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Review

Fruit Crop Species for Agrivoltaic Systems: State of the Art

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Abstract: This review explores the combination of renewable energy production and agriculture through agrivoltaic, with a focus on its impact on fruit crops. As the world seeks alternatives to fossil fuels, agrivoltaics offers a promising solution by integrating solar panels with farming practices. The study examines various agrivoltaic configurations with different fruit crops, emphasizing their influence on microclimatic conditions beneath the panels and the effects on crop production. In particular, it underscores the need for tailored solutions to balance energy yield and crop productivity and quality, with different shading levels affecting fruit quality/production. Despite ongoing research, a comprehensive understanding of agrivoltaics' potential benefits and challenges remains crucial for its successful application and implementation in sustainable agriculture.

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

1. Introduction

Fossil fuel sources have been the main drivers for several human activities in the past and even in the recent years. Continued intergovernmental policy targets try to optimize energy inputs as urgent actions for reducing its reliance but with several feasibility concerns on expected outcomes [1]. Rising frequency and intensity of conflicts, climate extremes, and economic shocks, along with escalating inequality, are impeding the fossil fuel decoupling and the achieving of sustainable development global goals [2]. This pattern invests even the agricultural sector in which the progressive increase in smart farming technologies and mechanization requires high energy demand not to mention the industrial sector. Energy plays a direct role in all stages of agriculture, from plant production to transportation of agricultural goods. Simultaneously, it exerts an indirect influence beyond the farm, encompassing the production and transportation of fertilizers, pesticides, and machineries. All these operational practices cost 30% of the world's energy along the entire agri-food chain and produce still over one-third in greenhouse gas emissions as recent studies confirmed [3–5]. Currently, in order to meet a gradual diversification of energy sources used (not only) in agriculture, renewable sources are much required [6]. Various applications exert biomass fuel product as gasoline replacement in the chain or simply for electricity and heat production on-site [7–9]. Alternative renewable solutions, as solar and wind power are considered reliable sources that align effectively with the mitigation purpose reducing over 53,000 metric tons of GHG emissions [3]. Photovoltaics (PV) in particular, are the leading renewable technologies in the world due to continuous decrease in costs over the years along with technological improvements in manufacturing and installation. The theoretical concept is described as a complex system in which agriculture just required elevating the tilt-mounted panels on a stable support structure to optimize both crop (primary use) and electricity yield (secondary use). [10] defined for the first time the hybrid combination agrivoltaic system (AV). This configuration enhancing the increased land use efficiency as key role to improve productivity on the same land unit, even better than agroforestry systems [10]. Nowadays, the success of AV implementation has opened new PV arrangements: mounted vertically on the ground or integrated into greenhouse roofs [11,12]. Under this perspective, a multidisciplinary study (photovoltaic technology, agronomy, engineering) needs to be formalized in view of desired quality objectives [13].

Unused or underutilized drylands/ marginal lands could be potentially restored as productive agricultural lands covering the challenges of loss of cultivable areas [14–16].

However, to ensure all these mentioned purposes the reduction of solar radiation for the crops remain the main crucial factor for a successful planning of a promising agricultural activity. In the recent years, several studies focused on horticultural (i.e., lettuces, tomatoes, broccoli, eggplant etc.) and arable crops (i.e., rice, wheat, maize, potato etc.), showing a general profitability from the application of AV systems [17]. Most of these preliminary works have focused on simulations and modelling [18]. More recently, empirical results confirm such profitability maintained up to 25% of shading cover ratio and decrease in yield on around 14% [19,20]. A study on meta-analysis revealed interesting benefit effect on yield responses with shade considering a crop type approach. Berries, fruits, and fruits vegetables may experience increase in harvestable yield under moderate shading conditions [21], however a limited amount of data is available on many crops. Based on their physiological behavior, majority of fruit tree species are generally classified as shade-intolerant crops [22]. Such aspect can partly be justified by long-term yield drawbacks that could be significantly detrimental over years of excessive shade exposition [23].

