horticulturae

MDPI

Article

Exploring the Grape Agrivoltaic System: Climate Modulation and Vine Benefits in the Puglia Region, Southeastern Italy

Andrea Magarelli , Andrea Mazzeo and Giuseppe Ferrara *

Department of Soil, Plant and Food Sciences, University of Bari Aldo Moro, Via G. Amendola 165/A, 70126 Bari, Italy; andrea.magarelli@uniba.it (A.M.); andrea.mazzeo@uniba.it (A.M.)
* Correspondence: giuseppe.ferrara@uniba.it; Tel.: +39-0805442979

Abstract: Climate change poses significant challenges to agriculture, a sector with a long-standing tradition in the Mediterranean basin. The region faces altered rainfall patterns, extreme temperatures, aridification, loss of biodiversity, and changes in crop yield and quality. These impacts, combined with intensive farming practices, threaten long-term agricultural sustainability. This study investigates agrivoltaics (AVs), a dual-use technology that integrates solar energy production (photovoltaic panels) with agriculture, as a potential solution to enhance resilience and adaptation of crops. Research at an AV system in Puglia (Southeastern Italy), combined with grapevine (*Vitis vinifera* L.), assessed soil moisture, temperature, and microclimate conditions together with vine yield and fruitfulness. Results showed that shading from photovoltaic panels increased soil moisture and moderated soil temperature, thus benefiting crops. Vines beneath the panels yielded more grapes (+277%) than in the full sun, confirmed by even the better bud fruitfulness of the shaded canes. While panels had minimal impact on air temperature, they reduced wind speed and vapor pressure deficit, creating a better microenvironment for vines. Spectral analysis revealed an increase in UV and blue light under the panels, potentially affecting photosynthesis. The AV system also produced substantial electricity, more than 90% compared to a ground-mounted system, demonstrating its dual-use application. The higher land equivalent ratio (LER) achieved by the AV system (3.54) confirmed that such systems can be advantageous in areas with a Mediterranean climate, allowing crop and energy production on the same land.

Keywords: grapevine; microclimate; spectral composition; energy; bud fruitfulness; yield

Academic Editors: Yang Liu, Hong Zhang, Haipeng Lan and Silvio José Gumiere

Received: 10 December 2024
Revised: 29 January 2025
Accepted: 30 January 2025
Published: 3 February 2025

Citation: Magarelli, A.; Mazzeo, A.; Ferrara, G. Exploring the Grape Agrivoltaic System: Climate Modulation and Vine Benefits in the Puglia Region, Southeastern Italy. *Horticulturae* **2025**, *11*, 160. https://doi.org/10.3390/horticulturae11020160

1. Introduction

In the context of prolonged and intensified climate change, human activity has emerging challenges to cope with in the present and near future. In regions with an ancient agricultural tradition such as the Mediterranean Basin, the risk of permanent modifications overcomes resilience and adaptation mechanisms without collective and coordinated environmental policies [1,2]. Even agriculture is becoming a highly vulnerable sector, threatening the supply of either food or a number of ecosystem services [3,4]. The clear changes in the quantity and seasonality of rainfall distribution and the higher frequency of extreme temperatures are affecting soil water reserves [5] and, consequently, many human activities. Current and future consequences also involve aridification, loss of biodiversity, and modifications in the composition of fruit [6–8]. These effects, coupled with intensive farming practices, lead to overexploitation of aquifers and thus long-term environmental unsustainability of crop production and other human activities [9].

In the most adverse climate change scenario, recent projections for southwestern and eastern rims of the Mediterranean region suggest that 48% of areas will experience extensive repercussions [10]. Typical Mediterranean horticultural crops such as grape, olive, citrus, tomato, and wheat are expected to face a significant worsening of drought and heatwaves, alongside with a declining climatic suitability for the cultivation of many varieties.

Grapevine production, in particular, is expected to suffer water scarcity despite its inner capacity to adapt to both reduced water availability and recurrent droughts [11]. The importance of grapes in the production of table grapes, wine, and raisins is well known; globally, over 7 million hectares of land was devoted to grape cultivation in 2023, with a production of almost 75 million tonnes [12]. In total, 40% of the global vineyard area is located in the Mediterranean region, where winegrapes are often cultivated in vulnerable and less fertile areas [12]. Negative climatic effects on such areas will strongly affect the global viticultural market, since wines produced in the Mediterranean basin (Italy, France, Spain, etc.) are exported worldwide [13].

To increase the resilience of these important crop systems in order to adapt to climate change conditions, agroforestry and agrivoltaics (AVs) can increase (or even maintain) yield while also advancing multiple sustainable development goals [14,15]. In particular, AV combines solar photovoltaic (PV) panels in agricultural land with different crops.

Furthermore, these two shared-land cropping systems can improve the land use efficiency of soil, as demonstrated by the land equivalent ratio (LER). LER is a key indicator used to compare the productivity/efficiency of intercropping systems against monocropping systems. It is calculated by summing the relative yields of each crop in an intercropping system compared to their yields in monoculture. An LER greater than 1 indicates that intercropping is more efficient, as it requires less land to produce the same total yield as monoculture. For instance, an agroforestry system with olive trees applied to Mediterranean cropland demonstrated a higher LER, reflecting its ability to use resources like water, light, and nutrients more efficiently [16]. This system not only boosted economic resilience—resulting in up to 50% higher income—but also delivered more agro-environmental benefits compared to traditional olive monocropping [16]. On the other hand, the LER values for yield in AV systems of different herbaceous crops (lettuce, cabbage, tomato, maize, etc.) can range from 0.85 to 2.97, whereas the LER for biomass ranges from 1.23 to 2.02 [17]. LER can exceed 2 under arid and semi-arid environments for some crops, suggesting that it may be extremely efficient to produce both electricity and food/non-food crops on the same land unit even more than agroforestry in marginal and difficult areas [18,19]. In addition, AV systems contribute largely to reducing carbon emissions—with 0.891 metric tonnes of CO_2-equivalent emissions saved for each megawatt-hour of solar electricity—with minimal impacts on crop production (up to 25%) at low shadow depths [20,21]. However, the suitability of AV systems in a particular agricultural region needs to consider several key parameters (i.e., annual available radiation, AV configuration, crop type, landscape experience, etc.) in the context of both the climate and the rural traditions of the area. Overall, models and simulation-based solutions focus on environmental features such as irradiance estimation and microclimatic fluid model independently from their impact on crop performance [19,22–24]. Recently, efforts were made to introduce a drought index that addressed information concerning temperature, potential evapotranspiration, and precipitation for a more comprehensive understanding of crop yield dynamics [25]. A recent study reported a model to evaluate the possible integration of olive groves in AV systems, with simulation of solar irradiance and the different components involved [26]. However, the lack of field data could limit the knowledge of the behavior of these AV systems in various agricultural areas.

In tropical and subtropical environments, AV effectively affects microclimate conditions, photosynthesis, growth, and yield [27–29]. PV panels placed in the dry–hot valley of southwest China with the cultivation of peanuts and ryegrass had positive effects on soil moisture, organic carbon, total nitrogen, phosphorus and potassium content, microbial biomass, and urease activity, with differences between row and inter-row locations [30]. Differently, no or very limited differences were reported for microclimate and soil parameters under a PV plant in Malaysia, but this latter study was conducted with no crops under the panels placed above the soil [31].

In the South of France, Juillion et al. [32] reported that tracking PV panels positively affected microclimatic conditions by reducing temperature (3.8 °C) and increasing humidity by 14% in an apple orchard with an average shading condition of 50–55%. These changes in the microclimate reduced the irrigation requirement between 6 and 31%, as well as alternate bearing, but also the photosynthetic capacity, with negative effects on the flowering and yield of apple trees. In contrast to studies on AV in temperate regions of Europe and the USA, which reported that high panel densities generally reduced the yields of most crops to different extents [32–34], Randle-Boggis [28] reported that a relatively moderate panel density of 50% in semi-arid regions can lead to significant yield improvements. Investigations on AV systems in hot and dry climatic conditions reported positive effects on both microclimate (lower air and soil temperature, reduced wind speed and evapotranspiration, etc.) and yield components [35–37]. However, very limited information is reported in the literature on grapes cultivated beneath PV panels in hot and dry climates [20,33,34]. Moreover, to our knowledge, the different shading conditions on canopies of grapes trellised with vertically positioned shoots (i.e., cordon, guyot, etc.) have never been investigated.

