



OPEN ACCESS

EDITED BY
Moritz Wagner,
Hochschule Geisenheim University,
Germany

REVIEWED BY
Andrea Magarelli,
University of Bari Aldo Moro, Italy
Marvin Pritts,
Cornell University, United States
Talat Özden,
Middle East Technical University, Türkiye

*CORRESPONDENCE
Bram Van de Poel
✉ bram.vandepoel@kuleuven.be
Thomas Reher
✉ thomas.reher@kuleuven.be
Jan Diels
✉ jan.diels@kuleuven.be

RECEIVED 30 September 2025
REVISED 19 January 2026
ACCEPTED 09 February 2026
PUBLISHED 25 February 2026

CITATION
Scheerlinck Z, Macdonald J, Lavaert C,
Cappelle J, Scheerlinck S, Diels J,
Van de Poel B and Reher T (2026)
Agrivoltaic layout types drive changes
in raspberry summer microclimate.
Front. Hortic. 5:1716398.
doi: 10.3389/fhort.2026.1716398

COPYRIGHT
© 2026 Scheerlinck, Macdonald, Lavaert,
Cappelle, Scheerlinck, Diels, Van de Poel
and Reher. This is an open-access article
distributed under the terms of the
[Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/)
(CC BY). The use, distribution or
reproduction in other forums is
permitted, provided the original
author(s) and the copyright owner(s) are
credited and that the original publication
in this journal is cited, in accordance
with accepted academic practice. No
use, distribution or reproduction is
permitted which does not comply with
these terms.

Agrivoltaic layout types drive changes in raspberry summer microclimate

Zoë Scheerlinck^{1,2}, James Macdonald³, Cas Lavaert^{4,5},
Jan Cappelle^{4,5}, Stijn Scheerlinck³, Jan Diels^{2,6*},
Bram Van de Poel^{1,2*} and Thomas Reher^{1,2*}

¹Molecular Plant Hormone Physiology, Division of Crop Biotechnics, Department of Biosystems, KU Leuven, Leuven, Belgium, ²KU Leuven Plant Institute (LPI), KU Leuven, Leuven, Belgium, ³ENGIE Research & Innovation – Laborelec, Solar Lab, Linkebeek, Belgium, ⁴Department of Electrical Engineering – Electa Ghent, KU Leuven, Ghent, Belgium, ⁵EnergyVille, Genk, Belgium, ⁶Division of Forest, Nature and Landscape, Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium

Soft fruit such as raspberry (*Rubus idaeus* L.) are commonly cultivated under protective structures to shield plants from adverse weather and extend harvest periods. Agrivoltaic systems offer an alternative to disposable plastic hoop covers by combining crop cultivation with solar energy production, yet their effects on crop microclimate remain poorly understood in temperate regions. In this study, we investigated summer canopy microclimate responses to different agrivoltaic layouts at two raspberry production sites in the Netherlands. At the first site, we compared semi-translucent portrait panels and landscape opaque panels with a conventional polyethylene tunnel. At the second site, an opaque panel system was evaluated alongside an open-field control. We monitored photosynthetically active radiation, canopy air temperature, humidity, and vapor pressure deficit from July to late August and compared both daily averages and diurnal maxima and minima. Agrivoltaic structures substantially reduced incoming radiation, with semi-translucent panels providing more uniform light distribution than opaque arrays. Average daily canopy temperature differed little across treatments (≤ 0.5 °C), but distinct diurnal patterns emerged: opaque arrays consistently cooled around solar noon on high-radiation days (up to 0.5°C cooler than control), while semi-translucent arrays occasionally induced midday warming of about 0.4°C under wind-calm conditions. Vapor pressure deficit under polyethylene tunnels was more similar to agrivoltaic systems than to open-air plots. Wind and rainfall modulated the microclimate changes independently of PV layout. Our findings highlight within-season design-specific trade-off for summer conditions: opaque panels favor thermal buffering but reduce light uniformity, whereas semi-translucent panels improve spatial light distribution at the cost of limited buffering and occasional warming. Microclimate contrasts depended on panel material properties, and are consistent with differences in radiation balance arising from material properties and ground coverage ratio among polyethylene films, opaque panels, and semi-translucent modules. They provide initial evidence that agrivoltaic systems can offer microclimate moderation comparable to conventional plastic polytunnels, while simultaneously generating renewable energy.

KEYWORDS

microclimate, APV, crop production, horticulture, radiation balance, shading effects, VPD

1 Introduction

Worldwide, the demand for both energy (International Energy Agency, 2025) and food (van Dijk et al., 2021) has been steadily increasing, driven by population growth and economic development. This growth, together with the associated human activities, is a major driver of climate change (Deuster et al., 2023). Addressing this dual demand requires more sustainable food production systems alongside the expansion of renewable energy. Solar energy stands out as one of the most economically relevant renewable energy sources to replace fossil fuels (Rongé et al., 2015). Global electricity generation from photovoltaics has risen sharply over the past 15 years and is projected to keep increasing (IEA, 2021). Furthermore, IEA forecasts an ongoing increase in this trend. However, setting up photovoltaic systems, especially on a utility scale, demands extensive land areas. This growing reliance on solar energy, combined with the limited availability of arable land, intensifies the competition for land use between photovoltaics (PV) and farming (Gomez-Casanovas et al., 2023). Agrivoltaics (AV), the combined use of land for solar panels and agricultural activity, has been highlighted as a solution to this land-use competition. By integrating PV systems with agriculture, AV not only addresses land competition but also contributes to several United Nations Sustainable Development Goals (Pandey et al., 2025; Zeddies et al., 2025). In addition to efficient land use, AV systems can, when properly paired with appropriate crops in appropriate geographies, offer protection to crops. The elevated PV panels above the crops can act as a protective shelter against extreme weather events (hail, wind and sunburn). However, installing a PV-based crop cover also causes significant changes to the crop's growing environment, primarily involving a reduction in solar radiation and modified water availability and distribution (Dupraz et al., 2011; Elamri et al., 2018b). Emerging agrivoltaic technologies, including semi-transparent and wavelength-selective PV materials, may additionally modify the spectral composition of transmitted light, although field-scale evidence linking such effects to crop responses remains limited (Ma Lu et al., 2024).