Nevertheless, as recent studies demonstrated, AV solutions on perennial crops may be successfully integrate as an efficient protection tool against climatic stress conditions often occurring in a climate change scenario [17,24]. On the other hand, no specific guidelines have been developed for defining the productive tolerance threshold over years and in-depth analysis and testing of AV system technologies (panels, height, tilt, etc.) are necessary for the purpose (Figure 1) [13].

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

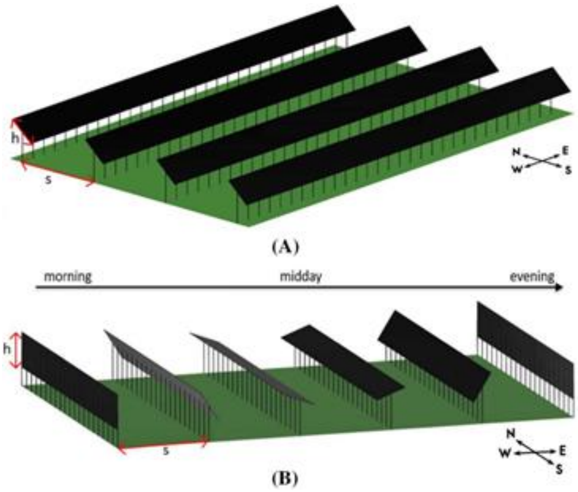

Figure 1. Solar PV configurations analyzed in this work for fruit trees: (A) static with optimal tilt, (B) single-axis horizontal tracking. The parameters inter-row spacing s and height h are shown in the figure. Adapted from Ali Khan Niazi & Victoria (2023).

2. Different types of agrivoltaic systems

In the last decade, an exponential progress of AV systems was observed, and a multitude of prototypes proposed worldwide thanks to the flexibility of the PV technologies [13,25]. Crop-specific structural criteria may be used to qualify an AV project and each spatial features (PV' arrays' transparency, size, height and spacing). To date, the research studies in the field of fruit crops cultivation (grapes, pome and stone fruit species, small fruits, etc.) are conducted on overhead configurations. For this purpose, an elevated support structure at a height of 2 meters or more is required to allow tree cultivation and machinery operation. The type of panel arrangement is determined among static tilted, mobile solar tracking, and mobile crop adaptive tracking [20,26]. Assuming an opaque panel structure, differences may be primarily related to the technical configuration (mounting structure added to the shade of the panels) that could affects shadow distribution underneath the panels and electricity generation. The static setup casts a distinct pattern of stripes with high level of shade intensity (only ≅56% of incident radiation on the ground). Furthermore, the distribution of the irradiance shows heterogeneity in both space and time with some area of the field experiencing significantly more shade than others. On the contrary, the dynamic configuration has a narrower span of available irradiance (from 78% to 94%) and a more homogeneous distribution over the field [27].

Another design related feature is the orientation and the height of PV. As can be seen (Figures 1 and 2), the static one facing a typical south orientation for maximizing electric energy generation (in the Northern Hemisphere) and a tilt angle variation that depends on the latitude. On this setup type, north-south tree distribution of the orchard is the proposed solution by majority of experimentations. Thereby, the trees can experience a partial shade portion of the canopy. Regarding the sun-tracking system, it is generally mounted on North/South direction facing east in the morning, horizontal at noon, and west in the evening. The tree rows could be aligned to the panels' orientation under or between the row based on shade crop sensitiveness and spacing required. In this regard, [28] proposed a simulation on backtracking strategy for hedgerow trees between trackers. According to this study, the tree crop production benefits from partial interrow shading without affecting the irradiance capture or the tracking mechanism. Moreover, from an energy point of view, the single-axis tracking/backtracking installation performs better electricity yield versus static schemes [27,29].

One attractive solution for tree cultivation is the agronomical tracking. Such advanced tracking is not a conventional system, and it provides more light to crops during light-demanding phenological stages. [20] proposed a conceptual analysis which estimates annual shade reduction on crops by 10% which would induce an increase in relative yield by 8%, assuming a period of direct light exposure two months per year. However, a technical description for both energy and shading comparison is still lacking. A similar approach would be employed on fruit crops by applying the smart-tracking strategy. During smart tracking, a trade-off between tracking (energy yield) and anti-tracking (crop yield) is achieved based on daily photosynthetic and energy production [30]. The author reveals a significant increase in energy yield (+30%) while maintaining comparable crop yield, although this technique has not been applied to fruit crops in any experiments yet.