Considering the studies conducted on AV, the current study aimed to measure the effects of a fixed AV system on the microclimate created by the PV panels in a vineyard in the Mediterranean area, characterized by hot and dry summer climatic conditions. This work seeks to quantify changes in air and soil conditions, as well as spectral quality at the vine level, by considering the shoot positioning of the vine in full and partial shade beneath the panels. Differently from previous studies, apart from different light conditions on the same vine, indicators such as the LER and the light interception efficiency (LIE) were also calculated to better analyze the effects of the AV system on the vines with vertical shoot positioning. This study also examines yield and bud fruitfulness, with the latter aspect aiming to evaluate the possible carry-over effect of the shade on vine physiology and productivity.

2. Materials and Methods

2.1. Experimental Site Description

The AV system investigated in this study is in the countryside of Laterza (Taranto province) at the Svolta Company solar farm, Puglia region, Italy (40.6819° N, 16.7643° E). In Figure 1, there is an overview of the AV system with the control plot (full sun). The vines of the 'Primitivo' variety are cultivated in rainfed conditions either below the panels or in full sun, with the PV array aligned in a north–south orientation. The vine spacing is enough to allow machinery operations for all the viticultural practices. The clearance space between the top of the canopy (tied to the second wire) and the lowest edge of the module is less than a half-meter. The solar panel width was 1.07 m, covering 43% of the ground surface when calculated as a projection against the horizontal plane position. Looking at the investigation area overall, a total area of 5400 m^2 is considered. Since the technology is under patent registration, more details will be available once registered with a Supplementary Material on vine spacing and structures.

Figure 1. View of the agrivoltaic vineyard, with the AV treatment above and full-sun exposure below.

2.2. The Environment Monitoring

According to the spatial variation in light environment caused by PV panels, shade intensity had a large span both on the ground and on the canopy of the vines. Due to this high heterogeneity throughout the day, environmental measuring points under and between panels were assessed as low shading (LS ~95% of transmitted radiation) and high shading (HS ~5% of transmitted radiation) treatments, respectively; the control treatment was reported as full-sun (FS ~100% of transmitted radiation) treatment. Hence, weather sensors were placed inside the AV system and were arranged at a 1.5 m distance from each other along the middle line of the inter-row space, while the external one was placed 20 m away from the AV area within the same panel row as in FS conditions. A thermohygrometer (TH Sense 2.0 model) and an anemometer (DW-7911, Davis Instruments) were installed 2.20 m above-ground at canopy level to measure ambient temperature, relative humidity, wind direction, and velocity. The vapor pressure deficit (VPD) was calculated through air temperature and humidity recordings.

A combined soil temperature–moisture sensor based on the FDR principle (PS-005-JB model) was installed at a depth of 0.25 m, in the middle of the rows, to measure both volumetric water content and soil temperature. Measuring points were set directly below the HS area, in the central position of the LS area, and outside this area in the FS treatment. The values were logged at 1 h intervals at 2 separate microclimate stations, the first assigned to the AV area and the other one to the FS treatment. All the sensors mentioned above were provided by Netsens Group (Florence, Italy). The sensors used are summarized in Table 1.

Table 1. Specifications of the sensors used in the vineyard.

Sensor	Parameter	Specification Range
TH Sense 2.0 model	Air temperature	Range −25 to +85 °C
TH Sense 2.0 model	Relative humidity	Range 0 to 100%RH
DW-7911	Wind speed	Range 1 to 322 km/h
PS-005-JB	Soil temperature	Range −20 °C to +50 °C
PS-005-JB	Soil moisture	Range 0% to field saturation

A UPRtek spectrophotometer (Handheld PAR Meter PG200N) was used for spectrum analysis in the ultraviolet (PFD-UV: 350–400), blue (PFD-B: 400–500), red (PFD-R: 500–600); and far-red (PFD-FR: 700–800 nm) waveband regions. Measurements were taken at 9:00–18:00 during the 2023 growing season to represent different solar elevation angles and radiation levels on the canopy. The measurements were conducted on both sides of the vine (LS and HS). The device's head was positioned approximately 20 cm above the upper wire at canopy level, pointing south and parallel to the ground, thereby exposing the quantum sensor vertically to the sky. Measurements were collected three times per treatment, resulting in a total of 18 measurements under AV (9 for HS +9 for LS) and 9 measurements under FS conditions for each sampling day in the season. Data collection and monitoring were conducted during the 2023 growing season on the following dates: 24 June, 7 July, 21 July, 4 August, and 12 September.

2.3. Vine Parameters

Vines from all treatments were harvested when grapes reached the technological threshold for winemaking. The yield (kg/vine) and the cluster number were determined at harvest as an average of 9 vines per treatment by using a portable scale. Harvest was accomplished on 20 September in 2023. From vine data, the yield was expressed as t/ha to better compare the two systems.

At the end of the growing season, during winter dormancy, bud fruitfulness was also assessed. A few days before winter pruning, from 9 vines of each treatment, a single cane with at least 10 nodes was selected and sampled, resulting in 9 canes for LS and 9 for the HS position; 1 cane per vine was also collected for the grapevines in FS. Canes were stored in black plastic bags at 4–6 °C until dissection at room temperature in the lab. The canes were cut to ten nodes but excluding the basal crown buds. Bud dissection and fruitfulness evaluation with a stereomicroscope (Nikon SMZ800) were performed according to the methodology reported by Ferrara and Mazzeo [38].

2.4. Electricity Production

Electricity production data at the AV facility were provided by Svolta Company. The thin-film modules are double-junction amorphous silicon (a-Si). Each inverter is loaded identically with panels arranged in stripes.

2.5. Light Interception Efficiency and Land Equivalent Ratio

The light interception efficiency of the canopy (LIE_c) was calculated by using the PPFD values with the following equation:

$$LIE_c = \frac{PPFD_{top} - PPFD_{bottom}}{PPFD_{top}} \quad (1)$$

The land equivalent ratio (LER) represents the land required for a single crop to achieve the same yield as the corresponding intercropping system on the same area, which is also used to quantify the land productivity between photovoltaic power generation and crop cultivation (Equation (2)). LER > 1 in AV systems indicates a higher land use efficiency than planting crops or PV power alone on the same land [39].

$$LER = \frac{Y_{crop_{AV}}}{Y_{crop_{Control}}} + \frac{Y_{energy_{AV}}}{Y_{energy_{Control}}} \quad (2)$$

2.6. Statistical Analysis

For statistical analysis, the Kruskal—Wallis and Dunn tests (at α = 0.05, 0.01, 0.001, and 0.0001) were applied to multiple-comparison distributions of microenvironment parameters between measuring points and the control. Statistical tests were performed and relevant charts were created with R ver. 4.4.1 [40].

3. Results and Discussion

3.1. Soil Moisture and Temperature

The presence of PV panels spatially altered the soil moisture distribution. As shown in Figure 2, this heterogeneity was detected for all the treatments, as can be observed by the color under each relative curve. The FS area had the lowest median soil moisture content (5.5%) compared to positions in the two AV treatments (LS and HS). As a semi-arid environment, the soil's moisture levels in full sun were typically low during the growing season due to the high rate of solar irradiance and, thus, massive evaporative losses. In our case, the amount of radiation transmitted varied greatly, as did soil moisture, which ranged from 3.6% (LS area) to 16% (HS area), with the latter values on shaded soil being significantly higher than the control value. Similar variations in soil water content (seasonally and daily) have been reported within AV systems in different geographical locations [31,41,42]. Recently, improvement effects on soil quality parameters have been reported to be higher in the inter-row soil than in the under-panel soil [30], but in this study, we detected values at different positions in the row (HS and LS) and for the same vine. However, the root systems of the vine may have been adapted to this different soil water distribution (HS and LS) to optimize water absorption and distribution within the canopy.

