PV technologies, c-Si solar cells are favored in large-scale AV systems. A continuous increase in bifacial solar cells is predicted (Fig. 4C). Bifacial modules generate additional energy from the ground or crop-reflected light, which is especially relevant for elevated AV structures. To achieve semi-transparency, the spacing between c-Si cells or module strings can be increased to allow light to pass through. Semitransparent c-Si PV modules installed in a lettuce greenhouse reduced air temperature by 1–3 °C and lettuce yields were like those in unshaded area [112]. c-Si PV modules with 47% transparency installed on a south facing tomato greenhouse showed similar growth to those in unshaded area [113]. Three different pilot lettuce greenhouses with (i) c-SI PV modules of 50% transparency (AV-50), (ii) without PV modules (AV-ref) and (iii) with light diffusion film (AV-film) below the PV modules were tested [114] with lower yields reported in the AV-50 greenhouse. The company Insolight is investigating dynamic light management AV systems with bifacial semitransparent c-Si PV modules [115]. In the Netherlands, BayWa r. e. has installed glass-glass semi-transparent c-SI PV modules in raspberry (35% module transparency) and redcurrant AV farms [54,55]. They reported lower temperatures under the AV setup. An AV pear orchard with c-Si PV modules of 40% transparency was also installed in Bierbeek, Belgium [60]. They reported positive microclimatic conditions and a minimum pear yield loss of 16%.

2.5. Modelling of agrivoltaic systems: options and challenges

2.5.1. PV energy yield modelling

To improve the performance and better predict the yield of AV systems, various parameters such as PV array orientation, solar intensity, tilt angle, seasonality, and ground/crop albedo need to be considered. There exists many established software for simulating solar PV system energy yields [116] such as PVsyst, INSEL, PV*SOL Expert, HOMER, SolarPro, TRNSYS, etc., [117]. Further models were adapted to simulate bifacial modules [118] and SolidWorks Flow Simulation® was used to evaluate the temperature distribution and energy yield of vertical bifacial PV modules for AV applications [119]. The energy produced by a PV system was modelled based on plane of array irradiance, the nominal power, and cell temperature [120]. PV output modelling can be done reliably when accurate environmental datasets are available.

2.5.2. Crop light models for AV are plentiful

A range of models has been implemented to approximate crop yield under AV systems. At its basis lie radiative models using daily global radiation and the site's latitude as inputs [14]. Decomposing PAR into direct and diffuse components is critical for accurately integrating PV-induced shading across the plant canopy [121]. Simulated light distribution under conventional N–S and E-W PV modules and checkerboard PV modules showed that the checkerboard layout created a

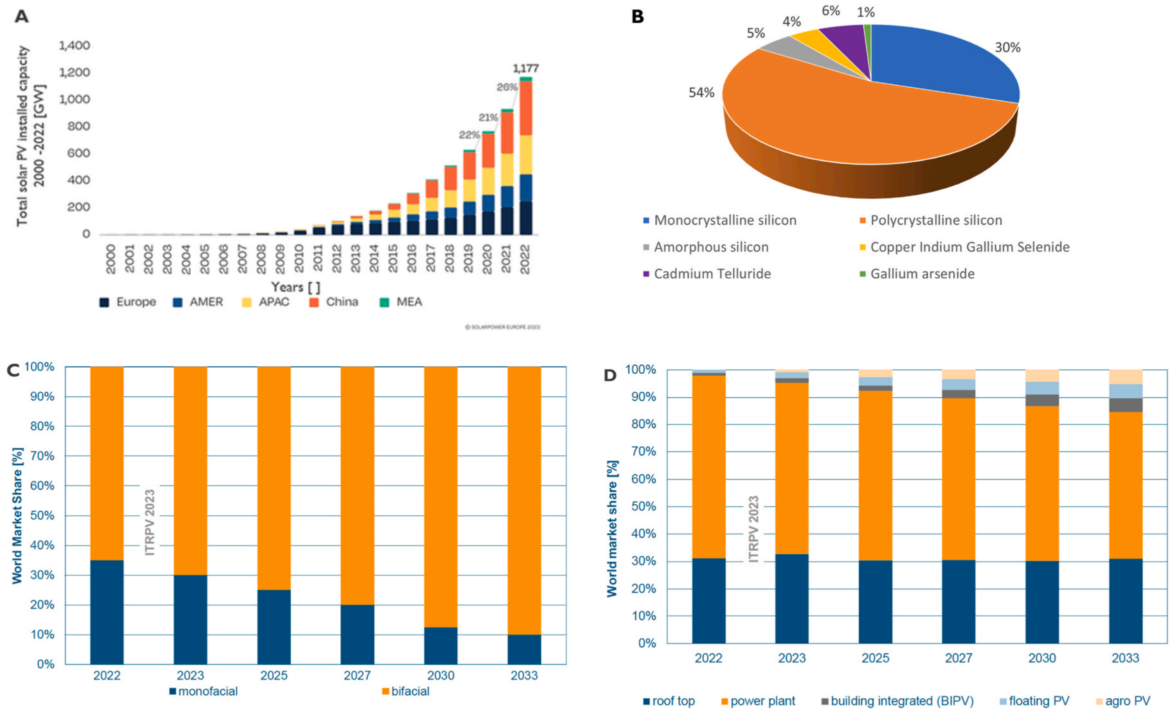

Fig. 4. (A) Total installed PV capacity by Europe, the Americas (AMER), Asia-Pacific (APAC), China and the Middle East and Africa (MEA) [88]. (B) Market share of solar cell technologies adapted from Ref. [89]. (C) World market share of monofacial and bifacial solar cells from ITRPV roadmap 2023 [90]. (D) World market share of different end-use PV systems [90].

patchy shading with sharp irradiation gradients [33]. A model in Matlab® assessed the temporal and spatial distribution of PAR at crop level for fixed and one and two-axis tracking systems [48], while [32] developed an optimization model for vertical bifacial AV system. A simulation program to calculate the ground irradiation based on PV module layout has been proposed [122].

For more advanced irradiance modelling, view factor (VF) (2D and 3D) and ray tracing (RT) are the two main optical methods [123,124]. The VF model assumes isotropic scattering of reflected rays while RT is used in applications where material properties (emissivity, transmissivity, and reflectivity) are included [124]. By using RT software such as bifacial RADIANCE, complex scenes can be reproduced [125]. RT has been employed in irradiance modelling of AV systems [31,33,47]. Bifacial modules mounted close to the ground can be accurately modelled using either the VF or RT method [124]. However, at higher elevations, the VF model greatly underestimates the irradiance on the rear side of the modules [126]. A geometric ray tracing algorithm for AV greenhouse has been developed [127] while [128] implemented a digital-twin and machine learning framework for AV solar farms. A simulation combined with SunnySD for tomato reported 28.9% increased joint crop and energy production [129]. Despite these irradiance models being used to incorporate more parameters affecting crop irradiation and growth in AV systems, more complex crop models (for e.g., perennials or trees) also need to be developed and validated. Ultimately, AV system simulation tools should focus on co-simulating the impact of the PV panel design, PV technology, the microclimate, crop selection, seasonal albedo variations and soil type on the energy and crop yields.

2.5.3. *Crop yield models are rarely calibrated for AV*

Crop models can accurately estimate factors affecting crop yield in AV systems. The Simulateur mulTIdisciplinaire pour les Cultures Standard (STICS) model was used to predict durum wheat productivity under AV [31]. STICS uses generic crop parameters [130]. However, STICS might be limited in its ability to accurately simulate crop behavior under intense shade. A simulation model coupling PVsyst to STICS concluded that shade-tolerant crops in AV systems created a 30% economic increase [16]. The impact of panels on rainwater and fluctuating shading on stomatal conductance was studied using the AVirrig model [34]. Similarly, the AVrain model predicted rainwater redistribution by PV panels [19]. CERES-Rice, CERES-Barley, and CROPGRO-Soybean fall under the decision support system for agrotechnology transfer (DSSAT) group of models and have been used to simulate rice, barley, and soybean under shading respectively, for South Korea [131]. Model calibration for AV was largely done by the use of a constant shading value in an AV setup. Also [32,132], used the environmental policy integrated climate (EPIC) model to predict the yield of oat, potato, and maize respectively for vertically mounted bifacial PV modules based on PAR daily light integral. This crop model was limited by the use of estimated leaf area index alone. The ability of Agricultural Production Systems sIMulator (APSIM) to simulate maize yields under shading was studied using field experimental data with shade cloth [133]. The APSIM model accurately simulated maize grain yield, above-ground biomass, and leaf area index for up to 50% shading. Four PV shading field experiments (9%–27%) on soybean in Monticelli d'Ongina (Italy) were conducted to validate a GECROS crop model-based platform [134]. This model underestimated yield under high shading. Other crop models developed for full sun only include the crop-adaptable SIMPLE model [135], CropSyst [136], and the SUBSTOR-potato model [137]. Despite these vast amount of crop models, few are tailored to the specific boundary constraints of an AV system.

2.6. *Shading affects both plant development and crop yield*

Plants rely on PAR light (400–700 nm) for photosynthesis. A distinction between "shade-avoiding" and "shade-tolerant" plants has been proposed [138]. Shade tolerant plants can still efficiently perform photosynthesis when exposed to lower light intensities. Shade avoiding plants principally deploy the shade avoidance syndrome (SAS) to improve light perception (e.g., by stem or petiole elongation or changing the leaf angle), mediated by phytochrome photoreceptors [139].