Laterza, Apulia, Italy	Piolenc, Provence-Alpes-Côte d'Azur, France
Vineyard, Primitivo Variety	Vineyard, Grenache noir Variety
Static tilted, N/S faced	Agronomic Mobile Tracking E/W faced
Distance between solar collector: 1 m	Distance between solar collector: 2 m
Height: 2 m	Height: 4.85 m
GCR:	GCR: 0.75

Figure 2. Two AV experimental sites on vineyards in Italy and France respectively.

3. Panels and fruit species: a new agricultural system

The positive adoption of solar PV use in orchard crop can be found in the possibility of replacing plastic cover protection as a current common practice towards a wide range of climate hazard (heavy rainfall, rain, sunburn, hail, etc.) [24]. However, instead of temporary plastic frame, AV systems introduce a permanent fixation of the structure with effects on microclimatic conditions in the orchard.

3.1. Microclimatic condition under the panels

Several mechanisms related to technology implementation of the PV structure (opaque, checkerboard, semi-transparent) as spatial configuration and geographic location may modify considerably the microclimate beneath the panels (such as wind, temperature, and humidity of soil and air). Another factor included is the placement of monitoring systems with respect to different crops [31].

The reduction in solar radiation (shading) underneath the AV canopy is the most apparent change occurring in these new agricultural systems. This, in turn, directly influences air temperature. Significant changes /reductions in the daily fluctuations are observed up to 4 °C in some studies [32–34]. Depending on short wave radiation transmitted, the dampening is more pronounced in maximum and minimum values during hot days and cold nights of cloudless sky, preventing damages from summer heatwave and spring frost events, respectively [24,31]. According to this, one set-up placed in China with kiwifruit [35] shows uniform air temperature compared to full sun condition throughout the trial.

Numerous studies deployed on arable and horticultural crops reported an increase in air humidity under AV [36,37]. These results are in line also with regards to taller and permanent crops, in which air mass is more retained between canopy walls of hedgerows.

As shown for kiwifruit, relative humidity resulted higher with increased level of shading [35]; similarly, with an apple orchard, in which a general increase has been detected around midday [32]. This may be beneficial for species with high humidity requirements as kiwifruit for example but can also become adverse with potential risk of pest outbreaks (fungal diseases).

While air pattern tended to be more referenced, only very few studies address the impact of these environmental drivers on 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. [38] found in a vineyard 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 temperature reduction of 1-3 °C under shaded area with respect to full sun conditions [34,39]. This inconsistency may be due, apart for the different climatic conditions of the sites, to different PV transparency levels and spacing, affecting both portion of transmitted irradiation and temperature of the soil itself.

The impact of PV coverage seems to be also positive for soil water savings. Experiments conducted on grape and cranberries display the panels' role on the soil moisture retention, especially in cooler days and after irrigation [33,34]. Furthermore, a careful consideration must be given to panel-induced heterogeneity of moisture distribution on soil, an aspect that requires further investigations since it is typically a strong predictor of productivity [16]. In terms of evapotranspiration, a proper evaluation is still controversial. A general assessment establishes a reduction of atmospheric water demand but, due to insufficient spatial and crop behavior characterization available in literature for fruit crops, a formal evaluation is still pending. However, it could be emphasized that during periods of severe drought a positive plant response on water limitations is expected [24,40].

3.2. Fruit crop performance and quality

With respect of arable and horticultural crops, a low number of fruit tree species has been subjected to AV studies focusing on growth, yield, and quality (Table 1). Study results are mostly carried out under 30 and 60% shade with yield losses ranging from 16 to 42% (Figure 3). Cranberries cultivation results most negatively affected than other species on total productivity [33]. With lesser shading rate the average yield drop for kiwifruit and apple is approximately 29% by semitransparent and opaque PV configuration types, respectively [32,35]. Exception should be made for a pear orchard based on an estimation model. The simulated results show better performance then studies mentioned above, with only 16% yield reduction predicted [31]. A similar slight reduction (15%) has been recorded under more than 60% of shading rate by a wine grape experiment in Italy [34]. To this severe shading level, no comparable studies are available in literature on other fruit and berry fruit species, neither consistency is detected on yield decrease with increasing shade intensity [20]. Thus, additional data on tree performance are required to confirm whether any tolerance trait is effectively enhanced for perennial crops more than annual ones as observed in that study and further highlighted by the author [20].