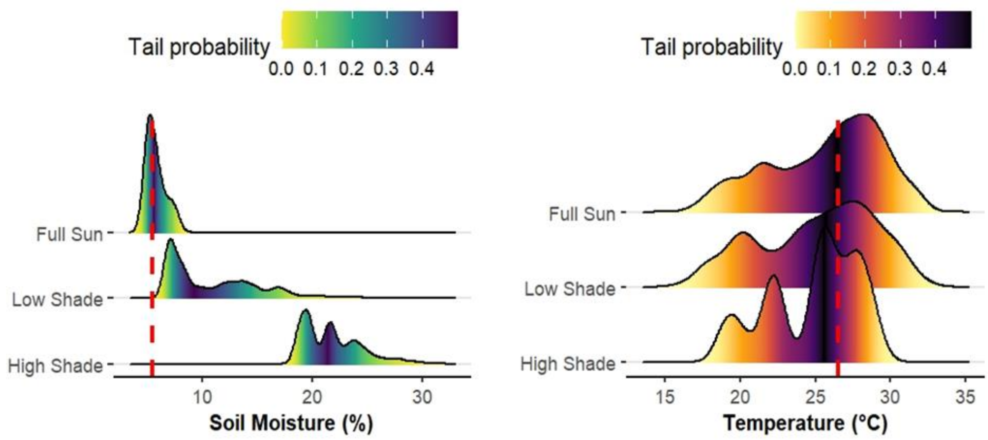

Figure 2. Distribution of soil moisture (**left**) and soil temperature (**right**) at various positions throughout the experimental period (growing season). The color under the curve indicates tail probability, which is 0 at the darkest point and 50% (median) at the highest point. The dashed red line means the median value for the full-sun treatment.

The influence of PV panels was less pronounced for the soil temperature profile compared to the soil moisture. Distribution curves are wide and multimodal for all the treatments, although less prominent in the FS. However, the pattern of variation was inconsistent among treatments. HS treatment showed lower variability compared to those characterized by different degrees of radiation transmitted on the ground. As expected, the FS treatment was expressed by the highest median value of soil temperature (Figure 2). Comparison between treatments suggested that the reduction in soil temperature variation under the HS treatment was mainly related to solar radiation intercepted by the panels, as recently reported in other studies [42,43]. Furthermore, chemical and physical characteristics of the soil and the presence of cover crops instead of bare soil could affect these differences in soil temperature distribution [43,44]. Moreover, the presence of panels with vegetation growing beneath them may preserve the soil's ability to store nutrients, sequester carbon, and host organisms by providing protection against erosion and the excessive increase in soil temperature due to climate change, even favoring biodiversity [45].

This could also explain the slight positive correlation observed between air temperature and soil temperature for the LS area, partially accounting for the daily peak values recorded.

3.2. Microclimate

The general microclimate pattern seemed to confirm the trend of soil temperature. The daily mean and maximum air temperatures do not show statistical differences among treatments. For both the AV treatments and the control, the corresponding values of the coefficient of variation were 0.17, 0.17, and 0.16 for LS, HS, and FS, respectively. However, the median daily mean temperature was approximately 1 °C lower in the LS and HS treatments compared to the FS treatment. With the same extent of difference, the daily maximum air temperature was lower only in the HS treatment compared to the other two treatments. In climatic conditions occurring in the Puglia region during the summer season, such reductions in temperature during the day can play an important role in plant growth and productivity. Radiation reduction influences soil temperature, evapotranspiration, and soil water balance, with more favorable conditions for crops that adapt to the new light conditions in different ways (i.e., increasing leaf area, re-arrangement of the light harvesting area) thus allowing for better productivity of the crop, as reported in this study and in others [17,42,46,47].

In the case of air humidity (RH), the results indicated significant differences in the maximum and mean values during the day [48]. LS experienced the highest maximum values and narrowest variation (0.05) compared to other treatments. This result could be explained either by the differential thermal retention between shaded zones or the more stable stratification effect because of the windbreak effect of the panels, thus limiting air moisture reduction in the LS site. The modifications of wind patterns in mean and max values further support this statement (Figure 3). Studies generally report a reduction in RH beneath the panels, often occurring in greenhouses covered with photovoltaic panels where there is no windbreak effect [49].

Moreover, the reduced air turbulence below the open structure possibly led to changes in microclimatic signals perceived by the vines. At crop level, vapor pressure deficit (VPD) has a strong influence on vine transpiration, but no significant effect of shading was noticed between the FS and HS treatments as reported in the literature [47]. However, inconsistency has been detected for the LS treatment since the VPD was found to be lower than 0.24 kPa and more variable (1.05) compared to both HS and FS areas. It is interesting to note that another study of AV systems under a semi-arid environment reported higher RH and an associated low VPD pattern [50]. Unfortunately, none of these studies reported multiple monitoring positions for this parameter, thus requiring further insights.

On a daily basis, the presence of narrow pitch discontinuity (panel spacing) assumed significant implications on heat transfer and thus wind speed profile (over the upper and lower surface) [51]. This aspect requires particular attention to explain the VPD differences recorded and the consequent plant growth responses. For the reasons exposed above, the study suggested that wind penetration through the AV system studied was the main driver of air circulation above and under the PV panels [52]. The ground conditions and panel height play important roles in AV system cooling [52]. VPD and RH, in turn, are directly affected by wind speed (and direction) and jointly regulate atmospheric water demand (Figure 3). This may be beneficial for the collocation of PV panels on crops to better face climate change with increasing high temperatures and drier conditions occurring for cultivation [50].

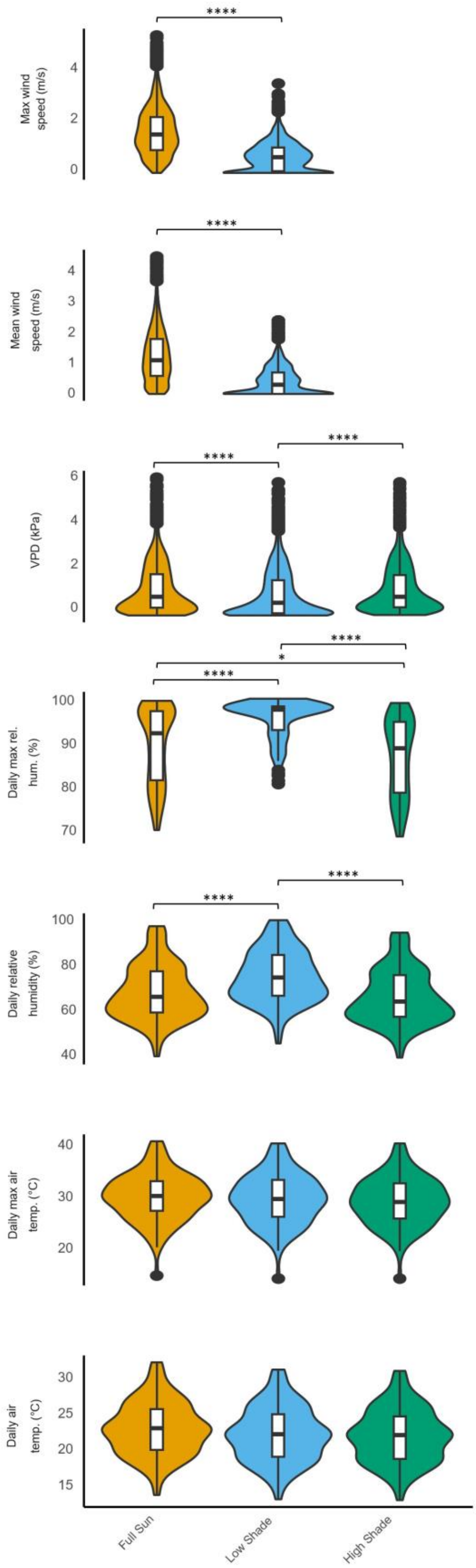

Figure 3. Box–violin distribution of microclimate parameters for each treatment during the growing season of 2023. Asterisks indicate statistical differences using the Dunn test (*: $p \leq 0.05$; ****: $p \leq 0.0001$).

3.3. Spectral Implications

Investigating the spectral composition is of relevance and importance for the correct estimation of the percentage of wavelength absorbance by green canopies such as grapevine.

In this study, we measured radiation in the full spectrum of the photon flux density range (PFD ~350–800 nm) to explore changes beyond the wider range of plant action spectra that are typically used for photosynthetic activity.