Plants simultaneously perceive UV-B light by means of the UVR-8 photoreceptor, which also influences plant morphology [140]. For example, high UV-B levels reduce plant height and leaf area and increase leaf thickness [141]. Semitransparent PV modules block out part of the UV spectrum [142] and crops may experience reduced UV under AV.

Fig. 5 shows the photosynthetic light response curve, which dictates the CO_2 assimilation rate in relation to the perceived light intensity and is a measure for the light use efficiency of plants [143]. In the linear phase, light is limiting for growth, while around the light saturation point, other factors such as CO_2 reduce photosynthetic rate. This light saturation point was suggested as a good indicator for crop selection for agrivoltaic applications [15]. Under light limiting conditions, this initial slope determines how well a plant can photosynthesize. Shade tolerant plants have a steeper slope and a lower light compensation point (the light level where net CO_2 assimilation by photosynthesis equals net CO_2 production by respiration) compared to sun-loving plants. Also, when plants are grown under low light intensities for a longer period, they can adapt and slightly uplift their light response curve (steeper slope) as shown in Fig. 5B [143]. Crops can thus adapt to AV by both photosynthetic and photomorphological adjustments.

2.6.1. Crop specific light requirements differ greatly

Identifying crops (or cultivars), and crop rotations suitable for agrivoltaics remains a bottleneck. Nevertheless, a considerable body of research on shade tolerance is available from studies using different shading setups (netting, agroforestry …). This section aggregates findings from AV sites, and shade experiments from other studies, grouped per crop type and compared to their unshaded counterparts (summarized in Table 2). This overview serves as a primary selection tool for crop suitability for AV.

2.6.1.1. Arable crops

2.6.1.1.1. Potato. Potato has been trialed under two PV module patterns: a checkerboard and straight-line module pattern [122]. From both trials, the checkerboard pattern resulted in a more uniform crop growth due to the homogeneous light distribution. In Germany [144], compared the production of potato under 12%, 26%, and 50% shading. Flowering, as well as time to senescence were delayed, but this did not affect tuber development. However, tuber number and weight decreased by 53% and 69% for the 26% and 50% shading, respectively. Furthermore, 34% shade during the early, late, or entire season of potato production led to 15–20% tuber yield loss for partial shading and a 30–40% loss for the entire season [145]. In the hot tropics (Peru; 5–12°S; 180–800 m above sea level), 50% shading increased tuber yield up to 39%, with an afternoon shade treatment being the most effective [146]. Shade seems to benefit potatoes to a certain degree, suggesting it could be a suitable crop for AV cultivation, especially in hot climates.

2.6.1.1.2. Wheat. Under dynamic shade, total dry weight of wheat was linearly related to irradiance [147]. Early season shading reduced the number of grains, but increased grain mass. Shading during the middle of the growing season mainly caused lower ear growth, while shading during the grain filling period led to a decrease in grain weight. Continuous shading (61%) and periodic shading (43%) led to a lower wheat yield of 45% and 25% respectively [148]. Yield reductions were mainly explained by a lower grain weight. Classic and shade-tolerant varieties grown under 8%, 15% and 23% shade, were compared [149], and the leaf area, internode length, and pigments were all higher in the shaded crops. For the shade-tolerant variety, yield was higher at 77% and 85% shading. Similar effects were demonstrated [150]. Furthermore, Ref. [151] evaluated wheat and barley cultivars with 10% and 50% shade using netting. A grain yield increase of 19% was observed. Those results were confirmed for 25% and 50% shading the following year with an increase in grain yield of 15–20% [152]. The effect of 44% shade was also studied in Argentina, and yield losses were consistently around 30% [153]. In an intercropping system with variable shade, a PAR interception ranging between 68% and 34% resulted in an average yield reduction of 51% [154]. In Montpellier, France, Ref. [31] investigated the effects of agrivoltaics using durum wheat and tested 25% and 50% shading. The development of ears was delayed, and yields decreased by 8% and 19% respectively under AV [31]. In general, correct cultivar selection appears essential for wheat cultivation for AV and suitability seems limited to warmer climates.

2.6.1.1.3. Maize. In Chiba Prefecture, Japan [15], reported 4.9% and 5.6% increase in maize stover biomass and maize yield respectively under a low PV module density. The timing of shade appears to have an important influence on maize [155], as trials in the USA (Missouri) with 50% shading confirmed that the flowering and grain filling stages are more sensitive to shade than the vegetative period [155]. Similar effects on grain filling were observed [156]. Maize yields in Ethiopia under

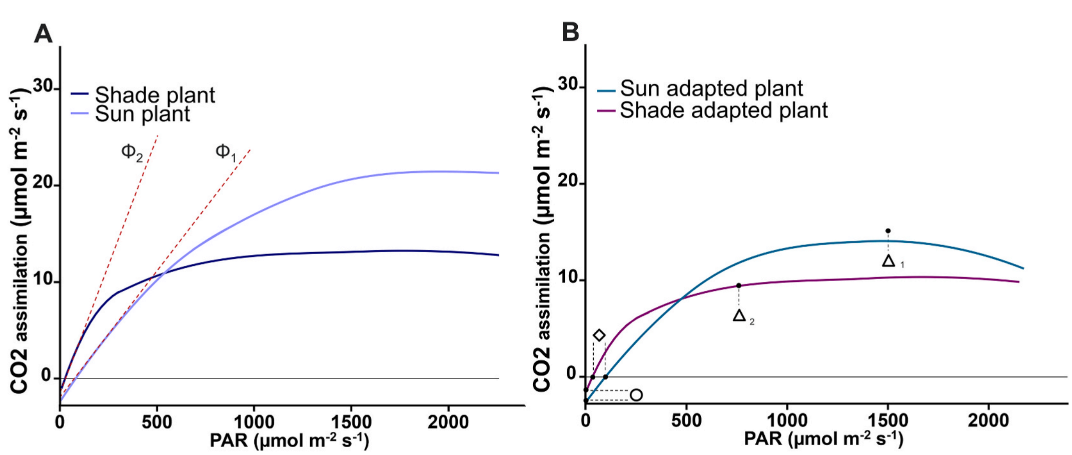

Fig. 5. Variations of the photosynthetic light response curves of C3 plants. (A) Comparison of a sun and a shade plant. Note the different slopes for the linear section Φ1 (sun plant) and Φ2 (shade plant) indicating higher quantum efficiency of photosynthesis at low irradiance for shade plants and relatively higher maximal photosynthetic rate (i.e., light saturation point) for sun plants. (B) Comparison between a sun-adapted and a shade-adapted crop of the same species and cultivar with different growth histories. Δ1 and Δ2: Light saturation point, ⋄: light compensation points (X = 0, photosynthesis equals respiration), and ○: respiration point (respiration in total darkness). Modified from Ref. [143].

Table 2
Summary table of shade response *per* crop, for various light levels, and climatic conditions.

Crop	Production System	Shade Type	Shade%	Shade Period	Region	Effects of shade	Ref
Potato	*Agroforestry*	*Netting*	*0%, 12%, 26%, and 50%*	*Full growing period*	*Rheinstetten-Forchheim, Germany*	- *Flowering* delayed. - Shift to above-ground biomass. - Smaller and less tubers. - Dry weight *decreased under 50% shade.*	[144]
	Field experiment	*Netting*	*0%, and 34%*	- *Early – from emergence to initiation,* - *Late – from late initiation to harvest,* - *Full season*	*New South Wales, Australia*	- *Larger* leaf area. - Lower tuber dry weight. - Early and late shade perform similarly. - Full shade *duration most pronounced effect.*	[145]
	Field experiment	*Spatial temporal shade (netting),* *Intercropping with maize,* *Mixed cropping with maize*	*0%, and 50%*	*Variable*	*Peru, three sites*	- *Increas*ed plant population. - Midday shading incr*eased yields.*	[146]
Wheat	*Field experiment*	*Dynamic*	*0% & 76–84% when >250j/m^2*	- *During canopy expansion,* - *Ear expansion,* - *Pre-flowering,* - Grain expansion, and -Grain filling	*Norfolk, United Kingdom*	- *Increased area* of top leaves. - Reduced number of grains *per* ear. - Reduced dry wei*ght per grain.*	[147]
	Agrivoltaics	*PV*	*0%, 30%, and 50%*	*Full growing period*	*Montpellier, France*	- *Slight delay in growth speed and maturity at harvest.*	[20]
	Agroforestry	*Camouflage netting*	*0%, 61%, and 43%*	*10-16 days before flowering till harvest*	*Gembloux, Belgium*	- *25% and 45%* yield reduction. - Lower grain number. - Lower grain weight. - Increased prot*ein content.*	[148]
	Field experiment	*Polyethylene screens*	*0%, 8%, 15%, and 23%*	*From jointing to maturity*	*Nanjing, China*	- *Increased* upper leaf area. - High shading causes reduced yields. - Yields increase over full sun for lowest shade level. - Shade tolerant cultivar outperformed shade sensitive at medium shading. - Thousand k*ernel weight main cause of yield loss.*	[149]
	Field experiment	*Polyethylene screens*	*0%, 22%, and 33%*	*From jointing to maturity*	*Nanjing, China*	- Leaf area index reduced under shading. - Increased upper leaf area. - Yield reduced proportional with shading, less severe for shade tolerant cultivar.	[150]
	Open air greenhouse pot experiment	*Polyethylene netting (green)*	*0%, 10%, and 50%*	*Full growing period*	*Plasencia, Spain*	- *19% increase in* yield. - Increased *leaf area.*	[151]
	Field experiment	*Polyethylene netting (green)*	*0%, 25%, and 50%*	*Full growing period*	*Plasencia, Spain*	- *Increased initial growth.* - *Longer time to ripening stage.* - *15-20% increased yields.*	[152]
	Field experiment	*Netting (Black)*	*0%, and 44%*	*From 65 days after emergence to 97 days after emergence and from 70 days after emergence to 91 days after emergence.*	*Balcarce, Argentina*	- *Grain* number reduced. - Yields *reduced by 27-30%.*	[153]
	Tree intercropping	*Paulownia intercropping*	*0%, 22%, 44%, and 56%*	*Full growing period*	*Henan province, China*	- *Grain number and dry weight decreased with shading between 25-36%.*	[154]