Crop species and cultivars differ strongly in their ability to cope with altered light and shading regimes, making their response to AV systems context-dependent. In Mediterranean (Csa, Csb), arid (BWh, BWk), and semi-arid (BSh, BSk) regions (Köppen climate classification (Beck et al., 2023), agrivoltaic shading has been shown to moderate crop and soil thermal conditions, while in arid and semi-arid climates it can additionally reduce atmospheric demand and alleviate plant drought stress through lower vapor pressure deficit and improved soil moisture retention (Marrou et al., 2013b; Barron-Gafford et al., 2019). Several studies demonstrate that these microclimatic benefits can translate into higher productivity for well-adapted crops. For example, in semi-arid regions (BSk), tepary bean (*Phaseolus acutifolius*) grown under PV shading achieved higher yields compared to full sun, attributed to extended growing periods and improved thermal and moisture conditions (Muir et al., 2026). Similarly, in Mediterranean regions of the Iberian Peninsula (Csa/Csb), AV systems have been reported to enhance crop productivity as well as nitrogen and water-use

efficiency, while reducing fertilizer-related greenhouse gas emissions (Rapella et al., 2026).

In more temperate regions, reduced light availability can constrain productivity and yields (Weselek et al., 2021). For example, in temperate oceanic climates (Cfb), such as Austria, reduced light availability can constrain productivity: maize and barley yields dropped by up to 25%, while winter wheat decreased by about 10% under AV shading, with the strongest negative effects occurring on cold, cloudy days (Thaler et al., 2024).

Agronomic research has therefore focused extensively on evaluating yield and quality performance of a wide range of crops under agrivoltaic conditions (Touil et al., 2021; Magarelli et al., 2024). These studies consistently demonstrate that crop selection is central to optimizing productivity in AV systems. Field and synthesis studies further show that positive responses are most consistently reported for fruit crops and grass-based systems grown under elevated, vertical, or dynamically managed AV configurations, particularly where microclimate buffering reduces heat and water stress, while arable crops in temperate regions display stronger sensitivity to reduced radiation and pronounced year-to-year variability (Magarelli et al., 2024; Rahimi Jahangirlou et al., 2026). Recent meta-analyses of crop shade responses have identified promising candidates for AV cultivation (Laub et al., 2022; Asa'a et al., 2024; Hermelink et al., 2024). Laub et al. (2022) suggested that berries, fruits and fruiting vegetables may benefit from shade and Asa'a et al. (2024) noted that Blackcurrant and Blueberries may tolerate shade up to a certain point. Berries and other soft fruits in general stand out as particularly well-suited for temperate regions due to their partial tolerance to reduced radiation levels and a shaded microenvironment (Hermelink et al., 2024).

Global warming has caused a marked and accelerating rise in VPD, which has emerged as a key driver of plant stress and drought-induced mortality (Grossiord et al., 2020). These effects are particularly relevant, as increased VPD tolerance can be considered a major determinant of plant performance and survival under drought conditions. The presence of PV panels in cropping systems affects light interception which can influence key microclimate parameters such as VPD, humidity, air and soil temperature, and wind speed. The reduction in daily solar radiation depends on a number of factors such as for example location, panel tilt, azimuth/direction, row spacing, and ground coverage ratio (GCR) of the PV modules (Dupraz et al., 2011; Majumdar and Pasqualetti, 2018; Weselek et al., 2019). In general, agrivoltaic systems can reduce air and soil temperatures by 1–4°C (Weselek et al., 2021; Juillion et al., 2022; Ferrara et al., 2023), improve crop water use efficiency by 20–47% (through reduced evaporative demand and moderated microclimate conditions) (Marrou et al., 2013a; Elamri et al., 2018a), and enhance drought resilience in water-limited regions (Ali Abaker Omer et al., 2025; Zhang et al., 2025b). Nevertheless, yield reductions may occur in light-demanding crops under strong shading. For example, in vineyards, opaque PV panels < 0.5 m above canopy level, (GCR 43%) mounted in rows perpendicular to the crop have been shown to lower daily mean air temperatures with a median decrease of about 1°C, while wind speed and VPD were consistently lower,

creating a slightly cooler and more humid canopy microclimate (Magarelli et al., 2025). In another AV trial on pears, no change in daily mean air temperature was reported but a reduced diurnal temperature amplitude was observed, with smaller differences between daytime maximum temperatures and nighttime minima under semitransparent AV, 4.2 m above ground-level (GCR 25.45% accounting for transparency (Reher et al., 2025).

Modifications in radiation, air temperature, humidity, wind, and soil moisture can have both positive and negative effects on crop physiology and are key drivers of the yield responses observed in agrivoltaic systems (Moore et al., 2021; Bernacchi et al., 2023). A thorough understanding of these microclimate effects is therefore essential to interpret agronomic performance and to evaluate which crops are most suited for agrivoltaic cultivation. Despite raspberries often being promoted as priority candidates for AV implementation, the effects of AV on their microclimate remain largely unexplored in temperate maritime conditions (Cfb) of Western Europe. In this context, the present study investigates how agrivoltaic and conventional shelter systems, differing in their degree of solar radiation reduction, influence key microclimatic parameters in raspberry (*Rubus idaeus* L.) production during summer.

We compared two pilot sites (less than 10 km apart) in the southeast of The Netherlands during summer, each with distinct shelter configurations. At the first site, one conventional polyethylene (PE) shelter was evaluated alongside two agrivoltaic designs with photovoltaic panels arranged in portrait semi-transparent and landscape opaque layouts. At the second site, an open-air reference was compared with a single agrivoltaic configuration. Together, these systems represent a gradient of radiation reduction from no shading in open-air conditions to different configurations of partial shading under the agrivoltaic shelters and the conventional PE raspberry shelters. Within this gradient, we quantified air temperature, light reduction, and vapor pressure deficit as primary indicators, and assessed how these microclimatic parameters interacted with environmental parameters such as rainfall, wind speed, and solar radiation. Our analyses reveal design-specific microclimatic effects: opaque agrivoltaic arrays tended to cool the canopy around solar noon and reduce VPD, whereas semi-transparent portrait arrays enhanced light uniformity but occasionally caused slight warming at midday, with minimal impact on daily averages. These responses varied depending on panel material properties, highlighting an important but understudied factor in agrivoltaic microclimate design. Our observations highlight potential trade-offs in agrivoltaic design for *Rubus idaeus* under temperate maritime conditions, where panel layout and density influence the balance between light availability and microclimate buffering.