As shown in Figure 4, the different spectrum values measured at each point were plotted against the relative transmittance level. Starting from the bottom of the chart, the fraction with the lower percentage was represented by UV radiation. The PFD-UV percentage tended to increase between 1.8% and 8% under the PV panels and recorded the highest coefficient of variation (0.3) among all spectrum wavebands. The negative value of the logarithmic curve and R^2 = 0.69 further confirmed the fitted model against transmittance values. The percentage values of PFD-B showed less variation (0.1) compared to the previous one; it increased from 17–19% (FS) up to 27% recorded beneath the panels. Furthermore, there was no relation with transmittance.

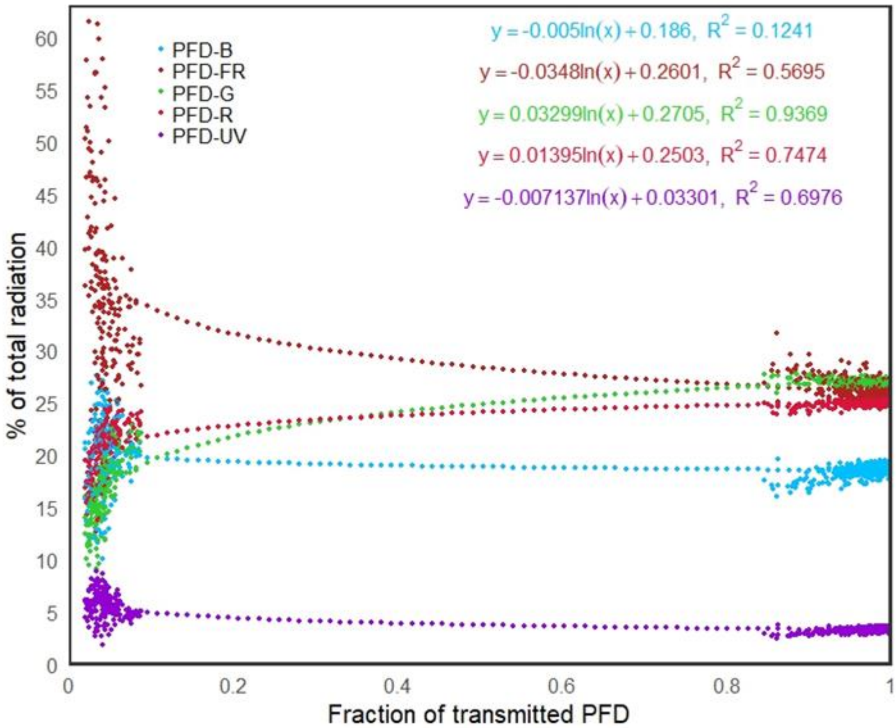

Figure 4. Relationship between the percentage composition of the radiation of the different spectra (ultraviolet: PFD-UV; blue: PFD-B; green: PFD-G; red: PFD-R; far red: PFD-FR) and the fraction of transmitted radiation under the PV panels and FS treatment.

Moving to PFD-G and PFD-R percentages, a reverse pattern occurred. Furthermore, the decrease under the PV panels was much more related to transmittance, especially for PFD-R (R^2 = 0.94). The percentage of PFD-FR, instead, increased exponentially under the PV panels, with large variation between the maximum and minimum values of 63% and 23%, respectively. In this case, the fitted model was unrelated to transmittance within the shaded area, and compounding effects may be involved.

In the investigated AV system, radiation transmitted through panels considerably changed its spectral composition.

A recent study on the qualitative assessment of spectral composition under panels reported altered radiation spectra, with increased in V and B and reductions in R and FR wavelengths [53]. Diffuse radiation represented almost the total amount in the inner air space of the AV, and it was particularly enriched in short-wavelength radiation due to the Rayleigh scattering effect [54]. It could be hypothesized that the resulting net radiation balance upon and below the PV panels was generally altered, as recently reported in a study in the Gobi desert in China [55].

Based on a complex interplay between the geometry, material, and color properties of a panel's rear cover, a regulatory effect of temperature could be assumed to be present at the surface level of the modules. This event was supported by several studies which recognized longwave infrared re-emission through opaque modules derived from surface temperature and emissivity characteristics of the PV panels [44,56]. In fact, in a model study, the longwave energy at ground level beneath the solar panels was much higher than the longwave energy in the control area [56]. The complex interactions between radiation composition, light intensity, temperature, and humidity play a pivotal role in plant water balance and carbon assimilation. Such aspects are of primary importance for driving growth and photomorphogenesis in plants [57–59]. Therefore, long exposure to altered light with lower R and G fractions, as observed in this study, may exert some significant implications on crops that should be carefully considered for further research and applications in vineyards.

3.4. Light Interception Efficiency, Bud Fruitfulness, and Productivity of Grapevines

Light interception is an important aspect, together with the spectral quality of light. In grapevines, moderate shading effectively induced a series of vegetative and morphological responses and adaptations at the expense of berries [60]. Among all factors, light use efficiency (LUE) plays an essential role in the evaluation of light-harvesting mechanisms. In our study, the LIE decreased due to the shading created by the PV panels (Table 2). However, an increase in LUE was hypothesized for this reduction, enabling the high crop load observed in the AV treatment (Figure 5), since yields could increase either by reduced photoinhibition (in shade) or increased plant WUE, or even a combination of both, and with a more efficient use of the more limited light (LUE). The increase in LUE was confirmed by AV studies across diverse species through the regulation of their morphology and photosynthetic parameters; *Bupleurum chinense* experienced increased height and electron transfer flux and up-regulated photosystem I protein (PsaA), whereas *Medicago sativa* reduced its leaf mass per unit area and dark respiration, increased its chlorophyll content, and down-regulated photosystem II protein (PsbD), and kiwifruit, a climbing species like grapevine, increased the distribution ratio of electron transport quantum in the PSII reaction center and reduced the quantum ratio for heat dissipation [61,62]. Despite these findings, discrepancies in yield responses have been reported, and this variability seems to depend not only on crop suitability/differences (i.e., C3 and C4 plants), but also on multiple factors such as system design, shading duration, and site location [27,28,63]. Experiments on potted vines of cv. Syrah revealed that total shading constrains berry formation and development, primarily due to reduced photosynthetic capacity, which negatively impacts fertility over time due to carry-over effects, likely because of limited carbon assimilation [64]. Higher berry growth and sugar loading were maintained when shading was combined with water deficit; panels over the vines can allow cooler conditions for ripening but at the expense of berry size and the sugar amount in berries [64]. In the current study, the shading strategy imposed by fixed PV panels exposed half of the canopy to low light throughout the daytime. This did not appear to limit yield in the vineyard, which was higher than in the FS treatment (Figure 5), differently from another study conducted in Northern Italy (cooler climate) using the same AV configuration but a different winegrape variety, where a ≈20% reduction in yield compared to the control was observed [34]. The data clearly suggest that shading intensity and duration should be adapted to evaporative and soil water conditions without altering production in the long term but even improving it in hot and dry areas [64]. Modifications in radiation patterns could have significant implications on photomorphogenesis, as previously detailed. However, this aspect remains under-investigated and could offer significant benefits for land productivity, as evidenced by the high LER value observed in this study.

Table 2. Changes in the efficiency of the interception of light (LIE) and land equivalent ratio (LER) caused by the AV system.

