agronomy

Review

Fruit Crop Species with Agrivoltaic Systems: A Critical Review

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Abstract: As the world seeks alternatives to fossil fuels, agrivoltaics offer a promising solution by integrating solar panels with farming practices. This review examines three key agrivoltaic setups—static tilted, full-sun tracking, and agronomic tracking—dissecting their engineering features' roles in optimizing both the electricity yield and the fruit productivity of some fruit crops. We emphasize the microclimatic modifications induced by agrivoltaic systems, mainly encompassing changes in solar radiation, air temperature, humidity, and wind. The data collected in this survey reveal a strong spatial heterogeneity distribution over different locations and a significant influence on fruit crops' growth, yield, and quality, with variations among species. Such findings on the overall performance recommend a 30% shading threshold to prevent substantial declines in fruit characteristics, i.e., fruit yield and quality. Shading conditions over this threshold influence the leaf morphophysiological characteristics, impacting the photosynthesis capacity and fruit dry matter accumulation. This emphasizes the importance of further investigation into spectral radiation quality and carbon assimilation kinetics as daily responses for different fruit species to be cultivated in such new environments. Starting from this point, this review underscores the need to extend studies on various fruit crops, particularly those cultivated in semi-arid horticultural regions (i.e., for saving water), and suggests the use of comprehensive and standardized indicators for comparability across studies. Finally, the authors conclude that engineering improvements, along with new research programs on agrivoltaic systems, could lead to agricultural, environmental, and economic sustainability, as well as their practical implementation and attractiveness to farmers in the coming years.

Keywords: fruit species; agrivoltaics; yield; physiological implication; quality; microclimate

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1. Introduction

Fossil fuel sources have been the main drivers of several human activities in the past and even in recent years. Ongoing intergovernmental policy targets are trying to optimize energy inputs as an urgent action to reduce reliance on them, but there are several feasibility concerns about the expected outcomes [1]. The rising frequency and intensity of conflicts, climate extremes, and economic shocks, along with escalating inequality, are impeding the decoupling from fossil fuels and the achievement of the global sustainable development goals [2]. This global situation dramatically affects the agricultural sector, in which progressive increases in smart farming technologies and mechanization require high energy demand, along with the agri-industrial sector for the processing of numerous agricultural products. Energy plays a direct role in all stages of agriculture, from plant production to the transportation of agricultural goods. Moreover, it exerts an indirect influence beyond the farm, encompassing the production and transportation of fertilizers, pesticides, and machineries, in addition to the processing steps. All these operational practices make up 30% of the world's energy use, and the entire agri-food chain still produces over one-third of all greenhouse gas emissions, as reported in recent studies [3–5]. Currently, in order to achieve the gradual diversification of energy sources used in (but not limited to) agriculture, renewable sources are greatly required and most necessary [6]. Various applications for biomass fuel products as a gasoline replacement in the agricultural chain or simply for electricity and heat production on-site have been described [7–9]. Alternative renewable solutions, such as solar and wind power, are considered reliable sources that align effectively with the mitigation purpose, thus possibly reducing over 53,000 metric tons of greenhouse gas emissions [3]. Photovoltaics (PVs) in particular are the leading renewable technology in the world due to a continuous decrease in their cost over the years, along with technological improvements in the manufacturing and installation of the panels. Thus, their large-scale production has become feasible, along with their integration on arable lands, as proposed by Goetzberger and Zastrow back in 1980 [10]. The theoretical concept is described as a complex system within agriculture where it is required to elevate the tilt-mounted panels on a stable support structure to optimize both the crop (primary use) and electricity yield (secondary use) [10]. Dupraz et al. [11] defined, for the first time, this hybrid combination as an agrivoltaic system (AV). This configuration enhances the land equivalent ratio as a key role to improve the productivity on the same land unit, even more so than agroforestry systems [11]. Recently, the success of AV implementation has led to new PV arrangements: mounted vertically on the ground or integrated into greenhouse roofs [12,13]. Under this perspective, a multidisciplinary study (involving photovoltaic technologies, agronomy, engineering, and the environment) needs to be formalized in view of the desired quality and yield goals [14].

To date, the coverage area of agrivoltaics is not sufficiently developed to generate adequate statistics on this aspect. Even countries utilizing this renewable source are not able to estimate the agrivoltaic power developed in their agricultural land nor the cultivation of each species as area covered.

In Italy, by 2021, about 1 million new photovoltaic systems (agricultural, residential, industrial, and tertiary) were installed in different regions (mainly southern), and the area taken up by ground-mounted systems was 152.1 square kilometers, accounting for just 0.05% of the national total area (https://www.enelgreenpower.com/media/news/2023/03/agrivoltaics-italy accessed on 16 March 2024). No specific information or data are available for the different crops cultivated beneath the panels, but the goal in Italy is the installation of agrivoltaic plants with 1.04 GW of additional energy production capacity by 30 June 2026.

Many of the agrivoltaic systems are still research sites or conventional agrivoltaic solar parks for enhancing pollination and livestock grazing, as is the case in USA. In the USA, the total registered agrivoltaics area includes 496 sites, reaching 8,2 GW, as reported by the latest survey [15]. The crop production is mostly oriented toward vegetable species (i.e., tomatoes, broccoli, peppers, lettuces, eggplant, radish, etc.), and fruits only include grapes, strawberries, and blueberries on a few operative sites and hectares [15].