2 Materials and methods

2.1 Site description

This study was conducted at two locations in the province of Noord-Brabant (The Netherlands) on a commercial raspberry farm

in a temperate maritime climate (Köppen class Cfb, Beck et al. (2023)). The first site was located at Eindje 6, 5715 PK Lierop (51.4428°N, 5.6662°E), on which raspberry plants are cultivated and the second at Nederweertseweg 5a, 5712 JX Someren (51.3280°N, 5.6960°E), on which raspberry canes are cultivated. At the Lierop site, two distinct AV configurations were implemented side by side (Figure 1A). Both systems consisted of photovoltaic panels mounted at a height of 1.97 m above ground level on the lower PV edge in a South-East orientation (azimuth 155°). The first configuration featured semi-transparent panels arranged in a portrait layout (Figure 1A1). While often referred to in industry terms as 'semi-transparent', we use the term 'semi-translucent' in this manuscript to emphasize that light transmission occurs primarily through intercell spacing and diffuse backsheet scattering rather than full optical transparency and that they are not transparent to longwave (heat) radiation. The second configuration employed standard opaque panels in a landscape layout (Figure 1A2).

Beneath these structures, hydroponically cultivated *Rubus idaeus* L. var. Sapphire plants were established from cold storage in early June. The plants were trained on a double trellis system, with rows spaced 2.6 m apart and individual plants spaced 0.33 meters within rows. For the control treatment, plots were covered with UV-stabilized PE plastic hoops (Figure 1A3), with a span of 2 m. At the Someren site, a single AV configuration was installed using standard opaque PV panels arranged in portrait, in South-West orientation (azimuth 240°) at a height of 2.2 m above ground level (Figure 1B). This setup supported hydroponically cultivated *Rubus idaeus* L. var. Majestic, which were propagated from cuttings in early June and trained using a dual-row trellis system, with rows spaced 2.5 m apart and individual plants spaced 0.25 m within rows. Control plots at Someren were maintained under open-air conditions without additional covering. Because plants were grown in a closed hydroponic system with controlled fertigation, soil properties and irrigation dynamics were not considered in this study.

At both locations, prototype agrivoltaic structures were installed. Both sites featured MiniAir Solar systems (manufactured and installed by Meteor Systems, Breda, The Netherlands, Appendix 1). In Lierop, two types of photovoltaic panels were compared: Bisol Lumina bifacial BX-200 panels (dimensions: 2110 × 1050 × 40 mm; 50% translucency, Prebold, Slovenia) and JA Solar JAM60S09 320/PR panels (dimensions: 1657 × 996 × 40 mm; opaque, Beijing, China). In Someren, only JA Solar JAM60S09 320/PR panels (dimensions: 1657 × 996 × 40 mm; opaque, Beijing, China) were installed. The first Lierop layout with portrait semi-translucent modules resulted in an inter-row gap of 0.49 m between the panels, whereas the landscape opaque modules resulted in an inter-row gap of 1.61 m between the panels. The Someren portrait configuration produced an inter-row gap of 0.85 m. These inter-row distances, combined with module dimensions, correspond to a ground coverage ratio (GCR) of 41% for the Lierop portrait layout, 38% for the Lierop landscape layout, and a GCR of 66% for the Someren site, as defined by Dupraz (2024) (see Appendix 2).

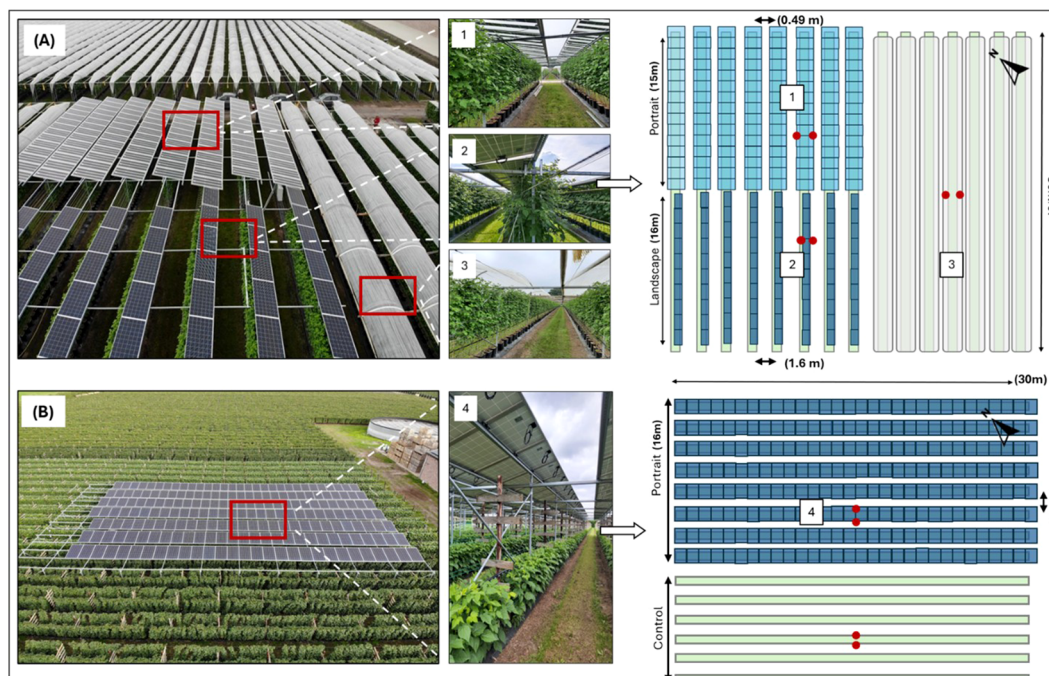


FIGURE 1

Trial location overview. (A) Lierop site with portrait semi-translucent panels (middle), landscape opaque panels (foreground) and control under polyethylene hoods (right). (B) Someren site with portrait opaque panels and control under open air (foreground). Red dots indicate the PAR at the top of the canopy on both sides and temperature/relative humidity sensor positions on the edge of the crop canopy. (PAR $n=2$, T°/RH $n=2$).

2.2 Microclimate monitoring

To characterize the microclimate within the raspberry canopy under AV structures and control conditions, a combination of radiation and atmospheric measurements was conducted at both research sites from July 22nd up to and including August 19th, 2021. Incident shortwave radiation data (J/cm^2) and wind speed (m/s) were obtained from the nearby Royal Netherlands Meteorological Institute (KNMI) weather station in Ell (51.1967°N, 5.7626°E, 15.35 km and 28.21 km to the south of the Someren and Lierop sites resp. at a similar elevation.). In addition, Photosynthetically active radiation (PAR) was measured at 10-minute intervals using SQ-500 quantum sensors (Apogee Instruments) connected to Squirrel SQ-2040/2F16 multi-channel data loggers (Grant Instruments). At both Someren and Lierop, sensors were installed at max canopy height (approximately 190 cm above ground level) along two opposing sides of the plots to quantify incoming radiation at the top of the crop canopy. At each timepoint, recorded PAR values were averaged across all sensor positions to estimate the mean photosynthetic photon flux density (PPFD) across the crop canopy. The Daily Light Integral (DLI) was then calculated from these averaged values according to Equation 1.

$$DLI(mol\ m^{-2}\ day^{-1}) = \frac{\sum_{i=0}^n (PAR_i \times \Delta t)}{10^6} \quad (1)$$

where n is the number of measurements per day, PAR_i is the instantaneous PPFD value at time i (in $\mu mol\ m^{-2}\ s^{-1}$), and Δt is the measurement interval (in seconds).