Treatment	LIE	LER
Shade	0.48	3.54
Full Sun	0.94	-

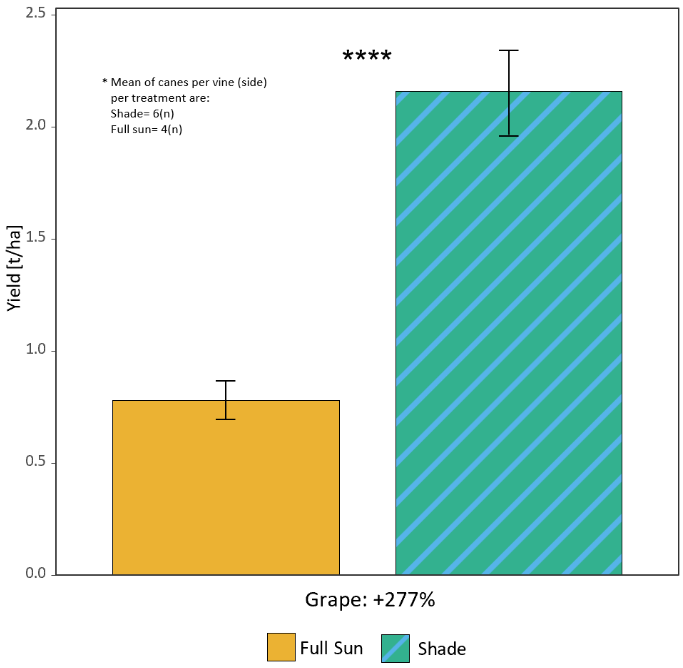

Figure 5. Yield (t/ha), at the vineyard scale, considering all vines for each treatment (n = 9 for AV plot and n = 9 for FS plot) harvested in 2023. Percentages indicate yield in the AV plot compared to the FS plot (****: $p \leq 0.0001$).

Berry fruitfulness seemed not to be affected by the shade of the panels, and in the LS and, to a less extent, HS areas, its values were even higher with respect to the FS (Figure 6). What we noticed in this study was a carry-over effect on bud fruitfulness, but with positive effects on grape yield, as also observed at harvest (Figure 5). Better environmental and nutritional conditions kept higher bud fruitfulness in shaded canes up to the distal nodes, with greater differences with respect to basal nodes. This is the first report on the long-term study of the effects of shade from photovoltaic panels on the bud fruitfulness of grapevine, since carry-over effects have been considered for other aspects such as ripening but in a different climate [64].

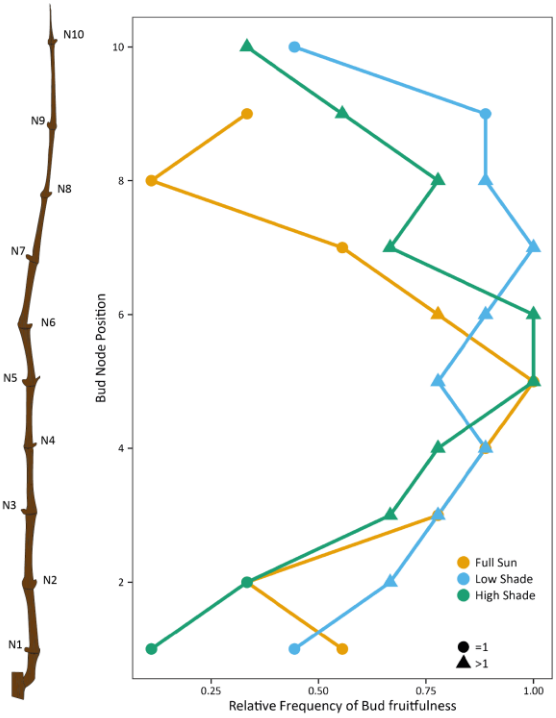

Figure 6. Relative bud fruitfulness in 10-node canes of grapevine Primitivo grown in full sun and low and high shade.

3.5. Electricity Generation

The energy production of the AV system was recorded over the course of 2023 (Figure 7). The system achieved an electrical generation of ~53 kWh/m^2/year. Monthly energy performance aligned with the irradiance profile except for May, in which the electricity production suffered a slight reduction (~6%) due to exceptionally cloudy conditions occurring in the area. Monthly production during the summer months (June, July, August) was two times higher than during the winter (December, January, February). The summer/winter amplitude was less strongly affected with respect to a recent study conducted in Belgium [65]. Latitude incidence and sunlight availability probably made a major contribution to this different result. Moreover, the latter represents a limiting factor for fruit tree/grape growth at higher latitudes, yet providing high contributions to energy load accumulation during summer months. At our experimental site and in similar conditions, a good trade-off between energy production and crop suitability and yield may be easily achievable.

In addition, the opaque conventional modules adopted in this study performed well while ensuring only 9% of power conversion efficiency. Current electrical properties of PV panels can reach up to 20% of power conversion efficiency using silicon semi-transparent modules and spectral beam splitting technologies in addition to providing relatively good light transmittance [66–68]. Despite their potential, only preliminary data on crop performance under these configurations are available. Among practical AV implementations, overhead systems with monoaxial trackers combined with grape as a crop can ideally produce approximately specific energy yields of 700 kWh/kWp per hectare [69]. In this case, the lower density of the panels compared to our study was a critical feature that limited maximum power generation. Conversely, interspace PV solutions have demonstrated an optimal trade-off, achieving specific energy yields exceeding 1000 kWh/kWp when combined with arable crops under smart-tracking configurations [70].

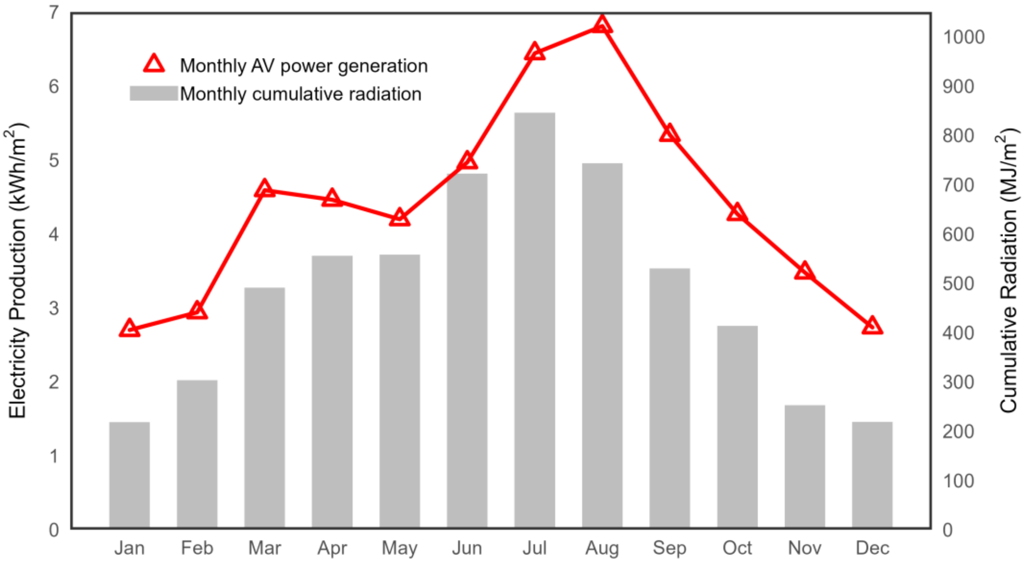

Figure 7. Monthly electrical power generation per square meter of land by the panels used in this study in 2023.

Semi-transparent PV technologies applied to orchards/vineyards offer the advantage of a more homogeneous light distribution, maintaining acceptable fruit yield losses, even in temperate and cool climates, while providing reliable PV capacity [65,71]. As reported for a pear orchard in Belgium, the specific energy yield was equal to 956 kWh/kWp [65], comparable with our results of 950 kWh/kWp with different crop and climate conditions. Geophysical, location, technical, meteorological, and environmental factors should be considered for geographical and agricultural site suitability to obtain such high-performance results. At a regional scale, the Puglia region can reach a maximum capacity potential of 761 GW, covering 12% of suitable areas, as supported by AV potential indicators [72]. This high profitability of AV implementation could be extended to all agricultural areas in Southern Europe, as well as other similar climatic areas, where an accelerated transition for key crops is expected in the coming years [73]. Our results, together with other field studies conducted worldwide, suggest that AV systems can achieve both energy and agricultural benefits by adopting conventional and advanced AV technologies in an integrated and site-specific manner in many rural areas of the world; finally, marginal, abandoned lands could be restored for agriculture for the production of different crops together with green energy production.

4. Conclusions

Soil and air microclimate evaluation confirmed the close relationship between the site and the grape AV system configuration. Changes in wind pattern altered site-specific air-current regimes and evoked substantial changes in microclimates, mainly occurring over short distances, with both air humidity and vapor pressure deficit.