Among other countries, Japan reported, in 2019, over 120 different crop species, including myoga ginger, Japanese cleyera, paddy rice, tea, blueberry, etc., to test 1992 agrivoltaic farms with an area of 560 ha, and fruit crops (grape, persimmon, blueberry, citrus) only on 11% of the surface [16].

By 2014, China country already reached 1.18 GW of electricity production, which is still increasing due to novel emerging technologies. Cultivation on the agrivoltaic farms includes crops like tea, grapes, kiwifruit, vegetables, and mushrooms [17].

In India, agrivoltaic farms are mainly devoted to experimental purposes with different crops, as is the case in Germany, which has vegetable crops, such as winter wheat, potato, and cabbage, but no fruit crops beneath the panels [17].

In France, the Energy Regulatory Commission allocated a total of 40 MW for agrivoltaic projects. This generation capacity is spread across 39 projects by the Sun'Agri company, which has installed 40 hectares of dynamic agrivoltaics and 100 MW of energy generation. Eight of the total number of sites are horticultural crops, including fruit species (i.e., peach, apricot, apple, cherry) and grape [18].

The emerging benefits reported in some studies could stimulate the application of agrivoltaics in view of also providing ecosystem services. Researchers have found increased floral abundance and a delay in bloom timing in partial-shade plots, which could have the potential to benefit late-season foragers in water-limited ecosystems [19]. Pollinator abundance, diversity, and richness were similar between full-sun and partial-shade plots and greater in both than in plots with full shade; moreover, pollinator–flower visitation rates did not differ among treatments [20]. Positive effects have been also reported for insect group diversity, native bee abundance, and total insect abundance, with the most noticeable temporal increases in native bee abundance thus acting as a pollinator support to proximal agricultural fields in rural landscapes [20]. Furthermore, AV implementation in arid and semi-arid regions may be an efficient tool to better manage soil moisture, irrigation water use, plant ecophysiological function, and plant biomass production, even extending the forage quality for some species over the season [21,22]. Additional studies have reported increases in both the soil moisture and biomass of grasses, and their combined production allowed for an increase in the total productivity per unit area up to 51% [22–24].

However, to reach the best combined results, the percentage of reduction of solar radiation for crops remains the main factor for the successful planning of promising agricultural activity (see Appendix A). In recent years, several studies have been performed mainly on horticultural (i.e., lettuces, cabbage, broccoli, eggplant, etc.) and arable crops (i.e., rice, wheat, maize, potato, etc.), with varying degrees of responsiveness to shade [25–29]. The suitability of AV configurations has also been tested on woody species (i.e., olive, pear) by simulations and modeling approaches [30–32]. Woody plants, such as fruit species, possess a phenotypic plasticity to rapidly cope with new and changing environmental conditions, and they may need a longer period to respond genetically to selective pressures than annuals, also because they are more likely to experience more environmental changes during their biologically longer cycle [33]. Shade can induce a radical but reversible decrease in flower and pod production in woody species, such as *Ulex europaeus* [33]. However, several comprehensive reviews on crop productivity have confirmed general profitability with no or limited effects on plant growth and quality with a shading cover ratio up to 25%, better water use efficiency for crops grown in dry land climates, a decrease in yield of around 14%, and a relative yield of >80% with respect to control [34,35]. Another review paper, based on a meta-analysis, revealed the positive effects of shade on yield responses using a crop-type approach. Berries, fruits, and fruity vegetables may experience increases in their harvestable yield under moderate shading conditions, i.e., 20–40% [36]. Overall, the findings of these studies maintain a high level of uncertainty due to scarce AV bibliographic resources on fruit tree species and the significant geographical/climatic variability among the experimental sites.

Nonetheless, as recent studies have reported, AV solutions on perennial crops may be successfully integrated as an efficient protection tool against the climatic stress conditions that often occur in a climate change scenario [25,37]. On the other hand, it is not possible to define a general threshold limit of shading that different species/cultivars of plants can tolerate without negative impacts on their yield since the results obtained are often contrasting [14]. In-depth analyses of AV system technologies (type of panels, height, tilt, etc.), species/cultivars, and season variability on the same site are necessary for this purpose [38].

To the best knowledge of the authors, there is no specialized review in the field of agrivoltaics related to fruit crops grown underneath an AV system. An overview of the main AV configurations is introduced in the first part of this review. In the second section and in Appendix A, we attempt to illustrate microclimatic alterations and the resulting impacts on fruit crop performance in terms of growth, yield, quality, and physiological implications.

2. Different Types of Agrivoltaic Systems

In the last decade, an exponential interest in AV has been observed, and a multitude of prototypes have been proposed worldwide thanks to the extreme flexibility of three-dimensional spatial patterns [14,39]. The main key features, including PVs' transparency, height, inter-row spacing ('pitch'), and tilt angle, provide crucial insight into enhancing either the PV system design or crop responses (Figure 1). For fruit crops (grapes, stone, pomes, and small fruits, etc.), eligible AV projects require an overhead configuration with a minimum above-ground height of 2 m to allow for the cultivation of tree species and essential agricultural (machinery) operations.