Air temperature (T°) and relative humidity (RH) were monitored using newly purchased and factory-calibrated EE08 probes (E+E Elektronik, Engerwitzdorf, Austria), housed within

RAD-17 passive radiation shields. No formal zero-drift test was performed, however sensor consistency was verified by comparing replicate sensors within each treatment during nighttime periods (00:00-04:00), when solar radiation does not affect readings and atmospheric conditions are well mixed due to sufficiently high wind speeds and fully overcast skies. For each treatment, the standard deviation of replicate measurements was calculated and verified (Appendix 3).

Sensors were installed on the canopy edge beneath the PV modules, rather than in the row gaps, to ensure measurements representative of the canopy microenvironment. The sensor locations are indicated by the red dots in Figure 1. All sensors were mounted on M10 threaded rods suspended from the AV structures using custom 3D-printed adapters, with placement ensuring at least one buffer row from the plot edge to minimize edge effects. Measurements were recorded at 10-second intervals and periodically uploaded to a cloud database.

VPD was calculated from the measured temperature and relative humidity. VPD (kPa) was computed in three steps. First, the saturation vapor pressure (e_s , kPa) was computed using Equation 2.

$$e_s(T) = 0.6108 \times \exp\left(\frac{17.27 \times T}{T + 237.3}\right) \quad (2)$$

Where T represents the air temperature in degrees Celsius. The actual vapor pressure (e_a , kPa) was then determined as Equation 3:

$$e_a = e_s \times \frac{RH}{100} \quad (3)$$

Finally, VPD (kPa) was defined as the difference between the saturation and actual vapor pressure (Equation 4):

$$VPD = e_s - e_a \quad (4)$$

2.3 Data analysis

2.3.1 Data processing and statistical analysis

All microclimate data were processed and analyzed using Python 3.11 (Python programming language, RRID: SCR_008394). Data handling was performed using the pandas, NumPy, and SciPy libraries, while visualizations were generated using matplotlib. Raw sensor data recorded at 10-second intervals were imported and chronologically sorted by timestamp. Short gaps in the data (≤ 5 minutes) were linearly interpolated to maintain continuity, while values falling outside predefined physical bounds (temperature $< -10^\circ\text{C}$ or $> 50^\circ\text{C}$; RH $< 0\%$ or $> 100\%$) were flagged for manual curation.

Ambient temperature differences between treatments and control (ΔT) were first tested for normality using the Shapiro-Wilk test. When the assumption of normality was satisfied, a one-sample t-test was used to test whether the mean temperature difference deviated from zero. If normality was violated, the Wilcoxon signed-rank test was applied as a non-parametric alternative with $p > 0.05$ considered non-significant.

2.3.2 Light availability calculations

To evaluate how AV configurations modified light availability, two complementary approaches were used. First, simulations of canopy-level PAR were conducted using a 3D view-factor model, following the methodology described by Willockx et al. (2022), using panel geometry and transmissivity as inputs. The model utilized a 3D representation of the AV system along with solar radiation data obtained from the nearby KNMI weather station in Ell. Only global horizontal irradiance (GHI) was available from the local weather station, so the Erbs model (Erbs et al., 1982) was used to estimate direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI), which are required as inputs for the light model.

Total horizontal irradiance at canopy height was calculated over a 2D grid and converted to photosynthetic photon flux density (PPFD) following Ge et al. (2011). This conversion was applied uniformly to both AV and control conditions at identical solar elevations. While semi-translucent and opaque PV modules can modify the spectral composition of transmitted radiation relative to open sky or PE covers, the spectral transmissivity of the Bisol Lumina panel backsheet used here has previously been shown to induce predominantly neutral attenuation across the PAR range, with limited wavelength selectivity (Reher et al. (2025), Supplementary Figure 2). Nevertheless, this represents a limitation of the model, as semi-translucent PV modules are likely to modify the spectrum differently than the PE covers. However, the authors of this study believe that the impact on the relative amount of PAR reaching the crops will be negligible.

The PPFD values were then compared to non-shaded reference conditions to determine the percentage of remaining PAR under the AV system. Secondly, field measurements of PAR were recorded within the crop canopy during the fruiting period to validate the

simulated patterns. Subsequently, DLI was derived from canopy PAR, and its relationship with external shortwave radiation from the nearest KNMI station was quantified.

2.3.3 Microclimate analysis

Canopy air temperature and VPD were calculated, and daily averages were derived to characterize baseline microclimate differences between treatments. Next, to characterize daily microclimatic extremes, we analyzed temperature data in fixed intervals around the expected minimum and maximum peaks: 11:00-15:00 for daytime maxima (maximum window after solar noon) and 00:00-04:00 for nighttime minima (minimum window before sunrise). All data points within these windows were subsetting from the original dataset and pooled to capture peak microclimatic conditions under variable weather. Within these windows, differences between the control and each AV treatment were calculated for both temperature difference (ΔT) and VPD difference (ΔVPD) (control - AV) from each recording. We report ΔT and ΔVPD as the difference between control and AV conditions, where positive values indicate warmer or drier canopies in control relative to AV. Subsequently, days were classified as warm if the daily maximum temperature of at least one treatment reached $\geq 25^\circ\text{C}$, and as cold if the daily mean temperature of at least one treatment remained below 18°C .

2.3.4 External climatic factors classification

While PE or AV shelters generally provide high levels of weather protection, external factors still play a role. The effect of these external factors were investigated to frame the remaining variability in microclimate responses: rainfall days were categorized into three intensity classes to test for effects on VPD, no rain (< 0.1 mm/day), light rain ($0.1\text{--}7$ mm/day), and heavy rain (> 7 mm/day). Radiation days were grouped into high (sunny days > 2000 J/cm²) and low (cloudy days ≤ 800 J/cm²) classes to examine how solar (energy) input and buffering influenced temperature differences between treatments. Finally, wind speed was analyzed in interaction with radiation intensity to evaluate whether air movement modulated temperature differences.