On the other hand, the physicochemical properties of the soil seemed to be the main drivers regulating soil thermodynamic fluxes under modified radiation regimes. Near-surface soil temperatures increased considerably along with the amount of radiation intercepted by soil, as observed under FS conditions. In contrast, soil moisture dynamics were influenced by shading, which efficiently counteracted water transfer between the soil and atmosphere. These elements of the energy balance highlighted the potential of AV implementation in semi-arid areas as a promising solution to address climate challenges and enact sustainable agriculture to reduce land loss. In such areas, the yield of crops such as grape can be definitively improved and sustainable in many rural areas.

In conclusion, the proposed technology introduces a reliable and innovative approach to land use transition in typical Mediterranean agricultural areas, as demonstrated by the higher LER values. Specific policies and strategies could effectively rely on these low-technology input solutions to accelerate the widespread adoption of AVs, ultimately supporting rural communities, fostering economic opportunities, and promoting sustainable land development on a regional scale.

5. Patents

The AV technology reported in this article part of a request for a patent.

Author Contributions: Conceptualization, A.M. (Andrea Magarelli) and G.F.; methodology, A.M. (Andrea Magarelli) and G.F.; formal analysis, A.M. (Andrea Magarelli); investigation, A.M. (Andrea Magarelli); data curation, A.M. (Andrea Magarelli) and G.F.; writing—original draft preparation, A.M. (Andrea Magarelli); writing—review and editing, A.M. (Andrea Magarelli), A.M. (Andrea Mazzeo), and G.F.; supervision, G.F.; funding acquisition, G.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by PON "Ricerca e Innovazione" 2014–2020, Asse IV "Istruzione e ricerca per il recupero"—Azione IV.4—"Dottorati e contratti di ricerca su tematiche dell'innovazione", Azione IV.6—"Contratti di ricerca su tematiche Green" finalizzate al sostegno a contratti di ricerca a tempo determinato di tipologia A, CUP H95F21001280006. This study was also carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)—MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4—D.D. 1032 17/06/2022, CN00000022). This research was also supported by MASE (Ministero dell'Ambiente e della Sicurezza Energetica) in the framework of the Operating Agreements with ENEA for Research on the Electric System—Progetto Integrato 1.1 "Fotovoltaico ad alta efficienza".

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: The authors want to thank Svolta Company for providing weather station data and partly supporting the research. In particular, the authors wish to thank Claudio Campanella for the data about the electricity generation.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Cramer, W.; Guiot, J.; Fader, M.; Garrabou, J.; Gattuso, J.-P.; Iglesias, A.; Lange, M.A.; Lionello, P.; Llasat, M.C.; Paz, S.; et al. Climate Change and Interconnected Risks to Sustainable Development in the Mediterranean. *Nat. Clim. Chang.* **2018**, *8*, 972–980. [CrossRef]
2. Grasso, M.; Feola, G. Mediterranean Agriculture under Climate Change: Adaptive Capacity, Adaptation, and Ethics. *Reg. Environ. Chang.* **2012**, *12*, 607–618. [CrossRef]
3. Hoff, H. Vulnerability of Ecosystem Services in the Mediterranean Region to Climate Changes in Combination with Other Pressures. In *Regional Assessment of Climate Change in the Mediterranean*; Navarra, A., Tubiana, L., Eds.; Advances in Global Change Research; Springer: Dordrecht, The Netherlands, 2013; Volume 51, pp. 9–29; ISBN 978-94-007-5771-4.
4. Malek, Ž.; Verburg, P.H.; Geijzendorffer, I.R.; Bondeau, A.; Cramer, W. Global Change Effects on Land Management in the Mediterranean Region. *Glob. Environ. Chang.* **2018**, *50*, 238–254. [CrossRef]
5. Dubrovský, M.; Hayes, M.; Duce, P.; Trnka, M.; Svoboda, M.; Zara, P. Multi-GCM Projections of Future Drought and Climate Variability Indicators for the Mediterranean Region. *Reg. Environ. Chang.* **2014**, *14*, 1907–1919. [CrossRef]
6. Bortoluzzi, L.; Casal, S.; Cruz, R.; Peres, A.M.; Baptista, P.; Rodrigues, N. Influence of Interannual Climate Conditions on the Composition of Olive Oil from Centenarian Olive Trees. *Agronomy* **2023**, *13*, 2884. [CrossRef]
7. Carvalho, D.; Pereira, S.C.; Silva, R.; Rocha, A. Aridity and Desertification in the Mediterranean under EURO-CORDEX Future Climate Change Scenarios. *Clim. Chang.* **2022**, *174*, 28. [CrossRef]

8. Newbold, T.; Oppenheimer, P.; Etard, A.; Williams, J.J. Tropical and Mediterranean Biodiversity Is Disproportionately Sensitive to Land-Use and Climate Change. *Nat. Ecol. Evol.* **2020**, *4*, 1630–1638. [CrossRef] [PubMed]
9. Iglesias, A.; Garrote, L. Adaptation Strategies for Agricultural Water Management under Climate Change in Europe. *Agric. Water Manag.* **2015**, *155*, 113–124. [CrossRef]
10. Zagaria, C.; Schulp, C.J.E.; Malek, Ž.; Verburg, P.H. Potential for Land and Water Management Adaptations in Mediterranean Croplands under Climate Change. *Agric. Syst.* **2023**, *205*, 103586. [CrossRef]
11. Santillán, D.; Garrote, L.; Iglesias, A.; Sotes, V. Climate Change Risks and Adaptation: New Indicators for Mediterranean Viticulture. *Mitig. Adapt. Strat. Glob. Chang.* **2020**, *25*, 881–899. [CrossRef]
12. International Organisation of Vine and Wine (OIV). Available online: https://www.oiv.int/what-we-do/global-report?oiv (accessed on 25 January 2025).
13. Santillán, D.; Sotés, V.; Iglesias, A.; Garrote, L. Adapting Viticulture to Climate Change in the Mediterranean Region: Evaluations Accounting for Spatial Differences in the Producers-Climate Interactions. *BIO Web Conf.* **2019**, *12*, 01001. [CrossRef]
14. Cuppari, R.I.; Branscomb, A.; Graham, M.; Negash, F.; Smith, A.K.; Proctor, K.; Rupp, D.; Tilahun Ayalew, A.; Getaneh Tilaye, G.; Higgins, C.W.; et al. Agrivoltaics: Synergies and Trade-Offs in Achieving the Sustainable Development Goals at the Global and Local Scale. *Appl. Energy* **2024**, *362*, 122970. [CrossRef]
15. Waldron, A.; Garrity, D.; Malhi, Y.; Girardin, C.; Miller, D.C.; Seddon, N. Agroforestry Can Enhance Food Security While Meeting Other Sustainable Development Goals. *Trop. Conserv. Sci.* **2017**, *10*, 194008291772066. [CrossRef]
16. Rezgui, F.; Rosati, A.; Lambarraa-Lehnhardt, F.; Paul, C.; Reckling, M. Assessing Mediterranean Agroforestry Systems: Agro-Economic Impacts of Olive Wild Asparagus in Central Italy. *Eur. J. Agron.* **2024**, *152*, 127012. [CrossRef]
17. Gomez-Casanovas, N.; Mwebaze, P.; Khanna, M.; Branham, B.; Time, A.; DeLucia, E.H.; Bernacchi, C.J.; Knapp, A.K.; Hoque, M.J.; Miljkovic, N.; et al. Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production. *Cell Rep. Phys. Sci.* **2023**, *4*, 101518. [CrossRef]
18. Trommsdorff, M.; Kang, J.; Reise, C.; Schindele, S.; Bopp, G.; Ehmann, A.; Weselek, A.; Högy, P.; Obergfell, T. Combining Food and Energy Production: Design of an Agrivoltaic System Applied in Arable and Vegetable Farming in Germany. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110694. [CrossRef]
19. Warmann, E.; Jenerette, G.D.; Barron-Gafford, G.A. Agrivoltaic System Design Tools for Managing Trade-Offs between Energy Production, Crop Productivity and Water Consumption. *Environ. Res. Lett.* **2024**, *19*, 034046. [CrossRef]
20. Magarelli, A.; Mazzeo, A.; Ferrara, G. Fruit Crop Species with Agrivoltaic Systems: A Critical Review. *Agronomy* **2024**, *14*, 722. [CrossRef]
21. Turnley, J.W.; Grant, A.; Schull, V.Z.; Cammarano, D.; Sesmero, J.; Agrawal, R. The Viability of Photovoltaics on Agricultural Land: Can PV Solve the Food vs Fuel Debate? *J. Clean. Prod.* **2024**, *469*, 143191. [CrossRef]
22. Bellone, Y.; Croci, M.; Impollonia, G.; Nik Zad, A.; Colauzzi, M.; Campana, P.E.; Amaducci, S. Simulation-Based Decision Support for Agrivoltaic Systems. *Appl. Energy* **2024**, *369*, 123490. [CrossRef]
23. Zainali, S.; Qadir, O.; Parlak, S.C.; Lu, S.M.; Avelin, A.; Stridh, B.; Campana, P.E. Computational Fluid Dynamics Modelling of Microclimate for a Vertical Agrivoltaic System. *Energy Nexus* **2023**, *9*, 100173. [CrossRef]
24. Zhang, L.; Yang, Z.; Wu, X.; Wang, W.; Yang, C.; Xu, G.; Wu, C.; Bao, E. Open-Field Agrivoltaic System Impacts on Photothermal Environment and Light Environment Simulation Analysis in Eastern China. *Agronomy* **2023**, *13*, 1820. [CrossRef]
25. Tekie, S.; Zainali, S.; Zidane, T.E.K.; Ma Lu, S.; Guezgouz, M.; Zhang, J.; Amaducci, S.; Campana, P. Unraveling the Crop Yield Response under Shading Conditions through the Deployment of a Drought Index. *Preprint* **2024**. [CrossRef]
26. Varo-Martínez, M.; López-Bernal, A.; Fernández De Ahumada, L.M.; López-Luque, R.; Villalobos, F.J. Simulation Model for Electrical and Agricultural Productivity of an Olive Hedgerow Agrivoltaic System. *J. Clean. Prod.* **2024**, *477*, 143888. [CrossRef]
27. Ukwu, U.N.; Muller, O.; Meier-Grüll, M.; Uguru, M.I. Agrivoltaics Shading Enhanced the Microclimate, Photosynthesis, Growth and Yields of Vigna Radiata Genotypes in Tropical Nigeria. *Sci. Rep.* **2025**, *15*, 1190. [CrossRef]
28. Randle-Boggis, R.J.; Barron-Gafford, G.A.; Kimaro, A.A.; Lamanna, C.; Macharia, C.; Maro, J.; Mbele, A.; Hartley, S.E. Harvesting the Sun Twice: Energy, Food and Water Benefits from Agrivoltaics in East Africa. *Renew. Sustain. Energy Rev.* **2025**, *208*, 115066. [CrossRef]
29. Al Mamun, M.A.; Garba, I.I.; Campbell, S.; Dargusch, P.; deVoil, P.; Aziz, A.A. Biomass Production of a Sub-Tropical Grass under Different Photovoltaic Installations Using Different Grazing Strategies. *Agric. Syst.* **2023**, *208*, 103662. [CrossRef]
30. Luo, J.; Luo, Z.; Li, W.; Shi, W.; Sui, X. The Early Effects of an Agrivoltaic System within a Different Crop Cultivation on Soil Quality in Dry–Hot Valley Eco-Fragile Areas. *Agronomy* **2024**, *14*, 584. [CrossRef]
31. Noor, N.F.M.; Reeza, A.A. Effects of Solar Photovoltaic Installation on Microclimate and Soil Properties in UiTM 50MWac Solar Park, Malaysia. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1059*, 012031. [CrossRef]
32. Juillion, P.; Lopez, G.; Fumey, D.; Lesniak, V.; Génard, M.; Vercambre, G. Shading Apple Trees with an Agrivoltaic System: Impact on Water Relations, Leaf Morphophysiological Characteristics and Yield Determinants. *Sci. Hortic.* **2022**, *306*, 111434. [CrossRef]