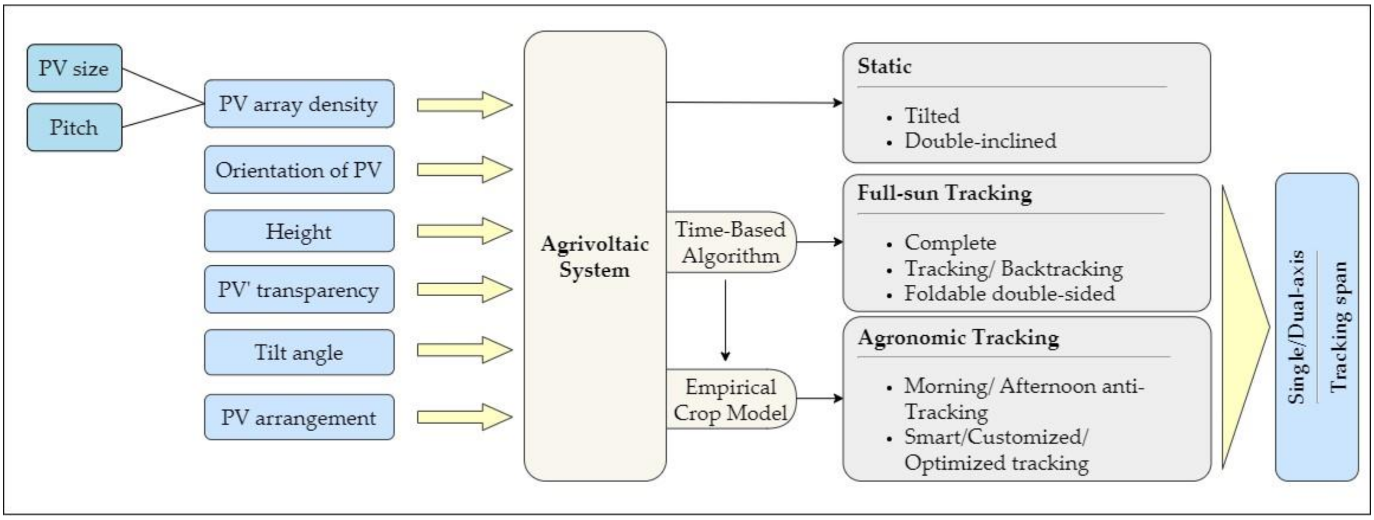

Figure 1. Schematic representation of emerging agrivoltaic system proposed for fruit crops.

From the prospective of engineering features, three horizontal schemes have been generally tested: static tilted, full-sun tracking, and agronomic tracking [35,40]. Ali Khan Niazi et al. [41] conducted a comparative study on photovoltaic configurations with an opaque bifacial structure (fixed size of the PV modules, and pitch = 6 m) and clearly analyzed the differences between the first two setups mentioned (Figure 2). The static setup casts a distinct pattern of stripes with a high level of shade intensity (only ≅56% of the incident radiation on the ground, pitch = 6 m) [40]. Furthermore, the distribution of the irradiance over the field shows heterogeneity in both space and time, with significantly lower light underneath the PV modules as compared to the inter-row open space [41,42]. In contrast, the full-sun single/dual-axis tracking system exposes the ground surface to continuously changing conditions (sunlight and shading), and consequently, the more homogeneous distribution of the shaded area has been addressed (narrower radiation distribution from 78% to 94%, pitch = 6 m) (Figure 2) [41,43].

Splitting the spatial features into their individual properties is the preferred solution to enable specific relationships between the geometrical parameters and the sunlight interception by the crop.

A preliminary evaluation on crop-specific responses to photosynthetically active radiation (PAR) reduction should test PV arrays with different densities. Assuming a standardized size of the panels, the pitch size (inter-row space) determines three conventional density types: full (pitch = 2), half (pitch = 4), and one-third (pitch = 6).

By varying the pitch to a greater or lesser extent, the daily PAR amount may satisfy the crop requirement, maintaining a full yield, or in contrast, may be potentially compromised [44]. However, despite its primary importance in the setup configuration, a combination of technical features and solar spectral properties (PAR decomposition) are involved in shading at the crop level and the consequent yield/quality performance.