3 Results

3.1 Light environment

3.1.1 Panel type and orientation determines both light reduction and distribution uniformity

Since available light, particularly PAR, directly influences plant growth and productivity, understanding light distribution is essential. The *in silico* simulations show distinct light reduction levels and spatial patterns for the different configurations (Figure 2, Table 1). At the Lierop site, the simulations showed that both the portrait semi-translucent (Figure 2A) and landscape opaque configurations (Figure 2B) reduced incoming PAR by an average

of 60.2% and 62.2%, versus open-sky respectively. In the portrait semi-translucent configuration (Figure 2A), light was distributed more uniformly across the canopy, as both the NW and SE side of the plant rows received similar levels of radiation under the portrait semi-translucent panels. By contrast, the landscape opaque configuration (Figure 2B) exhibited a higher heterogeneous PAR distribution. The SE side of the rows received substantially less light due to the opaque panels, while the NW side was well-illuminated, resulting in strong spatial variability in PAR (Table 1). Sensor measurements of PAR at Lierop, taken between 21st of July and August 19th, compared the AV plots with control under polyethylene covers rather than open-sky conditions. The measured DLI under the portrait semi-translucent configuration was 51% of the control, while the landscape opaque configuration transmitted 88%. At the Someren site (Figure 2C), simulations showed that, under the dense portrait opaque configuration, plants received only 35.6% of the PAR compared to the non-shaded reference condition, but the light distribution was largely uniform. The sensor measurements recorded 30% cumulative PAR under the AV panels.

3.2 Microclimate conditions

3.2.1 AV panels have minor effects on daily average temperature and VPD

Because PV panels capture energy and cause a reduced light availability, we expect an impact on canopy microclimate. We observed that daily average temperatures were generally higher in Lierop than in Someren, while differences between treatments within the same location were minor (Figure 3A). In Lierop, average daily temperature differences between PV configurations were small and approached the limit of detection of the sensors: the control vs AV landscape ranged from -0.069 to 0.20°C , the control vs AV portrait semi-translucent from -0.02 to 0.30°C , and AV landscape vs AV portrait semi-translucent from -0.13 to 0.22°C . At Someren, the average daily temperature difference between the control and AV configuration ranged from -0.14 to 0.21°C .

More pronounced effects were observed for the extreme temperature windows (both maxima and minima). In Lierop,

when comparing the control and landscape opaque configuration, the control plot exhibited on average $0.20 \pm 0.16^{\circ}\text{C}$ higher daily daytime maximum temperatures, while minimum temperatures differed only slightly ($-0.04 \pm 0.09^{\circ}\text{C}$). When comparing the control with the portrait semi-translucent configuration, maximum temperatures were similar ($0.08 \pm 0.24^{\circ}\text{C}$), but daily minimum temperatures were on average $0.28 \pm 0.1^{\circ}\text{C}$ lower in the portrait semi-translucent configuration. In Someren, where the control plot was fully exposed to open-air conditions, differences were more pronounced. The control plot recorded on average $0.52 \pm 0.26^{\circ}\text{C}$ higher daily daytime maximum temperatures than the agrivoltaic portrait opaque configuration, while daily minimum temperatures were on average $0.32 \pm 0.16^{\circ}\text{C}$ higher under the panels.

Daily average VPD values were generally higher in Lierop than in Someren (Figure 3B). In both locations, the control configuration typically exhibited higher daily average VPD than the AV configurations. In Lierop, differences between treatments were minor: the VPD difference ranged from -0.01 to 0.03 kPa for Control vs AV landscape opaque, from 0.00 to 0.04 kPa for control vs AV portrait semi-translucent, and from -0.01 to 0.03 kPa for AV landscape opaque vs AV portrait semi-translucent. In Someren, the difference between control and AV ranged from 0.01 to 0.03 kPa, indicating slightly more pronounced treatment effects compared to Lierop.

While daily averages show only subtle differences, AV panels appear to slightly moderate temperature extremes and reduce VPD, particularly in comparison with open-air conditions (Someren). To better understand these effects and their pattern, next, we explored how temperature differences evolve throughout the day and under varying weather conditions.

3.2.1.1 Solar radiation drives diurnal temperature differences between AV and control

Solar radiation intensity was found to be a key driver of diurnal temperature differences between control and AV plots. In Lierop (Figure 4A), the landscape opaque configuration showed minimal temperature differences with the control plot during the nighttime, regardless of radiation level. On high-radiation days, the control

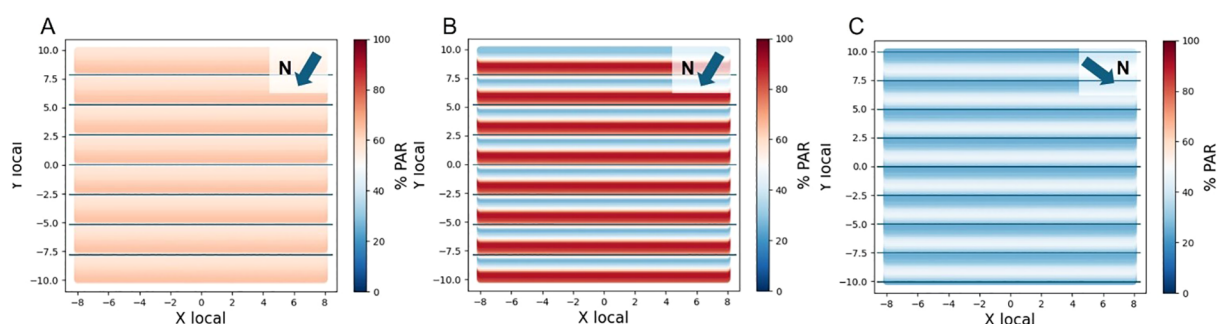


FIGURE 2

Simulated seasonal PAR radiation levels as compared to control, 0.7 m below canopy top. (A) Portrait semi-translucent bifacial panels, Lierop. (B) Landscape opaque panels, Lierop. (C) Portrait opaque panels, Someren. X axis along crop rows. Blue lines indicate center of crop row. Heatmap color code represents the % of PAR radiation modeled compared to the no-shading control plot. Edge effects and along-row heterogeneity are therefore not represented.

TABLE 1 Summary statistics of simulated seasonal PAR radiation relative to a non-shaded reference condition for the different agrivoltaic configurations shown in Figure 2. Average, standard deviation, minimum, maximum, and minimum-to-maximum PAR ratios are reported, quantifying both the overall light reduction and the degree of spatial heterogeneity within each configuration.