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Table 2 (*continued*)

Crop	Production System	Shade Type	Shade%	Shade Period	Region	Effects of shade	Ref
Maize	*Field experiment*	*Polypropylene fabric (black)*	*0%, and 50%*	During either - Vegetative growth, - The flowering period, or -Grain fill	*Missouri, USA*	- *Decreased yield.* - Kernel number decreased. - Kernel weight unchanged. - Shaded during grain filling, kernel weight decreased.	[155]
	Agrivoltaics	*30° tilt south facing raised PV array with 2.7 m elevation*	*0%, 21%, and 49% coverage peak shading at noon*	*Full growing period*	*Chiba Prefecture, Japan*	*For lower PV density:* - *Increased biomass by 4.9%.* - *Increased yield by 5.6%.*	[15]
	Hydroponic experimental setup	*Polypropylene shade cloth (Black)*	*0%, and 50%*	- A 30 to 33-d period before silking from 7-leaf tip stage, - A 21-d period during silking, or - A 21-d period after silking	*Ontario, Canada*	- *Total dry matter* decreased. - Inbred lines are more sensitive.	[156]
	Field experiment	*Natural canopy*	*N.A.*	*Full growing period*	*Illinois, USA*	- *Maximum* photosynthetic quantum yield decreased. - Very slight *compensation at low light level.*	[210]
	N.A	*Crop modelling in GECROS*	*Variable, 12.1% to 31.8%*	*N.A.*	*Emilia Romagna, Italy*	Simulated for 40 years of climate data: - *Average* grain *yield was higher and more stable under agrivoltaics, more so for dry years.*	[73]
	Field experiment	*Vertical barriers of shade cloth*	*Variable with row distance*	*Full growing period*	*Hawaii, USA*	- *4% yield reduction between shade barriers.* - *55% yield reduction between alley cropping.*	[157]
	Field experiment	*Self-shading of lower leaves*	*N.A.*	*Full growing period*	*Illinois, USA*	- *Maximum photosynthetic quantum yield* significantly *reduced.* - *Self shading costs 10% of potential canopy CO_2 assimilation.*	[158]
	Model validation with experimental data	*Shade cloth*	*50%, and 75%*	*Full growing period*	*Melkassa, Ethiopia*	- *Reduced yield and biomass production.* - *Shading of 50%* led to 44% reduction in biomass and 56% in yield. - *No significant difference between 50% and 75% shading.*	[133]
Sugar Beet	*Field experiment*	*Black screen-cloth,*	*56%*	*4 weeks*	*Hertfordshire, UK*	- *The sugar and dry matter of the beets was reduced, proportional with the shading percentage. Root-shoot partitioning remained the same across all shade levels.*	[160]
	Field experiment	*Camouflage net on a greenhouse tunnel.* *2015, on the south face.* *In 2016, shade layer on top causing shade in AM and PM*	*39%, 64% in 2015* *24%, 32% in 2016*	*From mid-June until harvest,* *2015 midday shade* *2016 Shade in AM or PM only*	*Gembloux, Belgium*	- *In 2015, higher leaf- and specific leaf area was recorded. Both years demonstrated Root-shoot partitioning changes with fluxes significantly favoring shoots.* - *Dry matter and sugar yield decreased under shade.*	[161]
Oilseed Rape	*Field grown over winter and transplanted to hydroponic greenhouse*	*Gray shade cloth*	*43%*	*From three weeks after transplanting till harvest*	*Caen, France*	- Increased *vegetative phase and leaf surface. Leaf senescence was delayed.*	[162]
Grassland	*Solar farm*	*50% ground cover, 18° tilt modules, 1.1 m minimum elevation*	*Three crop locations:* - Solar Fully Covered, - Solar partially open, - Sky Fully Open	*Full growing period*	*Oregon, USA*	- 90% more late-season biomass. - *Areas under PV panels were 328% more water efficient.*	[163]
Forage crops	*Agroforestry*	*Shade cloth and a horizontal slatted structure*	*51% under trees,* *59% under cloth,* *56% under slats*	*Full growing period*	*Canterbury, New Zealand*	- *Elongated stems and internodes.* - *Dry matter yield reduced (trees: 32%, cloth: 44%, slats: 43%).* - *Response under slats similar to agroforestry.*	[164]
Lettuce	*Agrivoltaics*	*Half-density and full-density stationary PV systems,*	*30%, and 34%*	*Full growing period*	*Montpellier, France*	- *Increased projected leaf area and final leaf area between PV vs. below PV or in full sun conditions.*	[165]

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Table 2 (*continued*)

Crop	Production System	Shade Type	Shade%	Shade Period	Region	Effects of shade	Ref
		solar tracking and controlled tracking				- *Decreased dry mass.*	
	Agrivoltaics	*Half-density and full density stationary PV systems, solar tracking and controlled tracking*	*30%, and 34%. Controlled tracking transmitted 30% more than solar tracking. Solar tracking transmitted 8% to 23% more than half density.*	*Full growing period*	*Montpellier, France*	- *18% decreased dry mass for var. Madelona, none for var. Kiribati.* - *Reduced number and thinner leaves per plant which were more expanded per unit biomass.*	[17]
	Movable tunnel	*Shade cloth*	*Variable, 52% to 66%*	*Full growing period*	*Kansas, USA*	- *Red lettuce reduced by 31% in spring and 40% in fall, green* lettuce *reduced 17% in spring and 40% in fall.*	[166]
	Greenhouse-grown	*Variable layers of shading nets*	*50%, 65%, and 85%*	*Full growing period*	*Teramo, Italy;*	- *The second-order polynomial model indicated that light severely affected lettuce biomass production and estimated the maximum harvested biomass at 0.9% PAR reduction and* 185 kg/ha.	[167]
	Hydroponic greenhouse	*Black shade cloths of variable mesh size*	*25%, 30%, 47%, 55%, 66%, 73%, and 92%*	*6 full cycles: 8 Aug.-8 Sep., 19 Nov.-17 Dec., 29 Dec.-26 Jan., 23 Mar.- 20 Apr., 1 May - 29 May, 1 June-29 June*	*Arizona, USA*	- *Lettuce* was able to utilize the highest PAR levels measured, 45 molm-2day-1. - Above 8 molm^{-2}*day*$^{-1}$*, quality was maintained at the cost of growth speed.*	[168]
	Plastic film greenhouse	*Black screens*	*0%, 35%, 50% and 75%*	*Full growing period*	*Federal District, Brazil*	- *Maximum productivity in lettuce* cultivation *observed between 20% and 35% shading.*	[169]
Tomato	*Agrivoltaic*	*Agrivoltaic*	*South facing modules at 32°, 3.3 m above the soil at 1 m between rows*	*Full growing period*	*Arizona, USA*	- *Cumulative* CO_2 *increased by 65% in* agrivoltaic *installation and water use efficiency was also 65% increased.* - *Total fruit production was twice as great under agrivoltaics.*	[27]
	Greenhouse	*Red shade net below the polyethylene sheet*	*83%*	*Full growing period*	*Ladakh, India*	- *Delayed flowering and 48% reduction in marketable yield.* - *Total phenolic* content *and total flavonoid content dropped by 29% and 16% respectively.*	[174]
	Agrivoltaics	*Crops below solar panels or in rows between panels*	*3 m wide South facing modules at 18 °, 0.8 m above the soil*	*Full growing period*	*Oregon, USA*	- *Yields* reduced *by 32% to 38% in the row and 48% to 60% under panels.*	[175]
	Canary type PV greenhouse	*Canary type greenhouse covered on 10% of its roof in a checkerboard configuration*	*22%*	*Full growing period*	*Agadir, Morocco*	- No significant *effect.*	[176]
	Venlo type PV greenhouse	*PV greenhouse roof*	*15%, 30% and 50%*	*Full growing period*	*Almería, Spain*	- Significantly *decreased yield.* - *Delayed harvest onset and final harvest.* - *More green non-commercial fruits at final harvest.*	[177]
	Field experiment	*Colored shade netting: black, green, mixed*	*4%, 11%, and 40%*	*Full growing period*	*Nea Anchialos, Greece*	- *Marketable* tomato *production* increased *by 50% mainly due to better quality.*	[178]
Pepper	*Field experiment*	*Agrivoltaic*	*South facing modules at 32°, 3.3 m above the soil at 1 m between rows*	*Full growing period*	*Arizona, USA*	- CO_2 uptake *increased by 33% for var. Chiltepin and dropped by 11% for var. Jalapeño.* - *Jalapeño showed 65% increased water usage efficiency.*	[27]