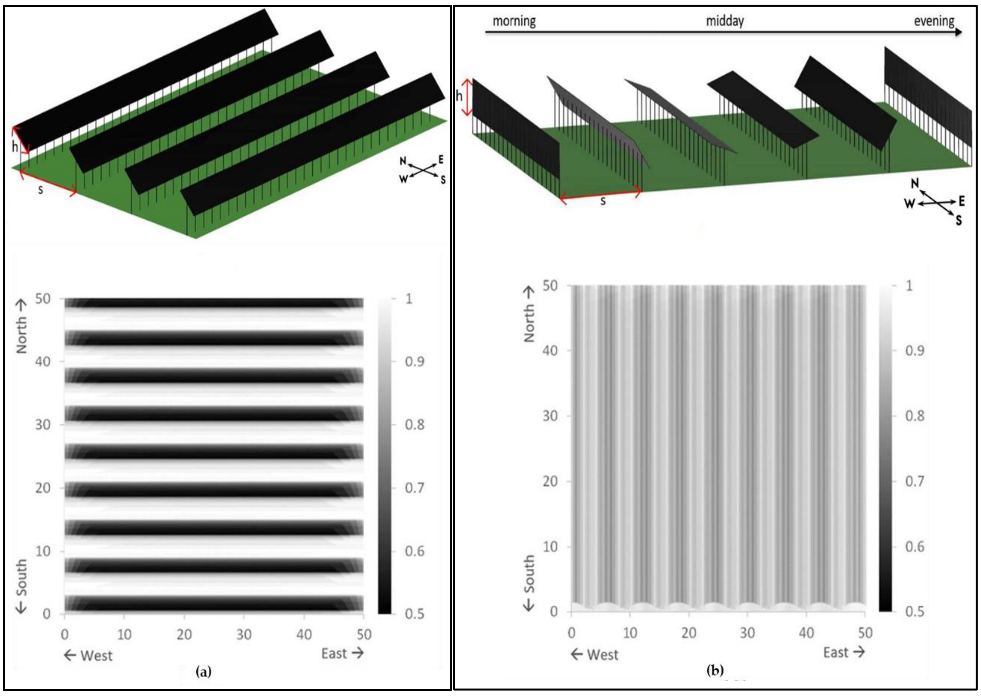

Figure 2. Solar PV configurations and ground shade pattern analyzed in this work for fruit trees: (**a**) static with optimal tilt, (**b**) single-axis horizontal tracking. The parameters of inter-row spacing (s) and height of the panels (h) are shown in the figure. Adapted from [41].

The second most relevant design feature is the orientation of PV modules as strictly related to the density pattern and orchard layout [43]. As can be seen (Figures 2 and 3a), a static model with both a typical N/S orientation for maximizing electric energy generation (in the Northern Hemisphere) and a tilt angle generally set based on the latitude is commonly adopted [41]. In this conventional setup type, the N/S tree distribution of the orchard is the proposed solution by the field experiment in Figure 3a. Species characterized by a vertical training system (i.e., palmette, cordon, espalier, etc.) experience a shaded area in one portion of the canopy (i.e., below the panels) and strong variation in the PAR pattern throughout both the season and day. The commonly adopted south-facing fixed-tilt PV modules result in a high spatial contrast, i.e., a significantly lower PAR underneath the PV modules with respect to the portions between the modules [42]. Conversely, another setup applied to a pear orchard has installed a static semitransparent double-inclined PV structure aligned to the tree row [32]. In this case, the application of crystalline silicon modules (with a 40% transparency level) was the recommended solution since they lead to more homogeneous light distribution with almost complete protection from unfavorable weather conditions, preserving reliable energy production (570 MWh/ha) [32,45]. Further confirmation on the latter point was also reported in a grapevine experiment, which showed sufficient power generation when comparing transparent to normal and bifacial modules over a period of seven months [46]. However, with regard to fruit tree species, we must keep in mind the different trellising systems that can be adopted, from a very continuous canopy (i.e., hedgerow palmette) to a discontinuous canopy (i.e., open vase configuration) and the consequent density of the canopy, which is very thin for a palmette or a spindle and much thicker for a vase or a globe.

Thanks to this high potential in energy concentration, several companies and research studies (Figure 3a–c) are trying to evaluate the application of PVs for pome fruits, berries, and grape by fine tuning the cell density and transmittance level [45]. However, the economic viability of its large-scale application remains unclear [32].

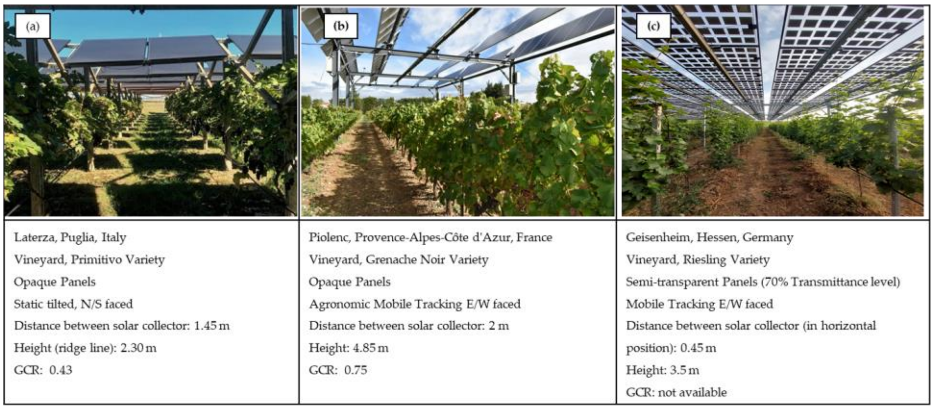

Figure 3. Three AV experimental sites with wine grape cultivation (**a**) . Static panels at height 2.30 m, ground coverage ratio (GCR) 0.43, and N/S oriented in Italy, (**b**) tracking panels at height 4.85 m, GCR 0.75, and E/W oriented in France, (**c**) tracking panels at height 3.50 m, GCR not available, and E/W oriented in Germany.