33. Dupraz, C. Assessment of the Ground Coverage Ratio of Agrivoltaic Systems as a Proxy for Potential Crop Productivity. *Agroforest Syst.* **2024**, *98*, 2679–2696. [CrossRef]
34. Ferrara, G.; Boselli, M.; Palasciano, M.; Mazzeo, A. Effect of Shading Determined by Photovoltaic Panels Installed above the Vines on the Performance of Cv. Corvina (*Vitis vinifera* L.). *Sci. Hortic.* **2023**, *308*, 111595. [CrossRef]
35. Fagnano, M.; Fiorentino, N.; Visconti, D.; Baldi, G.M.; Falce, M.; Acutis, M.; Genovese, M.; Di Blasi, M. Effects of a Photovoltaic Plant on Microclimate and Crops' Growth in a Mediterranean Area. *Agronomy* **2024**, *14*, 466. [CrossRef]
36. Soto-Gómez, D. Integration of Crops, Livestock, and Solar Panels: A Review of Agrivoltaic Systems. *Agronomy* **2024**, *14*, 1824. [CrossRef]
37. Disciglio, G.; Frabboni, L.; Tarantino, A.; Stasi, A. Association between Dynamic Agrivoltaic System and Cultivation: Viability, Yields and Qualitative Assessment of Medical Plants. *Sustainability* **2023**, *15*, 16252. [CrossRef]
38. Ferrara, G.; Mazzeo, A. Potential and Actual Bud Fruitfulness: A Tool for Predicting and Managing the Yield of Table Grape Varieties. *Agronomy* **2021**, *11*, 841. [CrossRef]
39. Dupraz, C.; Marrou, H.; Talbot, G.; Dufour, L.; Nogier, A.; Ferard, Y. Combining Solar Photovoltaic Panels and Food Crops for Optimising Land Use: Towards New Agrivoltaic Schemes. *Renew. Energy* **2011**, *36*, 2725–2732. [CrossRef]
40. *R Core Team R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2024.
41. Hassanpour Adeh, E.; Selker, J.S.; Higgins, C.W. Remarkable Agrivoltaic Influence on Soil Moisture, Micrometeorology and Water-Use Efficiency. *PLoS ONE* **2018**, *13*, e0203256. [CrossRef] [PubMed]
42. Armstrong, A.; Ostle, N.J.; Whitaker, J. Solar Park Microclimate and Vegetation Management Effects on Grassland Carbon Cycling. *Environ. Res. Lett.* **2016**, *11*, 074016. [CrossRef]
43. Choi, C.S.; Macknick, J.; Li, Y.; Bloom, D.; McCall, J.; Ravi, S. Environmental Co-Benefits of Maintaining Native Vegetation With Solar Photovoltaic Infrastructure. *Earth's Future* **2023**, *11*, e2023EF003542. [CrossRef]
44. Ali, N. Agrivoltaic System Success: A Review of Parameters That Matter. *J. Renew. Sustain. Energy* **2024**, *16*, 022703. [CrossRef]
45. Choi, C.S.; Macknick, J.; McCall, J.; Bertel, R.; Ravi, S. Multi-Year Analysis of Physical Interactions between Solar PV Arrays and Underlying Soil-Plant Complex in Vegetated Utility-Scale Systems. *Appl. Energy* **2024**, *365*, 123227. [CrossRef]
46. Amaducci, S.; Yin, X.; Colauzzi, M. Agrivoltaic Systems to Optimise Land Use for Electric Energy Production. *Appl. Energy* **2018**, *220*, 545–561. [CrossRef]
47. Marrou, H.; Wery, J.; Dufour, L.; Dupraz, C. Productivity and Radiation Use Efficiency of Lettuces Grown in the Partial Shade of Photovoltaic Panels. *Eur. J. Agron.* **2013**, *44*, 54–66. [CrossRef]
48. Şentürk, B.; Oylek, Y.; Kanar, Z.; Çelik, R.; Kurtuluş, G.; Ozden, T. The Impact of Photovoltaic Panels on the Environment and Yield Parameters in an Open Field Agrivoltaic System: A Case Study in Ayaş, Ankara. *Preprint* **2024**. [CrossRef]
49. Touil, S.; Richa, A.; Fizir, M.; Bingwa, B. Shading Effect of Photovoltaic Panels on Horticulture Crops Production: A Mini Review. *Rev. Environ. Sci. Biotechnol.* **2021**, *20*, 281–296. [CrossRef]
50. Barron-Gafford, G.A.; Pavao-Zuckerman, M.A.; Minor, R.L.; Sutter, L.F.; Barnett-Moreno, I.; Blackett, D.T.; Thompson, M.; Dimond, K.; Gerlak, A.K.; Nabhan, G.P.; et al. Agrivoltaics Provide Mutual Benefits across the Food–Energy–Water Nexus in Drylands. *Nat. Sustain.* **2019**, *2*, 848–855. [CrossRef]
51. Glick, A.; Ali, N.; Bossuyt, J.; Calaf, M.; Cal, R.B. Utility-Scale Solar PV Performance Enhancements through System-Level Modifications. *Sci. Rep.* **2020**, *10*, 10505. [CrossRef]
52. Williams, H.J.; Hashad, K.; Wang, H.; Max Zhang, K. The Potential for Agrivoltaics to Enhance Solar Farm Cooling. *Appl. Energy* **2023**, *332*, 120478. [CrossRef]
53. Rosati, A.; Kyle, P.; Azad, D.; Maggie, G.; Serkan, A.; Kirschten, H.M.; Higgins, C.W. Agroforestry versus Agrivoltaic: Spectral Composition of Transmitted Radiation and Implications for Understory Crops. *Agroforest Syst.* **2024**, *98*, 2697–2710. [CrossRef]
54. Dye, D.G. Spectral Composition and Quanta-to-energy Ratio of Diffuse Photosynthetically Active Radiation under Diverse Cloud Conditions. *J. Geophys. Res.* **2004**, *109*, 2003JD004251. [CrossRef]
55. Li, Z.; Zhao, Y.; Luo, Y.; Yang, L.; Li, P.; Jin, X.; Jiang, J.; Liu, R.; Gao, X. A Comparative Study on the Surface Radiation Characteristics of Photovoltaic Power Plant in the Gobi Desert. *Renew. Energy* **2022**, *182*, 764–771. [CrossRef]
56. Shepard, L.A.; Higgins, C.W.; Proctor, K.W. Agrivoltaics: Modeling the Relative Importance of Longwave Radiation from Solar Panels. *PLoS ONE* **2022**, *17*, e0273119. [CrossRef]
57. Paradiso, R.; Proietti, S. Light-Quality Manipulation to Control Plant Growth and Photomorphogenesis in Greenhouse Horticulture: The State of the Art and the Opportunities of Modern LED Systems. *J. Plant Growth Regul.* **2022**, *41*, 742–780. [CrossRef]
58. Terashima, I.; Fujita, T.; Inoue, T.; Chow, W.S.; Oguchi, R. Green Light Drives Leaf Photosynthesis More Efficiently than Red Light in Strong White Light: Revisiting the Enigmatic Question of Why Leaves Are Green. *Plant Cell Physiol.* **2009**, *50*, 684–697. [CrossRef] [PubMed]
59. Trojak, M.; Skowron, E.; Sobala, T.; Kocurek, M.; Pałyga, J. Effects of Partial Replacement of Red by Green Light in the Growth Spectrum on Photomorphogenesis and Photosynthesis in Tomato Plants. *Photosynth. Res.* **2022**, *151*, 295–312. [CrossRef] [PubMed]