Nevertheless, under low shading percentage (≅30%), crops behave well, and productivity is maintained or only little affected (5%) [35,38,39]. Yield components are little affected by mild shading systems thus ensuring a good marketable production. By contrast, over this threshold value, all papers reviewed report a significant decline of fruit mass, size and number [31–35]. Leaf photosynthesis seems to be affected by light shortage under high shading conditions reducing in turn dry matter accumulation and volume of the fruits [32,35]. Occasionally this aspect may not be a completely negative factor when associated with fruit trees that exhibit an alternate bearing behavior as apple. Thereby, shading interaction on flowers and young fruit could naturally regulate florabundity, influencing positively yield load over years as reported by the authors [32].

The decrease in carbon fixation and allocation also impacts quality parameters at harvest. With values of shading above 30% and conventional opaque PV modules such effect on total soluble sugars, and acidity is generally confirmed [33,34,41] with a decrease in the sugar/acid ratio and fruit firmness. More recent studies instead, reveal discrepancies in minimal standard quality and harvest date. As reported in a pear orchard, semitransparent structures should ensure similar fruit quality to full sun conditions [31]. Fluctuant shading rate, conversely, is supposed to not prevent physiological maturity and marketability of apples at harvest time [41]. In addition, it worth to be noting that there are some berry fruits (i.e., raspberries and blueberries), deemed to be compatible with higher shading conditions and in turn able to maintain relevant quality traits [20]. The above statements are supported by preliminary study only, more confirmations on these potential benefits should be provided in future research.

Regarding the skin color of fruits, influenced by compounds such as anthocyanins and polyphenols, the results indicate a high sensitivity to environmental changes [41]. Even for low degrees of shading, the commercial color of grape clusters has been reached with 10 days delay in response to radiation and temperature reduction, in two Korea's experiments [38,39]. Likewise, apples and grape in the Mediterranean regions resulted greener at harvest because of the shade [41]. To obtain more clarity on these responses, combined effects of shade, panel transparency and transmitted radiation quality aspects should be investigated as suggested by [42]. In fact, if changes in radiation composition will confirm a direct role on qualitative and quantitative performance, novel advancement on panel structure (i. e., semi-transparent organic photovoltaic) and shading strategy (i. e., smart tracking) may optimize internal metabolism of the fruit and ensure a long-term productivity of perennial crops.

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Table 1. Fruit tree publications under agrivoltaic system.

Fruit crop tested	Location	Type of panels	Structure	Ground Coverage ratio	Shading rate (%)	Remarks		References
						Yield	Fruit Quality	
Apple	Mallemort, France	Single-axis horizontal, adaptive solar tracking	opaque	0.43	42%	Significant affect yield from 27 to 32%, alternate-bearing reduction	minimum standard reached though less sugar concentration	[32,41]
Pear	Bierbeek, Belgium	double-sided, fixed, inclined	semitransparent	0.6	35%	slight 16% yield reduction (estimation)	quality aspects remain equal (estimation)	[31]
Grape	Illasi (Verona province), Italy	Fixed, tilted	opaque	-	75%	observed a decrease in yield, at least in two years	Total soluble solids resulted lower, reduction of both polyphenols and anthocyanins	[34]
Grape	(Ongjin Country) South Korea	Fixed, tilted	opaque	-	<30 %	No significantly affected	Not affected sugar content and anthocyanins, late skin coloration	[39]
Grape	Onjin-Gun, South Korea	Fixed on a umbrella-shaped facility, tilted	opaque, bifacial, semitransparent	-	≤30%	Not available (berry weight and number not affected except for opaque type)	Similar grape sugar-content level, delay in coloration	[38]
Kiwifruit	(Puijiang country), China	Fixed, tilted	semitransparent	0.15; 0.25; 0.31	19%; 30.4 %, 38%	Remarkable yield reduction	-	[35]
Cranberries	Massachuttes (USA)	Fixed	Plywood sheet	-	29.3-41.5%	Significantly reduced yield	Significantly reduced fruit firmness and total soluble solids, color non affected	[33]