Regarding the height of the modules, there is a correlation between increases in the module height and shifts in the shaded area away from the space beneath the PV panels and closer to the ground the panels are, the higher the heterogeneity of radiation over the crops in the same land unit will be [14]. To this extent, a simulation-based study examined different heights, in the range 3.0–4.5 m, of static bifacial modules positioned between the tree rows of three olive cultivars [31]. The PV energy yield was maximized when the tilt angle was close to the latitude of the site, whereas a vertical inclination was optimal for maximizing the yield of the olive trees. With regard to the height, the results indicated that PV modules had the best impact on crop yield at 3 m. The variation in the tilt angle had a greater impact on the PV yield, while the variation in the PV module height primarily affected the yield of the olive trees [31]. However, the simulation provided by the study had difficulties in properly assessing the productivity estimation without direct and diffuse PAR decomposition during the day [47].

Concerning the full-sun tracking method, the single/dual-axis tracking system optimizes the angle of incidence of sun rays during the day, maximizing electrical production. The main options are based on testing the most appropriate orientation between N/S- and E/W-facing PV modules. A model analysis proposed by Tahir et al. [42] assessed that N/S orientation resulted in a good trade-off between the crop requirements and energy production. Unfortunately, no crop description is provided in the literature for this specific tracking scheme. For comparison, tracking in the E/W direction has the highest power production among the various AV commercial schemes [42]. PV modules are generally mounted in the E/W orientation, facing east in the morning, horizontal at noon, and west in the evening. The tree rows aligned to the panels experienced a large PAR fluctuation throughout the day, reaching a peak of photosynthetic deficit around noon [42,48]. Casares de la Torre et al. [49] reported a simulation study that considered hedgerow trees between trackers and a backtracking solution to limit the shading between panels. According to this strategy, PV modules are forced to move closer to the horizontal position at the beginning and the end of the day without significantly affecting either the irradiance or the tracking mechanism [49]. However, it is worth noting that light computation was quantified by module interception only, and experimental validation in the field was not performed.

A previous examination of the full tracking algorithm was recently applied to a foldable double-sided PV structure. The study by Lama et al. [50] investigated the effectiveness of a foldable solar panel system equipped with a dynamic tracking algorithm. By adjusting the tilt angles to improve the solar exposure, energy efficiency outperformed the static-based modules by 15%, with consistent power gain during the day [50]. Conversely, panels may provide direct protection from extreme climate conditions by reverting to the minimum tilt angle (an almost horizontal position). This is an effective solution for fruit crops that should be better evaluated by in situ measurements, and although shaded areas occur in the early morning and late evening, this system can be an effective solution for creating favorable microclimates for various crops [50], mainly in dry climates.

A sector of relatively new techniques may be grouped under the name of agronomic tracking. The main approach involves the traditional sun tracking algorithm equipped with an empirical crop model. This helps to optimize the real-time orientation of panels, maximizing the energy benefit and ensuring a period of direct light exposure on the crop during critical phenological stages [37,51]. Such an application to light-sensitive crops, such as many fruit species (e.g., olive, fig, pomegranate), may ensure regular yields, thus increasing land productivity and a slightly reduced PV power yield. A reduction in power generation during anti-tracking times (the most sensitive phenological stages) would allow for 86.71% more power generation over a year compared to solar tracking [35,52]. In particular, a critical anti-tracking algorithm measures incoming short-wave solar radiation, which, below a set threshold, selects the angle for the minimum shaded area, thus allowing for PAR flux during critical phenological stages [52].

Despite their commercial purposes, the Sun'Agri company designed an agronomic model specifically to be implemented for the management of solar panels in fruit orchards [36,51]. Their design solution consists of single-axis opaque panels aligned with the tree row direction (Figure 3b) and a rotation angle of ±90°, which allows for complete solar tracking or anti-tracking positions. Looking to the experimental findings provided by their virtual simulations, the best-performing solution combines an anti-tracking strategy in the morning and sun-tracking in the afternoon. Shading in the afternoon is slightly beneficial compared to shading in the morning according to the photosynthesis and canopy temperature output indicators of the simulation model [37]. However, there is a gap in PV performance and energy yield provided by this solution.

Along the same research line, Willockx et al. [53] proposed an agronomic tracking solution with a slight tracking span (±50°) based on an empirical crop model that utilizes radiation use efficiency to simulate crop yield and quality. With smart tracking, a trade-off between sun-tracking (energy yield) and anti-tracking (crop yield) is achieved based on the daily PAR and energy production [53]. The authors reported a significant increase in energy yield (+30%) while maintaining a comparable crop yield.

3. Panels and Fruit Species: A New Agricultural System

The positive adoption of solar PV use in orchards can also be found in the possibility of partially replacing the current common practice of using plastic cover/net protections for a wide range of climate hazards (heavy rainfall, rain, sunburn, hail, etc.) [37]. However, instead of temporary protection devices, AV systems introduce a permanent anchoring (concrete or reversible) of the mounting structure. This imposes an important issue regarding the microenvironment, crop productivity, and fruit quality, which is discussed within this section.

3.1. Microclimatic Conditions under the Panels

Several mechanisms related to the technological implementation of a PV structure (opaque, semi-transparent) as a spatial configuration and its geographic location may significantly modify the microclimate beneath the panels (such as the wind, temperature, and humidity of both the soil and air). Another crucial factor to be taken into account is the placement of sensors for monitoring the microclimate underneath the modules [32]. For reasons of comparability, only shading experiments focusing on fruit crops have been effectively carried out and discussed.