(*continued on next page*)

Table 2 (*continued*)

Crop	Production System	Shade Type	Shade%	Shade Period	Region	Effects of shade	Ref
	Field experiment	*Polypropylene black shade net*	*0%, 30%, 47%, 62%, and 80%*	*From 4 weeks after transplanting*	*Georgia, USA*	- Total plant leaf area, individual leaf area, and individual leaf weight increased. - Leaf number *per* plant and specific leaf weight decreased. - Shade between 30% and 47% were the most favorable for bell pepper.	[179]
	Field experiment	*Polypropylene black shade net*	*40%, 41%, 42%, and 47%*	*Full experimental period*	*Georgia, USA*	- Marketable and total fruit number, yield, and individual fruit weight increased. - Total phenols, flavonoids, and TEAC, decreased.	[211]
	Field experiment	*Polypropylene black shade net*	*30%, 47%, 63%, and 80%*	*From three weeks after planting in 2017 and four weeks after planting in 2018*	*Georgia, USA*	- *Plant water use reduced due to reduced eva*porative demand enhancing plant growth. - Total fruit yield and number of sun-scalded fruit *diminished with increasing shade level, while marketable yield was maximal at 30% shade.*	[180]
	High tunnel	*Shade cloth*	*30%, and 50%*	*at 34 and 47 days after transplanting for 2017 and 2018 resp.*	*Iowa, USA*	- Decrease in both marketable number (32%) and weight (29%). - Decreased sunscald by 59% under 50% shade. - Plant height increased by an average of 14.5 cm. - The average leaf size was 11.2 cm^2 larger under 50% shade.	[181]
Aubergine	*Net house*	*Quad-crossover netting fabric*	*11%, 21%, and 30%*	*Full growing period*	*Western Australia, Australia*	- *Eggplants grew taller and bushier and gave higher fruit yield. Best yield was estimated at 21% shading.*	[182]
Cucumber	*Field experiment*	*Plastic nets*	*0%, 15%, 35% and 60%*	*From transplanting to harvest*	*Tehran, Iran*	- *Quality was best at 35% with more defects under higher irradiance.* - *Fruit* numbers *peaked at 35% shade decreasing at higher rates.*	[183]
	Arched roof greenhouses, with vertical side walls, covered with a single sheet of 180 μm *thick polyethylene film*	*Netting*	*35%, and 50%*	*From transplanting to harvest*	*Volos, Greece*	- *Leaf* photosynthesis reduced linearly under shade. - Shaded *plants did not acclimate to shade.*	[184]
Pear	*only in Korean, from conference abstract*	*Folding PV Agrivoltaics*	*30%*	*NA*	*Jeollanam-do, Republic of Korea*	- *Flowering improved.* - *At a similar harvest time, yield decreased by 6.7%. Size and brix similar. Later harvest made up for decrease.*	[185]
	Field experiment	*Shade cloth on branches only*	*80%*	*from 6 to 18 weeks after full bloom*	*Neuquén, Argentina*	- *Shading* reduced *specific leaf mass, decreased fruit fresh mass by 20% and increased firmness.*	[186]
Apple	*Field experiment*	*Shade cloth, timer controlled, morning, afternoon, entire day*	*73%*	*From two to ten and again from 16 through 23 weeks after full bloom.*	*West Virginia, USA*	- *Full shade* showed *the highest yield reduction.* - *Avoiding morning shade seemed most important for limiting shade losses.*	[187]
	Field experiment	*Shade cloth*	*90%*	*For one week starting 30 d after full bloom*	*Emilia-Romagna, Italy*	- *Fruit drop delayed by 7 days.* - Thinning *levels are similar to chemical standard.* - *Fruit size was similar, acidity and hardness higher.*	[188]
	Agrivoltaics	*Single axis tracked PV*	*variable, 4% - 88% mean of 50–55%.*	*Full growing period*	*Mallemort, France*	- *7% starch accumulation in shoots.* - *31% flowers at shoot scale.* - *Less* alternate *bearing.* - *Fruit size similar in some years.* - *34% lower fruit dry mass.*	[190]
Cherry	*Field pot experiment*	*White fiberglass netting*	*variable, 20–30%*	*Full experimental period*	*Lazio, Italy*	- *No differences in photosynthetic rate or midday peak observed.*	[191]

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Table 2 (*continued*)

Crop	Production System	Shade Type	Shade%	Shade Period	Region	Effects of shade	Ref
	Field pot experiment	*White fiberglass netting*	*variable, 20–30%*	*Full experimental period*	*Lazio, Italy*	- *Dry mass increased for up to 30% shade.* - *Reduced photosynthetic rates, thinner mesophyll, and larger specific leaf area.* - *Reduced transpiration.*	[192]
	Field pot experiment	*Silvered polyethylene shade cloth*	*53% and 78%*	*16 July to 16 September*	*Kagawa, Japan*	- *Frequency of double pistils reduced by 24% at 78% shade, less at lower levels.* - *Shading reduced frequency of double pistils to under 3%.*	[193]
	Orchard system	*Green plastic netting*	*45%*	*From 15th of June until the end of August*	*Adana, Turkey*	- *At high temperature double pistils were reduced* under *shade.* - *This effect is attributed to lowering of ambient temperature under shading.*	[195]
	Orchard system	*Polyethylene film rain hoods*	*24-42%, various*	*Full growing period*	*Limburg, Belgium*	- *Under* polyethylene hoods, bud formation decreased. - Lower sugar *content at identical yield flavor similar.*	[196]
Blackcurrant	*Field experiment*	*Shade netting*	*37%, 45%, 65%, and 83%*	*From before full leaf out in 2016 and before full flower bloom in 2017 and 2018, until after leaf fall*	*Illinois, USA*	- *Bigger* and thinner leaves. - Yield remained similar up to 65% shade. - At higher shading, there was decreased stem diameter*, increased height.*	[204]
Raspberry	*Orchard system*	*Shade cloth*	*30%, 50%, and 80%*	*From leaf emergence at an adjacent forested parcel until plant lifting*	*New York, USA*	- *Primocane growth broadly similar apart from diameter and number of nodes.* - *Best canopy development at 30% shade. Photosynthesis saturated at 30% shade or less.* - *Shading caused more spaced-out harvest.*	[205]
Blueberry	*Field experiment*	*Black, white, gray, and red nets*	*29%, 41%, 47% and 53%*	*From fruit set until early leaf fall, October to late march*	*Miraflores, Chile*	- *Yields under colored shade nets increased between 24.9% and 90.5% depending on year and type.* - *Black nets caused no difference or reduced yield depending on density.*	[207]
	Field experiment	*Black, red, and white nets*	*25%, 50% and 75%*	*From fruit set (July) and removed at the onset of leaf drop.*	*Michigan, USA*	- *Chlorophyll increased and photosynthesis decreased under shade.* - *Fruit development delayed.* - *Fruit weight increased.* - *Decreased soluble solids.*	[208]
	Field experiment	*Black, red, and white nets*	*25%, 50% and 75%*	*one month after fruit set until one month after the end of harvest*	*Michigan, USA*	- Flower bud development decreased, and the number of flowers increased. - Harvest delayed. Yields not different for up to 50% shade.	[209]
Grape	*plastic-roofed greenhouse*	*Blue, green, and black shade nets, and aluminum foil gray shade nets*	*43%, 60%, 83%, and 54%*	*The treatment period was from 24 July 2020 (50% color change) to September 3, 2020.*	*Shanghai, China*	- *Shading alleviated grape softness. The total soluble solids and grape coloration were negatively affected under some shade nets.* - *Peel color was not significantly affected under gray or blue shade nets and unshaded grapes showed clear heat-*	[197]

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Table 2 (*continued*)

Crop	Production System	Shade Type	Shade%	Shade Period	Region	Effects of shade	Ref
						stress damage. High light intensity and heat was thought to cause premature leaf senescence.	
	Field experiment	*Agrivoltaic*	*75%*	*Full growing period*	*Valpolicella, Italy*	- *Shading reduced both air and soil maximum temperature. At midday, transpiration values were significantly higher in AV vines. Photosynthesis followed the same pattern.* - *Vine productivity parameters (yield, cluster number and weight) were influenced to a limited extent; anthocyanins, TSS and polyphenols were reduced in grape juice from AV vines.*	[198]
	Shade house pot experiment	*Hollow cylindrical structures with shade cloth*	*66%, 75%*	*The experiment of 2017 took place from October through December*	*Mendoza, Argentina*	- *Shaded plants presented lower stomata differentiation and lower water use efficiency.*	[212]
	Rain protected Field experiment	*Agrivoltaic; 3 PV module types*	*72%*	*Full growing period*	*Ongjin-Gun, South Korea*	- *Slower grape growth under shade. No difference in grape growth for different PV module types. Grape sugar-content level could be equalized by delaying the harvest time by about 10 days under AV.*	[199]
	Greenhouse experiment	*Shade cloth*	*54%, 90%, and 99%*	*3 to 10 weeks after potting*	*Ontario, Canada*	- *Leaf size was maintained but leaf fresh weight, volume, density, and thickness were immediately reduced with increased shading.* - *Root to shoot weight ratio was reduced. Light compensation point was reduced.* - *The morphological compensation for shading allows shaded leaves to use available light more efficiently. Long term growth may be negatively impacted.*	[200]
	Field experiment	*Shade cloth*	*70%*	*budbreak till harvest*	*New South Wales, Australia*	- *No impact on shoot growth but later reduced leaf growth and later still bunch growth.* - *Shade covering impacted most on biomass accumulation to leaves and bunches at the stage when the vines became autotrophic, consistent with the reduction in carbon acquisition.*	[201]

50% and 75% shade were studied and yield losses of 56% and 64% respectively were observed [133]. Also, Ref. [73] simulated normal years, and years with different environmental conditions. The agri-voltaico setup in Italy with shading percentages between 13.4% and 29.5% reduced seasonal variability but also yield. Similarly, Ref. [157] studied maize under AV and observed a 55% reduction in yield. However, Ref. [158] did show the adaptation potential of shaded leaves of maize, under full sun. From these studies, this review can infer that high shading levels (40–50%), especially after flowering would lead to high yield losses for maize.