60. Poupard, M.; Gallo, A.; Boulord, R.; Guillem, P.; Rolland, G.; Simonneau, T.; Christophe, A.; Pallas, B. Source-Sink Manipulations through Shading, Crop Load and Water Deficit Affect Plant Morphogenesis and Carbon Sink Priorities Leading to Contrasted Plant Carbon Status in Grapevine. *Ann. Bot.* **2024**, mcae203. [CrossRef] [PubMed]
61. Zhang, S.; Gong, J.; Xiao, C.; Yang, X.; Li, X.; Zhang, Z.; Song, L.; Zhang, W.; Dong, X.; Hu, Y. Bupleurum Chinense and Medicago Sativa Sustain Their Growth in Agrophotovoltaic Systems by Regulating Photosynthetic Mechanisms. *Renew. Sustain. Energy Rev.* **2024**, *189*, 114024. [CrossRef]
62. Jiang, S.; Tang, D.; Zhao, L.; Liang, C.; Cui, N.; Gong, D.; Wang, Y.; Feng, Y.; Hu, X.; Peng, Y. Effects of Different Photovoltaic Shading Levels on Kiwifruit Growth, Yield and Water Productivity under "Agrivoltaic" System in Southwest China. *Agric. Water Manag.* **2022**, *269*, 107675. [CrossRef]
63. Tiffon-Terrade, B.; Simonneau, T.; Boulord, R.; Saurin, N.; Caffarra, A.; Romieu, C.; Veyret, M.; Rolland, G.; Jacquet, O.; Berud, F.; et al. Could Intermittent Shading, as Produced in Agrivoltaics, Mitigate Global Warming Effects on Grapevine? In Proceedings of the IVES Conference Series, GiESCO 2023, Ithaca, NY, USA, 16–21 July 2023.
64. Tiffon-Terrade, B.; Simonneau, T.; Caffarra, A.; Boulord, R.; Pechier, P.; Saurin, N.; Romieu, C.; Fumey, D.; Christophe, A. Delayed Grape Ripening by Intermittent Shading to Counter Global Warming Depends on Carry-over Effects and Water Deficit Conditions. *OENO One* **2023**, *57*, 71–90. [CrossRef]
65. Willockx, B.; Reher, T.; Lavaert, C.; Herteleer, B.; Van De Poel, B.; Cappelle, J. Design and Evaluation of an Agrivoltaic System for a Pear Orchard. *Appl. Energy* **2024**, *353*, 122166. [CrossRef]
66. Gorjian, S.; Bousi, E.; Özdemir, Ö.E.; Trommsdorff, M.; Kumar, N.M.; Anand, A.; Kant, K.; Chopra, S.S. Progress and Challenges of Crop Production and Electricity Generation in Agrivoltaic Systems Using Semi-Transparent Photovoltaic Technology. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112126. [CrossRef]
67. Shalom, B.A.; Mittelman, G.; Kribus, A.; Vitoshkin, H. Optical and Electrical Performance of an Agrivoltaic Field with Spectral Beam Splitting. *Renew. Energy* **2023**, *219*, 119438. [CrossRef]
68. Zhang, Z.; Chang, T.; Zhang, X.; Liu, Y.; Zhao, H.; Li, M.; Liu, W.; Zhu, X.-G. Solar Spectral Splitting for Improved Photosynthetic Yield and Energy Polygeneration. *J. Clean. Prod.* **2024**, *442*, 140948. [CrossRef]
69. Fumey, D.; Lopez, G.; Persello, S.; Juillion, P.; Hitte, V.; Elamri, Y.; Tiffon-Terrade, B.; Christophe, A.; Simonneau, T.; Saurin, N.; et al. Dynamic Agrivoltaics, Climate Protection for Grapevine Driven by Artificial Intelligence. In Proceedings of the GiESCO 2023, International Viticulture and Enology Society, Ithaca, NY, USA, 16–21 July 2023.
70. Willockx, B.; Lavaert, C.; Cappelle, J. Performance Evaluation of Vertical Bifacial and Single-Axis Tracked Agrivoltaic Systems on Arable Land. *Renew. Energy* **2023**, *217*, 119181. [CrossRef]
71. Reher, T.; Willockx, B.; Schenk, A.; Bisschop, J.; Huyghe, Y.; Nicolaï, B.M.; Martens, J.A.; Diels, J.; Cappelle, J.; Van De Poel, B. Pear (Pyrus communis L. Cv. Conference) Has Shade-Tolerant Features Allowing for Consistent Agrivoltaic Crop Yield 2024. *bioRxiv* **2024**. [CrossRef]
72. Fattoruso, G.; Toscano, D.; Venturo, A.; Scognamiglio, A.; Fabricino, M.; Di Francia, G. A Spatial Multicriteria Analysis for a Regional Assessment of Eligible Areas for Sustainable Agrivoltaic Systems in Italy. *Sustainability* **2024**, *16*, 911. [CrossRef]
73. Lazo, J.; Trujillo-Baute, E.; Watts, D. Land-Use Dilemma: Evaluating the Transition from Crops to Solar Pv Plants Using a Real Options Approach. *Preprint* **2024**. [CrossRef]