The reduction in solar radiation reaching the canopy underneath PV modules (shading) is the most apparent change occurring in these new agricultural systems, deeply affecting fruit crop yield. This reduction directly influences the air temperature and humidity together with the soil temperature and humidity. With regard to the air, significant changes/reductions of up to 4 °C in the daily fluctuations have been observed in some studies [48,54,55], whereas there was almost no variation in a study on kiwifruit in China [56]. The latter results are a little surprising and difficult to compare with other findings unless a wind-speed measurement is conducted. As argued by Willockx et al. [32], the temperature difference is highly sensitive to the wind speed [32]. The knowledge of the wind load in the agricultural area is also essential for the optimal stability of the structure bearing the panels [32]. The difference in temperature can be explained by two effects: (1) the studies were performed under different climatic/agronomic/structural conditions, and (2) the measurements were taken at different height positions. Solar panels mounted at 4 m with vegetation (soybean) underneath reduced the temperature by up to 10 °C compared to panels mounted at 0.5 m over bare soil; the ground conditions and panel heights play important roles in the microclimate of agrivoltaic systems [57]. A moderate wind speed and the height of a mounting structure beyond a specific range suitable for fruit crops (i.e., 2.5–4.5 m) significantly influenced both the air and ground temperature distribution, as well as the flow penetration of the wind itself [57]. This suggests a change in the soil/tree energy balance, which requires a holistic understanding of the local microclimate dynamic and the implementation of thermal–fluid models [32,57]. The distribution of the wind direction was significantly altered at all heights by the solar panels in an unirrigated pasture, and the mean wind speed was significantly different at all heights, with a general reorientation perpendicular to the solar array's rows [23].

Sensitivity to summer heatwaves and spring frost events could be managed effectively by static panels aligned with tree rows or tilting the panels to the horizontal position. A dampening effect has been detected in the maximum and minimum values during hot summer days and cold nights with a cloudless sky, preventing or reducing damages from summer heatwaves and spring frost events [32,37,58]. However, a high density of panels is required for a fully protective effect.

Numerous studies deployed on arable and horticultural crops have reported an increase in the air humidity under AV [59,60]. These results are in agreement with the values reported for permanent and woody crops, in which the air humidity became higher beneath the panels [48,56]. In particular, for kiwifruit, the relative humidity became higher with increased levels of shading [56], and in an apple orchard, a general increase was detected around midday [48]. This may be beneficial for species with high humidity requirements, such as kiwifruit, but it can also become problematic, with a potential risk of pest outbreaks (fungal diseases) for other fruit species.

While air patterns tend to be more referenced, only very few studies have addressed the impact of these environmental drivers on the soil. Because fruit trees are perennial crops, the soil is an important factor directly affecting root growth, budbreak, water, and nutrient uptake for several seasons. Cho et al. [46] found in a vineyard a higher average temperature of about 2 °C in spring and winter and no difference in August compared to the control site. For the same species, by contrast, two other studies showed a temperature reduction of 1–3 °C under shaded areas compared to full-sun conditions [55,61]. This inconsistency may be due to, apart from the different pedo-climatic conditions of the sites, different PV transparency levels and spacing, affecting both the portion of transmitted irradiation and the temperature of the soil itself.

The impact of PV coverage seems to also be positive for soil water savings. Experiments conducted on grape and cranberries suggest the panels' positive role on the soil moisture retention, especially on cooler days and after irrigation [54,55]. Furthermore, careful consideration must be given to the panel-induced heterogeneity of the moisture distribution in the soil, an aspect that requires further investigations since it is typically a strong predictor of productivity [22]. In terms of evapotranspiration, a reduction in atmospheric water demand has recently been reported, even in years with low precipitation [62]. Similarly, a model evaluation for arid and semi-arid environments predicted a reduction in crop water consumption by 30–40% for static arrays with a 50% shading rate [63].

3.2. Fruit Crop Performance and Quality

With respect to arable and horticultural crops, a consistently low number of fruit tree species have been subjected to AV studies focusing on growth, yield, and quality (Table 1). Studies on some fruit species have been mostly carried out under 30- 60% shade, with yield losses ranging from 16 to 42% (Figure 4). Cranberries were most negatively affected than other species with regard to their total productivity when a moderate shading level was present [54]. With a lower shading rate, the average yield drop for kiwifruit and apple was approximately 29% when using semitransparent and opaque PV configuration types [56,58]. An exception can be made for pear orchards based on an estimation model that showed they performed better than the species mentioned above, with only a 16% yield reduction predicted [32]. A similar slight reduction (15%) was recorded for wine grape under a shading rate of more than 60% by a trial in Italy [55]. For severe shading levels, comparable studies are not available in the literature on other fruit species, nor has consistency been detected in yield decreases with increasing shade intensity [35].

Nevertheless, under low–moderate shading percentages (≈30%), crops behave moderately well, productivity is maintained or only a little affected (5%), and yield components are scarcely influenced, thus ensuring good marketable production for the farmers [46,56,61]. By contrast, over this threshold, studies show declines in the mass, size, and number of fruits to different extents [32,48,54–56].