2.6.1.1.4. Rice. Studies of rice under PV panels in Japan reported that a maximum shading between 27% and 39% should be implemented to maintain at least 80% of crop yield [159].

2.6.1.1.5. Sugar beet. Lower sugar beet yield (50%) and sugar content after several shading periods of 55% have been reported [160]. However, sugar content per dry matter remained unchanged. Other research on beet cultivation in agroforestry systems contradicts this, Ref. [161] showing a lower sugar content and root weight compared to

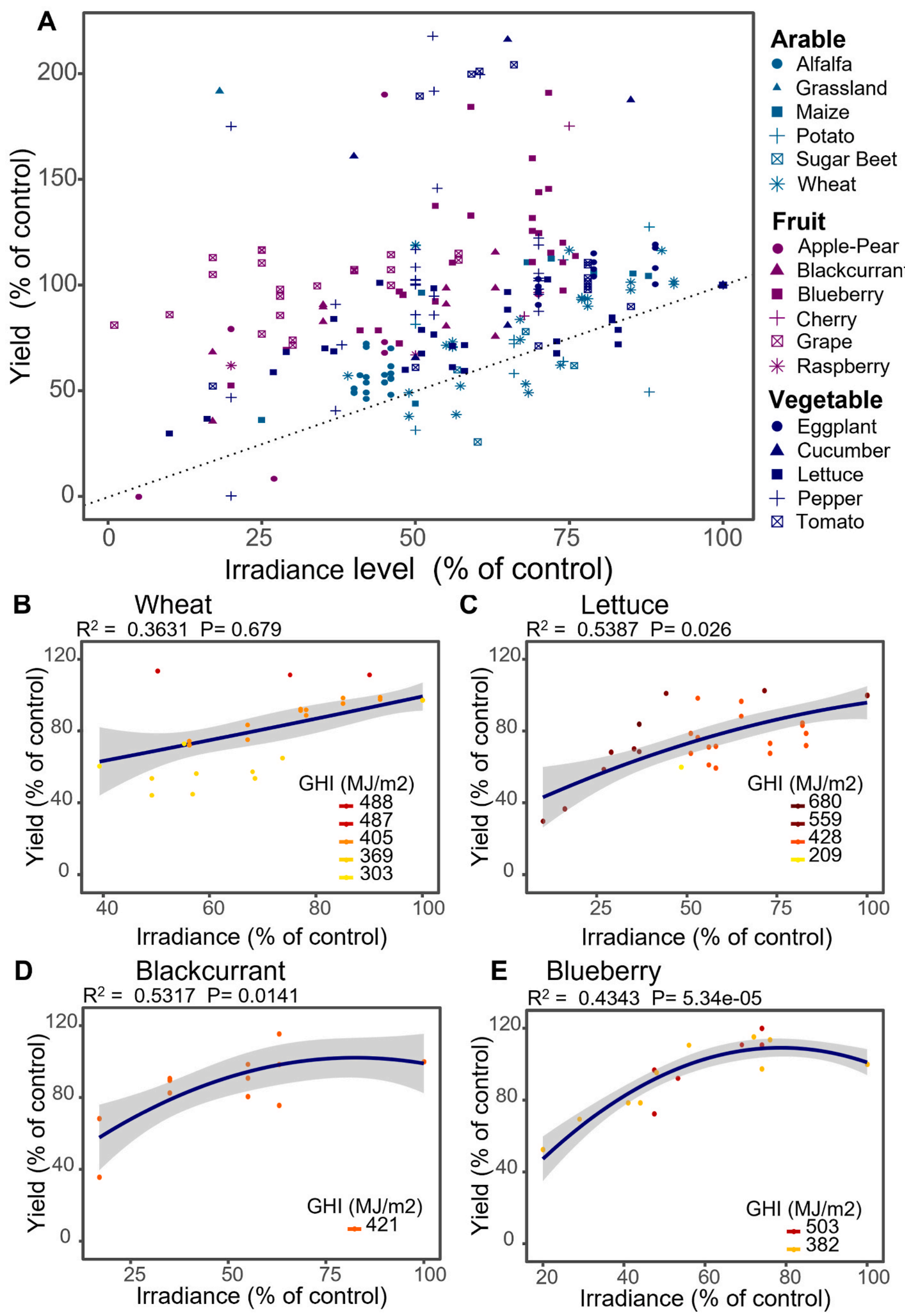

Fig. 6. Meta-analysis of relative crop yield responses towards shading. (A) Yield responses under variable shade for all field trial datasets analyzed, aggregated per crop type. Points above the dotted line represent trials where crop yields surpass the "1% light is 1% gain" rule. (B–E) Crop-specific relative yield responses towards shading levels. blue line: second degree polynomial fit with 95% confidence interval. Dots colored according to the study-specific irradiance level at the trial location (with a calculated GHI level). (B) Wheat (Triticum aestivum) yield as a function of shade level. Yield decreases relatively linearly with shade. (C) Lettuce (Lactuca sativa) yield as a function of shade level. Yield decreases linearly with shade, at a lesser rate than wheat. (D) Blackcurrant (Ribes nigrum) yield as a function of shade level. Yield remains relatively unchanged up to moderate shade levels. (E) Blueberry (Vaccinium corymbosum) yield as a function of shade level. Yield plateaus up to moderate shade levels before dropping off more steeply.

the full sun control.

2.6.1.1.6. Oilseed rape. The impact of light reduction on oilseed rape was analyzed [162]. A PAR reduction of 43.4% was applied during flowering for a duration of three weeks. Biomass decreased by 12.9%, but no significant effects could be determined.

2.6.1.2. Grassland and forage crops

2.6.1.2.1. Grassland. In Oregon, USA, Ref. [163] investigated the effect of periodic shading on grasslands under drought stress. Low mounted PV panels (1.1 m, causing up to 82% shading at midday), caused higher soil moisture content and increased grass biomass late in the season.

2.6.1.2.2. Alfalfa. In Canterbury, New Zealand, Ref. [164] compared shade nets and a dummy panel system. Although total light reduction was similar for both systems (41–44% light transmission), the spatial-temporal pattern of the panels was found to be more comparable to agroforestry than uniform shade netting. Biomass reduction (20–25%) was comparable between the two shading treatments.

2.6.1.3. Vegetable crops

2.6.1.3.1. Lettuce. Several AV studies have focused on lettuce, comparing 20%–34% shading [14,165]. The number of leaves was significantly lower under shading, but leaves adapted themselves and were wider and longer and the projected leaf area increased under AV. Two cultivars of lettuce under 55% shade showed 31% and 16% reductions in yield [166]. Also, Ref. [167] studied lettuce under 50%, 65%, and 85% shade with increasing yield loss. A biomass growth curve model for greenhouse-grown lettuce at 25%–92% shading was constructed [168]. Lettuce growth rates increased with irradiance, without plateauing. In Brazilian greenhouses [169], evaluated three shading levels (35%, 50%, and 75%), which proved beneficial up to 25% shading but negative beyond 48% shading. In Spain, Ref. [170] investigated lettuces under different PV designs. They reported better performance when irradiance was more homogeneous. Light diffusion films led to improved lettuce yield thanks to a better light penetration [114]. In the south of France, Ref. [14] assessed PV shading (50% and 70% shading) on the yield of lettuces and reported less than a 1:1 yield:light reduction. In an AV system in Hefei (China) [13], studied the growth of different crops including lettuces. Similar crop yields and quality were obtained for AV and open sun. In general, lettuce appears to be quite suitable for agrivoltaic cultivation in a wide range of regions, given that the crop can adapt itself to partial shade.

2.6.1.3.2. Tomato. Tomato plants were observed to avoid shade through hyponasty (erect leaves), and rapid leaf and stem growth [171]. Similarly, tomato number and weight increased under 25% shade [172]. In Arizona (USA), Ref. [27] studied tomato, and found fruit yield to drop under AV. In an agroforestry context in the south of France, Ref. [173] achieved comparable results, noting a lower sugar content and a higher acidity under shade. In India, Ref. [174] conducted a tomato trial. Shading led to a yield reduction of 48%. Tomatoes under AV conditions in Oregon (USA) were also evaluated [175]. They achieved 39%, 62%, and 75% yield losses depending on their field position. In a PV glasshouse on the Canary Islands, Ref. [176] evaluated tomato performance with 10% shading using flexible PV panels, which did not result in a yield decrease. However, plant height did lag significantly. Furthermore, Ref. [177] also studied solar greenhouses with 15%, 30%, and 50% shading in south-eastern Spain. A progressive drop in yield was observed, being 14%, 29%, and 49% respectively. In Greece, 34–49% shading with shade netting nearly doubled marketable crop yield [178]. In general, tomatoes do not seem to perform well under shading conditions, despite some clear photomorphological adaptations.