PAR metric	A) Portrait Lierop	B) Landscape Lierop	C) Portrait Someren
Avg PAR	60.2%	62.2%	35.6%
Std PAR	3.2%	22.1%	7.5%
Min PAR	54.9%	26.7%	24.8%
Max PAR	66.2%	90.5%	47.1%
Min PAR/Max PAR	0.83	0.30	0.53

was consistently warmer than the landscape configuration during the day, with ΔT values peaking around midday at approximately 0.5°C. This indicates a mild cooling effect of the landscape opaque panels under intense solar input. On low-radiation days, the same diurnal pattern in ΔT was present but much less pronounced, with ΔT values remaining close to zero throughout the day. The portrait semi-translucent configuration at Lierop showed a different pattern. At night, the control was consistently warmer than the AV-treated plot, with this effect being more pronounced on high-radiation days, showing nighttime ΔT values between 0.2°C and 0.4°C. During the first half of the day, however, the portrait semi-translucent configuration was about 0.4°C warmer than the control under high radiation conditions which diminished in the second half. In Someren (Figure 4B), on warm, high-radiation days, the control plot consistently exhibited higher temperatures than the AV plot during the day, with ΔT peaking around midday up to 0.8°C persisting till nightfall. During nighttime, temperature

differences were less pronounced and were about 0.3°C. On cold, low-radiation days, the same diurnal pattern was observed, but with reduced amplitude: ΔT peaked around 0.2°C at noon and again diminished to -0.15°C at night.

3.2.2 AV can have a cooling effect depending on the configuration

To investigate diurnal effects, temperature differences between the control and agrivoltaics configurations were analyzed separately for warmer and colder days. The violin plots (Figures 5, 6) show that the temperature response varied with solar panel configuration and time of day but generally followed a unimodal distribution. In Lierop (Figure 5) temperature differences between the control and agrivoltaics configurations were generally more pronounced during the day than at night. At night, the control and landscape opaque configurations showed little difference, while the portrait semi-translucent configuration was typically slightly colder than the control (0.25°C) - an effect that was more evident during warm nights. During warm middays, ΔT between the control and AV portrait semi-translucent ranged from approximately -1.0 to 0.5°C, while differences with the AV landscape opaque were mainly positive (-0.1 to 1°C), indicating a cooling effect of the PV panels during warm days.

Overall, temperature differences in Someren (Figure 6) were slightly more pronounced than in Lierop, with ΔT values ranging from approximately -1.0°C to +1.5°C. During warm midday periods, the agrivoltaics configuration tended to be cooler than the control, indicating a modest cooling effect under high radiation conditions. This effect was still present, but less pronounced, during colder midday periods. At night, in both warm and cold conditions, temperature differences were minimal, albeit it was slightly warmer under AV (0.1 - 0.5°C).

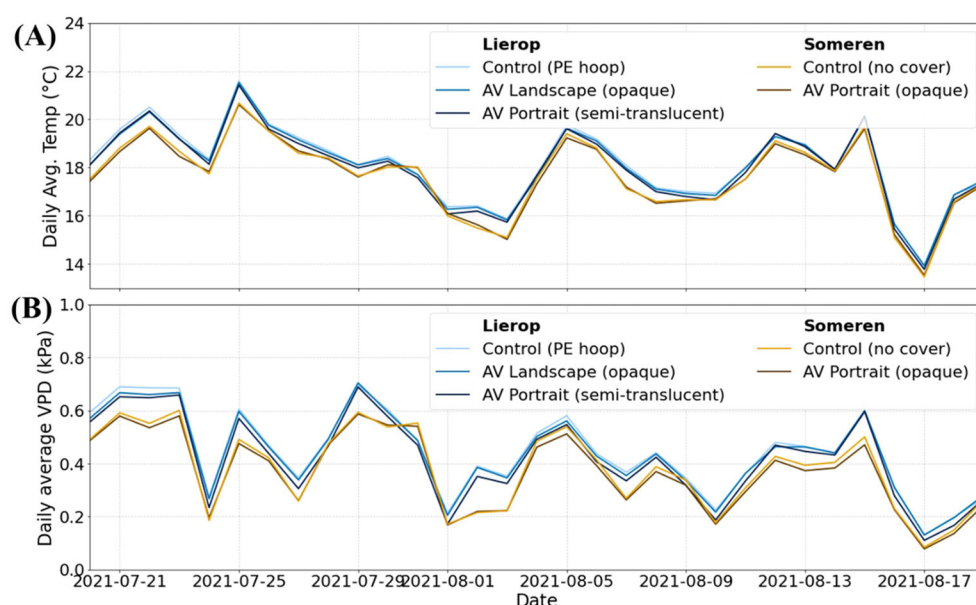


FIGURE 3

Daily mean canopy-air temperature (A) and VPD (B) recorded from 20 July to August 19th in two raspberry agrivoltaic sites under five treatments. Lierop in pale blue for polyethylene control, medium blue for landscape opaque and dark blue for portrait semi-translucent layouts and Someren in yellow for open air control and brown for portrait opaque layout.

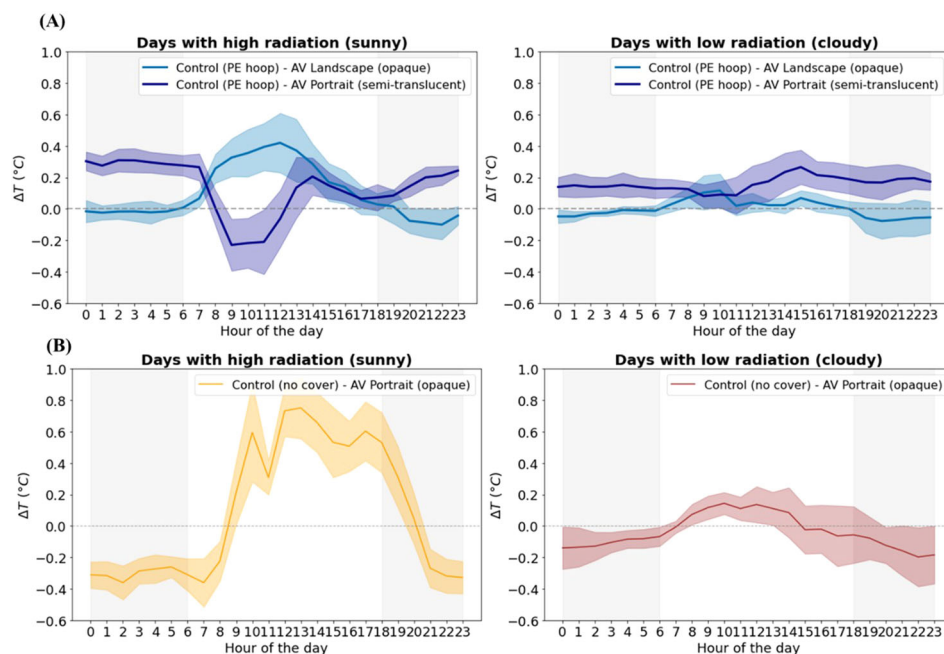


FIGURE 4

Diurnal canopy-air temperature differences (ΔT) between control plots and agrivoltaic (AV) configurations in (A) Lierop: landscape opaque (light blue) and portrait semi-translucent (dark blue) and (B) Someren, shown for days with high radiation (left) and low radiation (right). Lines represent mean ΔT (control - AV), with shaded areas indicating 95% confidence intervals.