Leaf morpho-physiological characteristics also seem to be affected by light shortage under either moderate or high shading conditions (≥30%), increasing the individual specific leaf area for intercepting more light [48,56]. However, the photosynthesis capacity was generally reduced with higher shading (38%) of kiwifruit, with the yield lowered from 26 to 39% [56], and a reduction of 18% in the photosynthetic activity for irradiances over 1000 $\mu mol/m^2/s$ was noticed for apple [48]. In the case of wine grape, photosynthetic activity was reduced by around 40% in the morning but became higher around midday [55], and shading protected the crop from excessive radiation, thus showing a better performance at midday with respect to full sun vines. The shading of panels may not be a negative factor for fruit species that exhibit alternate bearing behavior, like apple [48]. Shading effects on flowers and young fruit could naturally regulate the floribundity of several species, positively influencing the yield load over years, as reported by Juillion et al. [48], with a consequent reduction in the alternate bearing. Decreases in carbon fixation and allocation also impacts several quality parameters at harvest, such as the volume of the fruit [56]. With values of shading above 30% and conventional opaque PV modules, effects on starch, total soluble sugars, and acidity have generally been confirmed, with decreases in the starch to sugar accumulation and the sugar/acid ratio [54,55,58]. An acceptable explanation of the low soluble sugars and starch concentrations in apple fruits is that they are caused by the dilution effect of water, possibly due to a more comfortable water status under the shaded environment compared to the control treatment (more water entering the fruit) and reduced incoming carbon flows [58]. Similar effects were validated for a model of semitransparent PV panels, proving a coherent pattern for pome fruits [32].

In addition, it is worth noting that there are some berry fruits (i.e., raspberries and blueberries) that are deemed to be compatible with higher shading conditions, and in turn, are able to maintain relevant quality traits and yields [35,64]. The above statements are supported by a preliminary study only; more confirmation of the potential benefits of shade on such species should be provided in more comprehensive works.

Table 1. Scientific publications involving fruit species grown under agrivoltaic systems.

Fruit Crop Tested	Location	Type of Panels	Structure	Ground Coverage Ratio	Shading Rate (%)	Energy Production	Remarks		References
							Yield	Fruit Quality	
Apple	Mallemort, France	Single-axis horizontal, adaptive solar tracking	Opaque	0.43	42%	-	Yield reduction from 27 to 32%, alternate bearing reduction	Minimum standard reached, but lower sugar concentration	[48,58,65]
Pear	Bierbeek, Belgium	double-sided, static, inclined	Semitransparent	0.6	35%	950 kWh/kWp	A 16% yield reduction (estimation)	Similar quality (estimation)	[32]
Grape	Valpolicella, Italy	Static, tilted	Opaque	-	75%	-	Observed a decrease in yield, at least in two years	Total soluble solids were lower, reduction in both polyphenols and anthocyanins	[55]
Grape	Yeongheung, South Korea	Static, tilted	Opaque	-	<30%	-	Not significantly affected	Did not affect sugar content or anthocyanins, delay in skin coloration	[61]
Grape	Gyeongsan, South Korea	Static on umbrella-shaped facility, tilted	Opaque, bifacial, semitransparent	-	≤30%	Opaque: 25.2 MWh Bifacial: 21.6 MWh Semi-transparent: 25.7 MWh	Not available (berry weight and number not affected except for opaque type)	Similar sugar-content level, delay in coloration	[46]
Kiwifruit	Puijiang County, China	Static, tilted	Semitransparent	0.15; 0.25; 0.31	19%; 30.4%, 38%	-	Remarkable yield reduction	Fruit volume reduction	[56]
Cranberries	Massachusetts, USA	Fixed	Plywood sheet	-	29.3–41.5%	-	Significantly reduced yield	Significantly reduced fruit firmness and total soluble solids, skin color not affected	[54]

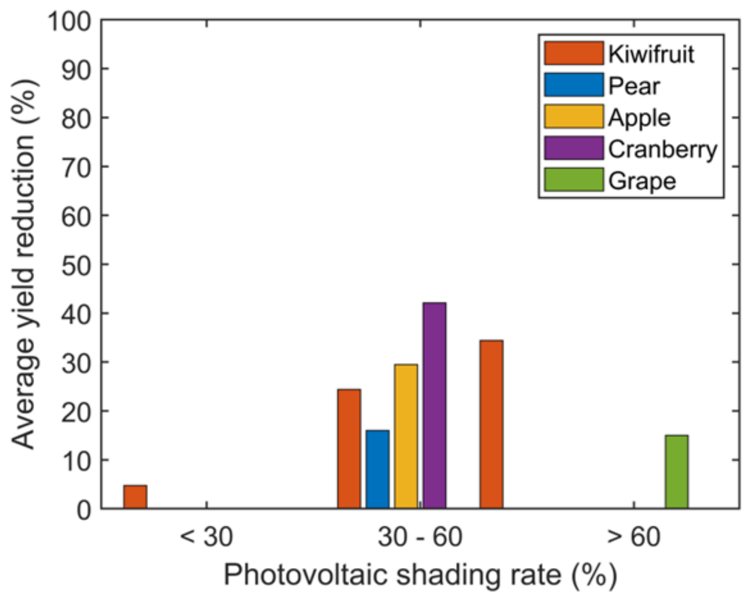

Figure 4. The average yield reduction of fruit crops depending on the photovoltaic shading rate.