2.6.1.3.3. Peppers. For jalapeño peppers grown under AV, the water use efficiency more than doubled and overall yield nearly tripled [27]. In the state of Georgia (USA), Ref. [179] observed longer internodes and fewer but larger and thinner leaves when the crop was shaded. Vegetative biomass was not significantly different between shade levels tested. In another trial in Georgia (USA) [180], noted that marketable yield was highest for 30% shade with sun scalding decreasing with increasing shade levels (47%, 63%, 80%). In Iowa (USA), Ref. [181] investigated the growth of seven pepper cultivars, using 30% and 50% shade cloth levels. The yield was significantly reduced for three cultivars in 50% shading, leading to a 35% decrease in marketable fruit. In sufficiently hot climates, peppers seem to benefit from shading, making them a suitable crop for AV in these regions.

2.6.1.3.4. Aubergine. In a hot, semi-arid climate in Australia, Ref. [182] studied four cultivars of eggplant under three shade levels (11%, 21%, and 30%). Plants were taller and bushier under the shade. Also, marketable fruit yield was greatest under 21% shade and lowest without shading. Shade performance under more temperate climate remains untested.

2.6.1.3.5. Cucumber. In Iran, Ref. [183] studied cucumber growth under 40%, 65%, and 85% shading. The yield was maximal for 35% shading levels in this climate. Cucumbers on an experimental farm in Velestino (Greece), under 35% and 50% shade exhibited decreased photosynthetic rates [184]. No yield data was reported. Yield gains for cucumber under AV are only expected in hot climates.

2.6.1.4. Fruit crops

2.6.1.4.1. Pear. In a recent experiment with Asian pear (*Pyrus pyrifolia*) in South Korea, Ref. [185] evaluated a variable shade AV setup (0–30%). The pears had a longer flowering period and reduced frost damage in winter and spring, leading to a better fruit set and less fruit abortion. At harvest, fruit yield was 4.5% lower, and sugar content was 11.8% reduced. However, harvest could be delayed by 14 days, spreading revenues. Pear fruit (*Pyrus communis* L.) decreased in diameter and increased in firmness when covered for six weeks after bloom with a shading level of 80% [186]. The fruit fresh weight was 20% lower. An AV pear Orchard in Bierbeek (Belgium) with 40% PV module transparency resulted in 16% yield losses [60,256(preprint)]. These reports seem to indicate that with proper harvest timing, pears might be suitable in AV.

2.6.1.4.2. Apple. Several temporal shading patterns affected apple yield in West Virginia, USA [187]. Continuous shade had the most negative effect, while morning-shaded plants suffered more than evening shaded plants, with yields of 7.8 kg, 72.5 kg, and 110.6 kg respectively compared to 201.6 kg per tree in full sun. Short intense shading of flowered branches served as thinning treatment [188]. In southern France, Refs. [189,190] tested a tracker system that intercepted about 50% sunlight on an irrigated apple orchard. No effects on fruit quality were observed for the shaded trees, but fruit set was greatly reduced, and there was a lower fruit yield per tree (−27% to −32%). While some quality parameters were acceptable, yields dropped significantly in 2019 and 2020 by 32% and 27% respectively but recovered in 2021 to 190% (due to bi-annual bearing). Apple seems to be only partially suitable for agrivoltaic integration but could show potential within correct boundary conditions.

2.6.1.4.3. Cherry. A shade level of 30% resulted in a decrease in ambient temperature of 3 °C and a reduction in crop transpiration for young cherry trees in Italy, while overall photosynthesis was not significantly different [191]. Similar findings were reported [192]. Cherry dry weight was slightly higher for shaded plants. For very warm years, shaded plants showed a reduction in double fruit by about 50% [193]. Also, the fruit set was better (35%) and dry weight and sugar content were both higher for cherries harvested from shaded trees [194]. Turkish research corroborated these findings, observing lower ambient temperature and fewer double fruit under 45% shade [195]. Rain shelters for cherry cultivation, reaching 24–42% light loss, also elevated ambient temperature compared to open air [196]. Bud formation and production were also reduced. The resulting fruit had a lower sugar content, while the taste was not adversely affected [196]. It seems that AV is suitable for cherry production as it has extra protection benefits to secure yield.

2.6.1.4.4. Grapes. Both wine and table grapes seem to tolerate shading up to a certain degree in hotter climates. Shading can improve fruit quality due to a lower ambient temperature [197]. Similarly, Ref. [198], recorded a reduced ambient temperature and improved photosynthesis under hot conditions. Also, Ref. [199] observed delayed ripening and [197,200,201] reported changes in leaf development and reduction in long term growth. Grapes are likely to perform at a sufficient level in hotter climates when cultivated under AV.

2.6.1.4.5. Red- and blackcurrant. Research on black current [202, 203] using 35%, 45%, 65%, and 85% PAR reduction in Illinois (USA), indicated that shade does not cause strong yield reductions (5–30% yield reduction for the lowest and highest shading treatment respectively). A modelling update on this research noted that yield showed significant losses with more than 83% shading, but little decline up to 65% shading [204]. Thus, these studies indicate that black currant is a suitable crop for cultivation under AV.

2.6.1.4.6. Black- and raspberries. In a study in New York State (USA), three shade levels (30%, 50%, and 80%) were evaluated for blackberries [205]. The 30% shading treatment had very little effect on the photosynthetic capacity. Similar conclusions for raspberries were attained [206]. It appears that at moderate shade levels, blackberries and raspberries are suitable for agrivoltaics.

2.6.1.4.7. Blueberries. Shade nets have been evaluated for blueberry cultivation [207–209]. Both black and colored nets with 35% and 50% screening caused between 29% and 53% reduction in PAR. No difference in other environmental parameters were observed. Black nets caused a yield decrease (−3.2% to −28%), while light nets improved yield (up to 190% of the control), probably due to an earlier flowering and a longer growing season, leading to an extra harvest moment. They also observed a higher chlorophyll content and chlorophyll fluorescence of leaves under shade, indicating that the leaves of blueberry can adapt to shading conditions, making them a suitable crop for AV.

2.7. Crop yield responses under shading show three trends

Studies on the correlation between Global Horizontal Irradiance (GHI) and the distribution of AV systems across the world suggested that GHI is sufficient for AV systems in latitudes below 45° and areas close to the equator [213]. However, the use of GHI alone as a yardstick for the optimum conditions for AV systems is not sufficient as plant growth is also affected by soil conditions, water availability, other climatic conditions, and local agricultural practices [213].

Expanding on GHI as an indicator for AV suitability, the research in this study carried out a meta-analysis of the crops' potential under AV. Fig. 6 summarizes the meta-analysis of 372 field trials with shading from 66 publications spanning 18 crops. By aggregating shading percentages per trial with the specific irradiance levels per site for that year from the global Solar Atlas 2.0 [214], this review compares relative crop yields with relative shading levels. Yield values under shading were expressed as a relative yield reduction from the unshaded control. Note that this analysis does not incorporate microclimate effects, soil characteristics or agricultural practices.

In general, no universal trend can be observed across all crops (Fig. 6A). Nevertheless, some specific crops show a more distinct yield trend to shading. This research distilled three different scenarios: (1) crops showing no real benefit from additional shading and display a linear effect without clear optimum (Fig. 6B and C). (2) some crops are equally yielding under limited shade conditions (depending on local irradiance), represented by a yield plateau up until a certain degree of shading (Fig. 6D); and (3) crops increasing in productivity under shading, showing their maximum yield at less than full irradiance (Fig. 6E). The latter two crop-shade-response categories are likely most suited for implementation in agrivoltaics.

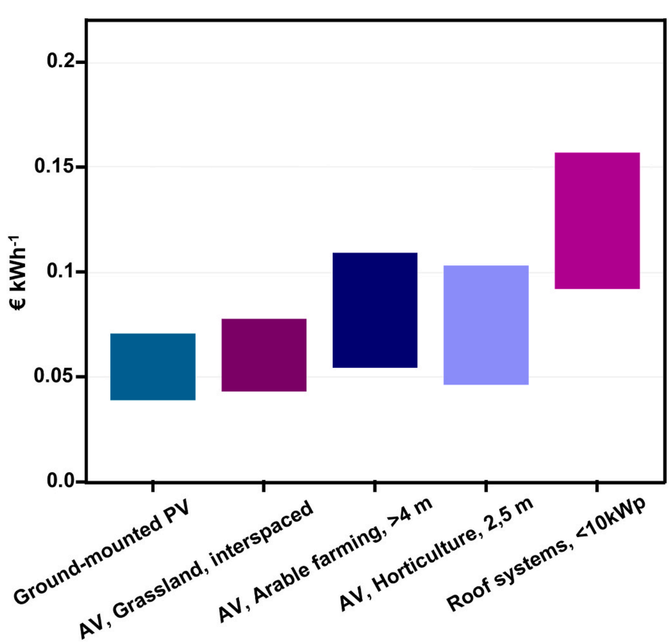

Fig. 7. The estimated levelized cost of electricity in 2023 for AV systems compared to utility scale ground-mounted and small-scale rooftop PV systems. Modified from Ref. [11].