3.2.3 AV microclimate effects vary with external weather conditions

3.2.3.1 Rainfall lowers VPD independently of AV configuration

The effect of rainfall on VPD was assessed by categorizing measurement days into three rainfall intensity classes: no rain, light rain and heavy rain. Statistical analysis showed that VPD values decreased significantly with increasing rainfall intensity, indicating higher atmospheric moisture following precipitation events

(Figure 7). The largest reduction in VPD occurred during heavy rainfall, consistent with the expected physical response of the atmosphere to increased water vapor. Despite these differences across rainfall categories, no significant differences in VPD were observed between the control and AV configurations.

3.2.3.2 Temperature contrasts under AV structures diminish with higher wind speeds

Figure 8 shows the relationship between wind speed and ΔT across different radiation regimes. Under low radiation conditions

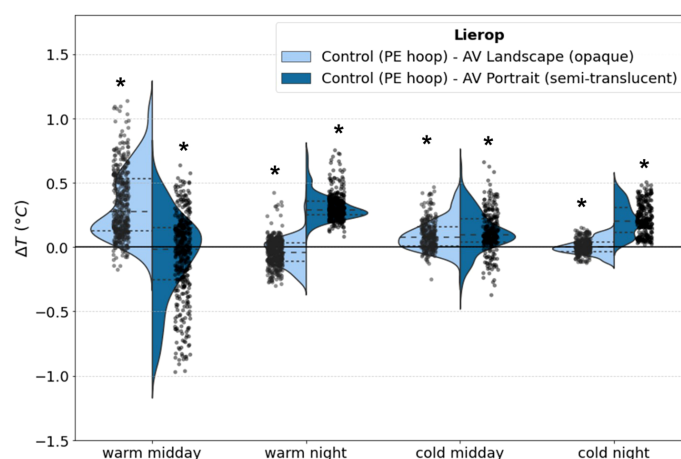


FIGURE 5

Violin plots showing temperature differences (ΔT) between the control and agrivoltaics (AV) landscape opaque (light blue) and portrait semi-translucent (dark blue) configurations in Lierop, separated by warm and cold days and by maximum (11:00–15:00) or minimum (00:00–04:00) temperature window (Appendix 4). Asterisks indicate significant differences ($p < 0.05$) between AV and control plots within each temperature and layout group.

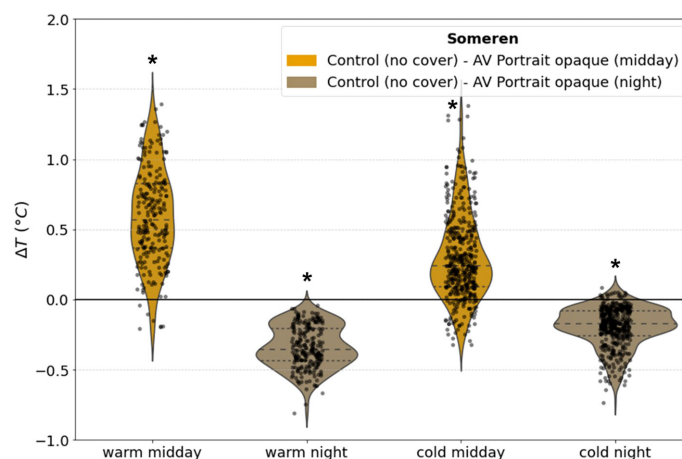


FIGURE 6

Violin plots showing temperature differences (ΔT) between the control and portrait opaque agrivoltaics (AV) configuration in Someren, separated by warm and cold days and by maximum (11:00–15:00, orange) or minimum (00:00–04:00, brown) temperature window (Appendix 5). Asterisks indicate significant differences ($p < 0.05$) between AV and control plots within each temperature group.

(<100 J/cm²/hour), wind had minimal impact on temperature differences across all treatments with ΔT around 0. However, under high radiation conditions (>175 J/cm²/hour), wind speed appeared to reduce the thermal contrast between control and AV plots.

The portrait semi-translucent configuration in Lierop (Figure 8A) revealed only minimal wind-induced temperature modulation under low radiation with ΔT mostly remaining constant. Higher wind speeds reduced temperature differences between AV and control fields. The landscape opaque configuration in Lierop (Figure 8B) exhibited a cooling effect under high radiation, with ΔT values dropping to -0.5°C at low wind speeds, which also diminished with increasing windspeed. In Someren (Figure 8C), higher radiation levels were associated with a cooling effect in the AV plot, with ΔT values reaching up to 1.0°C at low wind speeds, which gradually dissipates as windspeed increased.

4 Discussion

4.1 PV layout defines how radiation enters the crop

The modeled and observed variation in transmitted PAR intensity and its spatial homogeneity shows that each AV configuration creates a distinct canopy light environment (section 3.1). These differences are primarily governed by structural design parameters such as panel height, tilt angle, row orientation, and ground coverage ratio (GCR), which together determine both overall light availability and its distribution within the canopy. In addition to structural design parameters, the optical properties of PV modules also strongly influence canopy light conditions. Semi-translucent panels scatter incoming radiation, increasing lateral light penetration and improving homogeneity compared to