Regarding the skin color of fruits, influenced by compounds such as anthocyanins, carotenoids and polyphenols, the results indicate a high sensitivity to environmental changes [65]. Even for low degrees of shading, the commercial color of grape clusters has been reached with a 10-day delay in response to radiation and temperature reduction in two South Korean experiments [46,61]. Likewise, apples and grape in Mediterranean regions were greener at harvest because of shading [55,65].

As suggested by Rosati et al. [66], to shine more light on these responses, the quality aspects of spectral radiation, even under opaque panels, should be investigated since panels affect the radiation quality (i.e., higher R/FR and B fraction under PV panels).

Lastly, it may be interesting to evaluate consumers' acceptance and appreciation of these fruits considering their organoleptic and flesh texture modifications described so far [58].

4. Conclusions

The global interest in the agrivoltaic sector is growing, with significant and accelerated progress in emerging PV technologies and engineering design configurations. However, these advancements are deflected by limited investigations into agricultural performance, especially regarding fruit crop cultivation.

The majority of case studies have used simulation models or literature classification to define crop sensitivity to shade under the proposed agrivoltaic design solutions. However, accurate analyses of fruit species' suitability are clearly site- and structure-dependent, as the strong variations in crop yield performance have confirmed. Panel discontinuity, the height of the mounting structures, the tracking strategy, and their geographical location induce microclimate pattern heterogeneity in the light, air temperature, wind speed and direction, and air humidity, even during the course of the day, in addition to changes in the soil parameters (temperature, humidity). For the elements mentioned above, AV systems are conceptually distant from greenhouse-controlled environments, necessitating a novel agronomic-based approach to design structures (i.e., pest management, mechanical harvest, etc.). The implementation of standardized microclimatic measurements for better comparisons and the application of the ground coverage ratio with additional structural criteria (i.e., panel elevation and tilt angle) could be useful for comparability purposes.

Thus, the shading threshold of 30% for fruit tree cultivation, as suggested in the current review, to prevent significant decline in fruit mass, size, and numbers, could be revised in the future. The evaluation of different fruit species under arid and semi-arid conditions, which face extreme climate change (i.e., the Mediterranean basin, etc.), could contribute to the more sustainable development of agrivoltaic systems. To the same extent, more elucidations should be provided on the effects on tree physiology of the modified wavelength spectra composition and their implications for carbohydrates, acid kinetics, and metabolic compounds (i.e., polyphenols, anthocyanins). Investing in these aspects can help to integrate smart agrivoltaic tools that use dual-axis tracking, real-time data as a tilting strategy, tunable spectral-splitting modules, and PV-integrated plant health-monitoring sensors, for example. These improvements move the design of AVs to upper levels and enable the full potential of agrivoltaic suitability, customizing the systems for specific crop requirements and environments. Reaching this high potential also means ensuring the environmental and economic sustainability of the systems, their practical implementation and application, their attractiveness for farmers, and lastly, their acceptance by consumers. In the future, all these promising perspectives will allow for applying the concept of sharing agricultural soil with panels and developing a well-integrated dual model with synergistic benefits for the agricultural land while possibly mitigating the effects of climate change.

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Appendix A

Responses of Fruit Crops to Light Reduction

Light is the main necessary resource for the growth and development of a fruit tree, as we described previously in the article. It also plays an important role in the formation, development, and quality of fruit. Its behavior is a species-specific factor since excess or deficiency can be beneficial or detrimental to a crop. A summary of the productive, qualitative, and physiological implications of high-shading conditions for some fruit crops are detailed in Table A1. However, the effects reported are related to shading with the application of nets, and the results may somewhat differ for AV systems. The light requirement at the saturation point and the maximum photosynthetic level associated with full-sun conditions are also reported for better comprehension.

Table A1. Effects of shading net applications on the physiological, photosynthetic, vegetative, productive, and qualitative aspects of different fruit species to be possibly grown beneath PV panels. Data could be used for comparison with the light reduction from AV systems.

Fruit Crop	Light Saturation Point (µmol Photon m^{-2} s^{-1})	Maximum Photosynthesis (µmol CO_2 m^{-2} s^{-1})	PAR Reduction	Photosynthesis	Vegetative Growth	Reproductive Growth	SSC	Acidity	Ref.
Apple	1200–1600	15–20	(Shading net)	↑		No difference to number of fruits	↑/↓	No diff/↓	[67,68]
Grape	1500	10–15	50% (Shading net)	No diff	↑		↓	↑	[69,70]
Citrus (lemon, orange, mandarin)	750–1000	15–22	40–50% (Shading net)	No diff/↑	Taller trees, high leaf number	Low fruit set and number of fruits		↑	[67,69–71]
Kiwifruit	600–960	12–15	(Grey nets)		High number of long shoots	Decrease in fruit production	↑		[67,72]
Pomegranate	-	-	50% (Shading net)			Increased fruit weight and yield	↓	↓	[67,69]
Peach, nectarine, cherry	800–1200	7–15			↑	Enhanced fruit growth rates			[73,74]
Fig	700–1600	12–20 (or higher)	(Shading net)			Prolonged storage life of fresh fruits			[75–77]
Blackberry	750–1000	7–18	40% (Shading net)	↓	Increase in dry matter and length of canes	Longer harvesting period, higher yield	No diff	No diff	[78,79]

↑ = Increase; ↓ = decrease; No diff = no difference; SSC = soluble solid content.

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