2.8. Challenges to the large-scale success of AV

2.8.1. Technical challenges

The key technical challenges faced by AV systems lie in choosing a PV module design which balances both PV and crop yield. Further complexities arise in choosing a suitable PV array design which provides homogeneous light distribution at canopy level. Additionally, the type of mounting structure must be adapted to the specific AV system needs. The structures must be appropriately sized to allow agricultural machinery. Permanent foundations are generally not desirable on farmland [11]. Therefore, agricultural-friendly foundation systems would have to be developed. Effects on soil compaction/erosion due to construction should be prevented to secure agricultural yields.

Both electrical connectivity to the grid and on-farm self-consumption pose technical challenges. Self-consumption, and its distribution over time are essential elements in the economic balance of an agrivoltaic operation. Since most of the farmland suitable for AV installations are away from cities, the accessibility and integration in the electrical grid by transmission lines could be a major hurdle. Nevertheless, some authors argue that AV systems can play a role in opening these poorly connected areas for e.g., electric vehicle charging, reducing the cost of decarbonizing our fleet [215]. AV systems may also increase energy production in areas that are relatively remote or hard to connect to a central grid [216,217]. AV systems can also assist in the electrification of rural communities without direct access to electricity by implementing local microgrids [218].

For large scale AV systems with excess energy, storage systems such as batteries and super capacitors could be used to improve grid reliability. These surplus energy management strategies transferrable to AV systems have been discussed [219]. For example, physical energy storage systems such as flywheel- or gravity energy storage could also be co-developed. Power conversion technologies could convert excess electricity to fuels. Renewable fuels such as hydrogen can be generated from electrolyzers and later used in fuel cell technologies. The use of deferrable loads can further manage excess energy in AV systems [219]. Desalination technologies are one of the main systems where this could be implemented. Water desalination can reduce dumped power by 67% [220]. By imposing capacity shortages during peak hours, the generation of surplus electricity could also be prevented [219].

Several tools have been developed for AV modelling (see 2.5. Modelling of agrivoltaic systems). However, in AV systems, the main challenge is the co-simulation and co-optimization of energy with agricultural models. While PV yields can be predicted accurately, precise modelling of crop responses and yield to shading by AV systems remains challenging. Additionally, the influence of the crop microclimate on the PV system remains largely unaccounted for in energy models, though some steps are being made to include AV in PV yield modelling [221]. Other complexities in AV system modelling include incorporating glass, metal and mounting structures, the temporal and spatial variability of shading patterns arising from changing seasonal solar irradiation patterns and albedo variations from different crop shapes and colors. Furthermore, the spectral sensitivity of photosynthesis and the solar photovoltaic process must be incorporated because large parts of the solar spectrum required for energy generation by PV are not used by crops.

2.8.2. Socio-economic challenges

Agrivoltaics gives farms and farmers an opportunity to diversify their income by consuming or selling the solar energy generated. The operating costs of AV systems are expected to exceed those of ground-mounted systems. Nevertheless, AV systems above perennial crops and grasslands can be cost-effective, as the technical design can be constrained to a single crop. On average, the levelized cost of electricity in AV systems is slightly higher than that of ground-mounted PV systems but is more competitive than small rooftop PV systems [11]. However, synergistic cost benefits could be realized in agricultural systems with existing crop support structures [222]. Fig. 7 shows the estimated levelized cost of electricity for the different PV systems. Utility scale ground mounted PV is the most economical. Nevertheless, compared to the relatively high cost of residential scale roof mounted PV, AV systems present an interesting opportunity.

In many regions, there is currently a lack of an adequate legal and regulatory framework for implementing AV systems in a socially acceptable way [223], and determining how subsidies should be implemented. A working dialog between the agricultural and energy sector and the local communities and government is required to create a working plan which aligns all stakeholders. To avoid societal conflicts, stakeholders and citizens should be included in the planning and decision-making process for AV installations and clear rules should be laid out regarding their implementation and exploitation. The land on which AV systems are developed must preserve its primary purpose, which is agriculture, and the AV structures should not have a negative impact on the visual appreciation of the countryside.

2.8.3. Agronomic challenges

Proper crop selection is at the center of an AV design. The light requirements of these crops will determine the PV density and PV array design while the crop system dictates the AV support structures (e.g. dimensions of the agricultural machinery). This determines the eventual return-on-investment of the system. The central challenge of AV is to safeguard crop productivity. For example, in Japanese AV systems, a crop production level of 80% must be maintained [224]. Arable crops make up the bulk of agricultural land, relying on crop rotations for maintaining a healthy soil microbiota [225], and carbon content, and limiting pest and disease pressure buildup [226]. AV farming systems require that either all crops be adapted specifically to a desired shading level, or inversely, PV density should be adapted to the most shade-sensitive crop in the rotation. Little to no information currently exists on shade tolerance of cultivars, even though a wide range of responses to shading can be observed between cultivars [227]. Specific shade tolerant cultivars can benefit AV implementations [228].

2.9. Opportunities and future of agrivoltaics

New AV concepts are continuously being explored. For example, PV-tracking with dynamic shading can solve several of the optimization challenges of AV systems. However, the cost of tracking systems and availability of a good crop-proof tracking algorithm are limiting factors for many PV systems [11,229]. Improved light utilization in AV systems could also be realized by using wavelength-selective PV module technologies such as the OPV, DSSCs and PSCs. However, the efficiency, scalability and stabilities of these solar cell types remain limited. Spectral shifting module technologies such as LSCs with organic dyes or rare-earth complexes also provide a future element of light control for the crops.

Besides open-air AV, PV can also be installed on greenhouses. Greenhouses provide a highly controlled microclimate for crops and therefore extend production duration [230], enabling optimal plant growth for a higher yield and quality [231]. PV greenhouses also protect crop growth and provide additional energy. Different PV greenhouses have already been developed or studied [75,232–238], and the global area is more than 9.5 million ha [239]. PV greenhouse shading might be beneficial for mushroom germination and shade-adapted leafy vegetables. Energy generated in PV greenhouses could also be used for heating, cooling, irrigation [240], and lighting [241] or sold. Solar energy can also be used to generate solid sorbents in the simultaneous heating and dehumidification of winter greenhouses [242]. An existing regular greenhouse could act as the mounting structure for PV panels, thereby reducing investment costs.

AV system design is most of all highly location specific. The energy generated from AV systems could benefit off-grid farmers, especially in developing countries [83]. H_2 generated from the AV systems could be used to power farm machinery. Beyond the farms, higher benefits could be achieved through the electrification of rural areas while excess energy can be sold to local communities. However, despite the synergies offered by AV systems, they remain a trade-off between energy yield and crop yield. This could lead to opposition to the implementation of AV projects. This opposition is being exacerbated by the expansion of ground-mounted PV systems, as they encroach on arable land, resulting in the loss of European Union CAP (common agricultural policy) subsidies for farmers and loss of biodiversity. Therefore, a legal framework which distinguishes AV systems from ground-mounted PV systems needs to be established. Similarly, minimum crop yield requirements need to be established for AV systems. It was proposed that yield reductions should not exceed 20% to ensure the general acceptance of AV systems [11]. This value was also echoed by Ref. [222]. The DIN SPEC 91434 highlights a maximum reduction of 34%. This lower boundary would eliminate systems wherein mainly PV energy is generated, with little regard to the crops and farming practices.

Agrivoltaics is pushing the frontiers of solar PV potential. The EU holds 1.6 million km^2 of agricultural land [44]. At an average power density of 0.6MWp/ha, utilizing just 2% of that area for agrivoltaics would yield 1900 GW of generating capacity, more than ten times the current PV capacity in the EU [44]. Green H_2 could be produced via electrolysis or H_2 panels. At an average 17% capacity factor, 0.6 MWp/ha translates to 0.09 GWh/ha. Considering an average H_2 production efficiency of 55 kWh/kg for most electrolyzers, one may expect 16 ton H_2/ha/year. Roughly 4% of the agricultural land would suffice to produce 100 Mton per year, the equivalent of all the natural gas consumption across the EU in 2022 [243]. Agrivoltaics could serve as the missing piece for reducing fossil fuel imports and reaching aggressive renewable energy targets.

3. Global impact of AV and current research gaps

AV has the potential to alleviate land use conflicts through dual land use for PV energy and food production. The second SDG "Zero Hunger" and the seventh SDG "Affordable and Clean Energy" compete for land, delay the installation of ground-mounted PV systems, and jeopardize clean energy targets of many countries. AV systems allow for simultaneous growth in both elements. AV also reduces evaporative land water loss and irrigation needs and allows collection of rain runoff, thereby bringing benefits in water management across the food-energy-water (FEW) nexus. This effect aligns AV with the sixth SDG "Clean Water and Sanitation". AV systems also open up diversified revenue sources for farmers and aid in quality job creation for local communities. This contributes to the objectives of the eight SDG "Decent Work and Economic Growth". Centrally however, the production of clean energy leads to decarbonization of the energy and agricultural sectors and aligns with the 13th SDG "Climate Action". The implementation of AV can help meet certain international climate change and energy transition frameworks such as the European Green Deal, the REPowerEU [244] and the 10-year National Energy and Climate Plans (NECP) or the Green New Deal of the USA [245], the 2030 Strategic Framework of the UK [246], the Pan-Canadian Framework on Clean Growth and Climate Change [247], and the Just Energy Transition Investment Plan (JET IP) of South Africa [248].