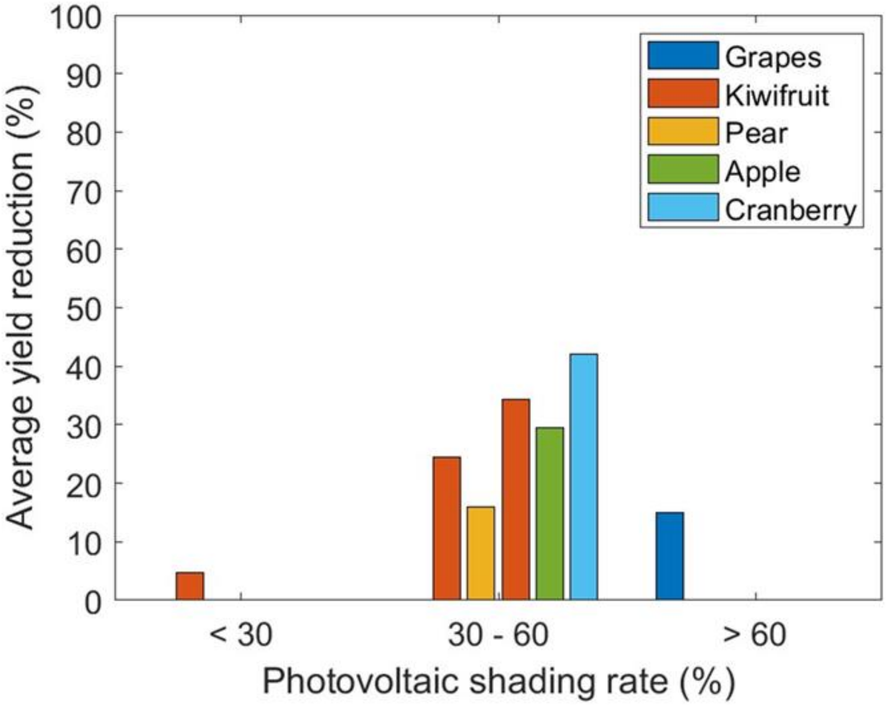

Figure 3. The average yield reduction of fruit crops depending on photovoltaic shading rate.

4. Conclusions

The global interest on the agrivoltaic sector is growing with significant and accelerated progress on new technologies, particularly concerning PV designs that implement wavelength selection with the aim of minimizing PAR alteration and reduction. Data collected in this review suggest that a shading rate of 30% could be acceptable with fruit tree cultivation. Higher shading levels should be more investigated depending on crop-specific (or variety) sensitiveness. Data are necessary on order to collect information on crop/panel compatibility in order to assist growers and energy providers to select the optimal crop for each agricultural area. However, limited data acquisition is still striking for fruit trees and grape, in semi-arid and arid regions strongly facing the climate changes. Using smart agrivoltaic tools as real-time data on plant stress signals then, it is possible to regulate tilting and thus impose different shading conditions on the canopy. This is particularly true for perennial crops, where such data will secondarily help both carbon assimilation flux and microenvironment, exploiting the full potential of agrivoltaic system suitability.

On the other hand, implementation of comprehensive indicators incorporating additional structural criteria, such as panel elevation above ground, is crucial for a more reliable understanding of agrivoltaic system impacts on perennial crop cultivation and in turn enhancing comparability across various experimental sites. Such aspects as panel elevation and spacing, in fact, are probably the main features to be considered for a reliable evaluation of fruit crops behavior.

The need for standardized measurements and comprehensive models to guide optimal agrivoltaic system have the goal of ensuring that crop productivity remains viable and attractive for farmers, with the ultimate objective of contributing to sustainable agriculture and renewable energy production.

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