Another variant in land use competition is more apparent in regions with high population densities, levels of urbanization or fragmented landscapes. The implementation of AV systems could therefore reduce the added land use competition in these regions by fitting in smaller local niches. For more remote farming areas with poor grid connections, AV could provide the much-needed local energy production.

c-Si PV modules continue to dominate the global AV installed. More bifacial semitransparent c-Si PV modules are being implemented to increase the amount of useful radiation reaching the crops. This however leads to a tradeoff as the PV module efficiency reduces with transparency. Low PV module transparencies could also be complemented with the use of light diffusing technologies. Diffuse light is desirable in compact crop canopies as it penetrates lower crop layers and leads to a uniform spatial and temporal light distribution [249].

Further advancements in the light use efficiency in AV systems involve spectral-shifting and diffusing coatings on semitransparent c-Si PV modules. Low-emissivity coatings applied to the rear of PV modules present a future synergy. These coatings could be used in frost protection of crops, as they can reflect long wave infrared radiation back to the ground and the crops and reduce radiative cooling at night. However, the potential thermal impacts of these coatings on the PV cell temperature must be well studied for different climates.

While this review principally focusses on crop production under AV, a few AV studies have experimented with intensive animal farming. PV panels with aquatic animals accelerated fish growth rate and improved PV system efficiency by 30% due to evaporative cooling of the PV panels [250]. Studies on pasture raised lambs in Oregon (USA) reported similar growth rates with or without panels [87,251]. Sheep grazing in AV systems doubled the land use efficiency [252]. However, these findings should not be extrapolated to all regions across the world, as they are limited to a few case studies and animal types. Energy policy makers, farmers and PV installers should therefore set AV guidelines for solar grazing, which might be different for arable farming AV systems.

A further research gap of AV systems is their life cycle's total impact. To date, only a few case studies have been presented. For example, in AV solar grazing systems, the main greenhouse gas emissions are methane and nitrous oxide from manure and methane from enteric fermentation in ruminants [253]. In arable farming AV systems, greenhouse emission sources mainly arise from combustion of fossil fuels by farm machinery. Therefore, researchers need to carry out specific life cycle assessments and standards need to be set for different AV systems to better quantify the sustainability and environmental benefits of these systems.

Another area for further research is the implementation of water management systems in AV systems. The installation of PV panels above crops interferes with rainwater distribution. Furthermore, rainwater runoff off the edge of PV modules can cause soil erosion. Therefore, rainwater collection systems for irrigation need to be meticulously designed to avoid PV system damage.

This review does not provide findings or trends in the soiling of PV modules in AV systems. It is however expected that the soiling rate (dust accumulation) in AV systems is higher than in standard ground-mounted PV systems due to tilling and harvesting. However, the soiling rate in overhead systems is also expected to be higher than in interspace systems. If and how regular cleaning of the PV modules is required, or what adequate cleaning methods should be implemented remains unexplored. Further developments in anti-soiling or self-cleaning solar glass could reduce soiling rates in AV systems. Soiling prediction models and AV module degradation models different from standard ground-mounted PV systems need to be further developed and validated for different regions and based on the agricultural activity.

Current simulation methods for AV systems still use broadband solar spectrum and albedo values. More advanced computational simulation methods such as spectrally resolved ray tracing must be developed. Furthermore, the modelling and simulation of AV systems must also consider complex structures such as frames, mounting structures, and different crop shapes to accurately predict crop and energy yields.

The performance of PV modules and crops is highly temperature dependent. The efficiency of solar cells reduces with increasing temperature due to internal charge carrier recombination rates, caused by increased charge carrier concentrations [254]. Like PV panels, the rate of photosynthesis is affected by many environmental factors such as light intensity, CO_2 availability, humidity, and ambient temperature. Under elevated temperatures or water stress, the stomata close and inhibit gas exchange leading a lower biomass yield [255]. Elevated temperatures also increase soil water loss (evaporation) which reduces crop yield. The effects of temperature on various AV systems has been described in "1.0. Introduction". To mitigate the negative effects of temperature on crop and PV performance, a suitable AV system design, location, crop selection and irrigation systems should be implemented. In regions with high solar irradiation, a high PV array density could be implemented to reduce the crop canopy temperature. This is nevertheless dependent on the crop light requirements. High PV elevations would result in better PV panel convective cooling while low mounted modules are more dependent on evaporative cooling from crop transpiration [23]. Tracking systems could also be used to manage the microclimatic conditions based on crop needs. In addition to increasing PV panel efficiency, reduced temperature will increase the lifetime of the PV panels, increasing the AV system economic potential.

4. Conclusion and future research perspectives

The rising global population has led to increased need for food and energy, creating competition for land. Agrivoltaics systems have been proposed as a solution to increase the land-use efficiency by combining PV and agriculture. Partial shading of crops by PV panels leads to some yield losses, but may provide synergistic benefits, including crop protection from extreme weather conditions such as hail, frost, snow, and sunburn. PV panels can also reduce the system heat stress due to better convective cooling, reduced evapotranspiration, and rainwater collection. Despite these synergies, shading by PV panels reduces the light availability for crop photosynthesis and consequently biomass production. This research focused on developments and performance of different existing AV systems and crop responses to shading. Spatial and temporal heterogeneities in shading resulting from the PV panels can also affect the local microclimate. Possible reductions in yield could be offset by focusing AV on areas for shade-tolerant crops or adapted cultivars. A meta-analysis on crop-shade tolerance reveals that leafy vegetables and berries under semitransparent PV are currently most suitable for AV systems. More homogeneous spatial and temporal distribution of radiation could be realized by using tracking systems, diffusion films, spectral shifting or selective PV modules and modules with optimized cell spacing.

Many research areas of AV systems remain underexplored. First, a life cycle assessment standard is needed for different AV systems for crops and animals due to the dissimilar sources of greenhouse gas emission and energy requirements. Second, research should expand on AV solar grazing by monitoring the grazing patterns of various animals over different seasons and regions. This would allow for the expansion of AV to the vast land area where only extensive grazing is done. Third, very few AV systems have reported or implemented water management strategies. The implementation of rainwater collection mechanisms for irrigation or frost mitigation would be beneficial to regions with changing precipitation patterns, saline groundwater, or frequent droughts. Fourth, the soiling patterns and PV degradation models in AV systems are not yet well defined. Soiling models should be different for both overhead and interspace systems. Additionally, the implementation of spectrally resolved ray tracing in the optical models for AV systems is needed to determine the optimal spectral band distributions for optimum location-specific AV system design and wavelength selective module technology. Finally, to facilitate future AV roll-out, a legal framework for AV needs to be developed that integrates different stakeholders such as farmers, utility and distribution companies, local governments, and citizens. Only then can AV become an integral part of future agricultural systems, benefiting both sustainable food and renewable energy production.

Despite these research and policy gaps, AV aligns with many of the SDGs and the energy transition and decarbonization frameworks of many regions and countries across the world. Guidelines such as the DIN SPEC 91434 have been developed to ensure the proper implementation of AV. In France, the French Environment and Energy Management Agency has defined new standards for AV while Italy's Recovery and Resilience Plan is aimed at supporting AV development. The research in this study suggests that AV systems are market-ready in their current form for specific farming situations and regions (specific crops) but have a large potential for further development into other branches of agriculture and geographical locations.

Author contributions

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Funding

This work is funded by the European Union through the Horizon Europe Research and Innovation programme SYMBIOSYST under grant agreement no. 101096352 and the Horizon 2020 research and innovation programme HyPErFarm under grant agreement no. 101000828. This work is also funded by VLAIO (Flanders Innovation and Entrepreneurship) "TETRA" grant: HBC.2019.2049 ("Agrivoltaics") and an LA-traject grant HBC.2022.0920 ("Agri-PV: Gecombineerd fruit en groene stroom produceren"). This work is also funded by the Fonds Wetenschappelijk Onderzoek (FWO) through the SB PhD Fellowship under applicant number 1SHF024 N. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of this work.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Michael Daenen reports financial support was provided by European Union and by Fonds Wetenschappelijk Onderzoek. Bram Van de Poel reports financial support was provided by European Union and by Flanders Innovation & Entrepreneurship.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank Adolf Goetzberger (who passed away this year) for inspiration, one of the main conceptualizers of agrivoltaics. This work would not have been possible without the feedback and support of colleagues. Many thanks to Nikoleta Kyranaki and Sara Bouguerra as well as Cas Lavaert and Jan Cappelle for their feedback and valuable insight. Thanks go out to Marleen Gysen and Tom Schaeken (Boerenbond) as well as Kevin Linthoudt and An Olaerts (KU Leuven), Alois Huber (Krinner Solar), Andreas Steinhüser and Lisa Ruf (both from Fraunhofer ISE), Solar Power Europe, Ogbomo et al. and Puzant Ballozian (VDMA) for the use of their images. Graphical abstract icons are partially sourced from Noun Project (CC BY 3.0) (Travis Avery, Nithinan Tatah and Laymik) with thanks to Eva Vanden Broeck for assisting in image assembly.

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