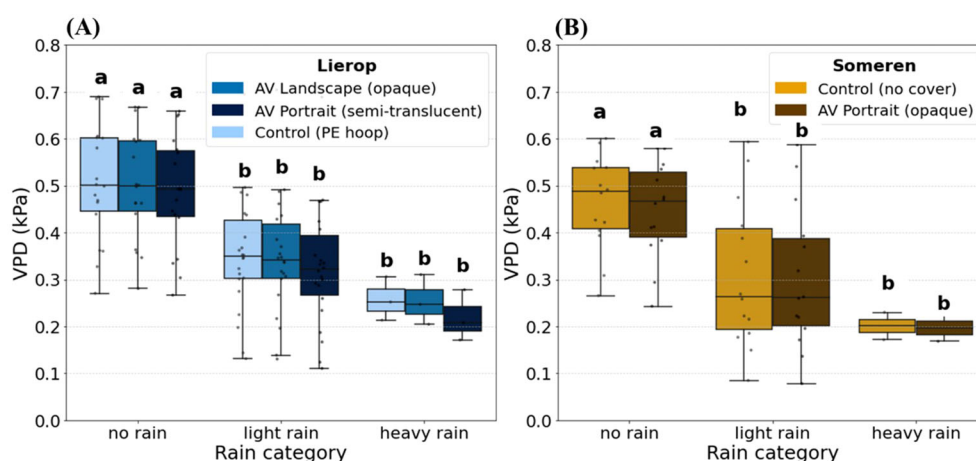


FIGURE 7

Daily VPD under different rain categories for the control and agrivoltaics configurations in Lierop (A) and the control and agrivoltaics configuration in Someren (B). Lierop in pale blue for polyethylene control, medium blue for landscape opaque and dark blue for portrait semi-translucent layouts, and Someren in yellow for open air control and brown for portrait opaque layout. Compact letter display indicates significant differences ($p < 0.05$) between rain categories and configurations within each location.

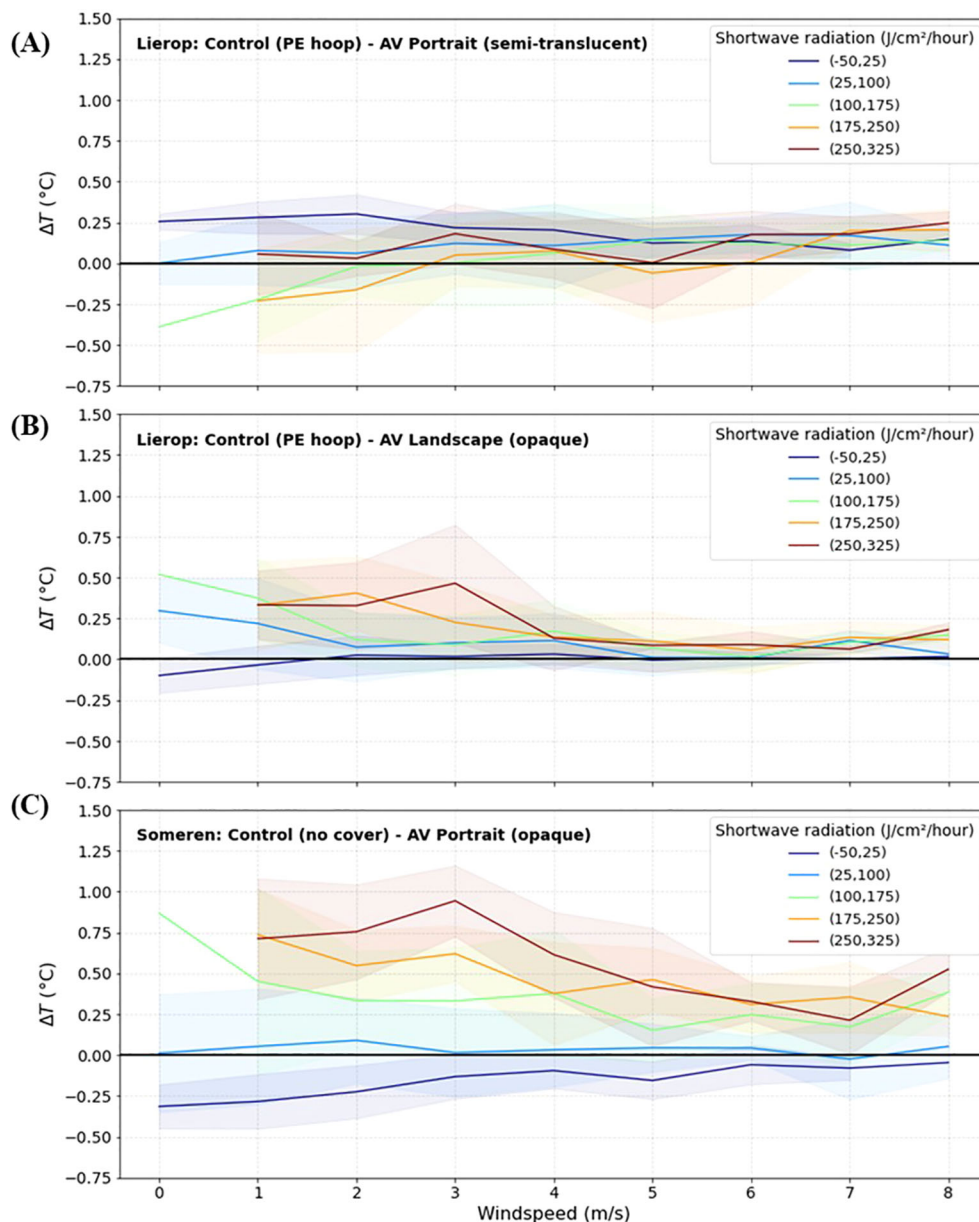


FIGURE 8

Relationship between wind speed (m/s) and daily canopy-air temperature difference (ΔT) under varying shortwave radiation levels ($\text{J}/\text{cm}^2/\text{hour}$) for both Lierop [portrait semi-translucent (A) and landscape opaque (B)] and Someren portrait opaque (C). Each line represents a radiation intensity class, with purple 0–25 $\text{J}/\text{cm}^2/\text{hour}$, blue 25–100 $\text{J}/\text{cm}^2/\text{hour}$, green 100–175 $\text{J}/\text{cm}^2/\text{hour}$, yellow 175–250 $\text{J}/\text{cm}^2/\text{hour}$ and red 250–325 $\text{J}/\text{cm}^2/\text{hour}$. Warmer colors indicating higher radiation with shaded areas indicating 95% confidence intervals.

opaque panels or polyethylene (PE) films. Such scattering effects resemble those of diffuse greenhouse glass, which has been shown to improve vertical light distribution and canopy photosynthesis under sunny conditions (Gu et al., 2002; Holsteens et al., 2020). Opaque modules, by contrast, reduce the sky view factor and diffuse radiation, producing discrete shading patterns of direct sunlight. The magnitude of diffuse light reduction depends mainly on module height and GCR, whereas the duration and intensity of these discrete shading patterns are governed by module width and elevation (Willockx et al., 2022). These differences help explain the contrasting spatial patterns observed in Lierop. In the portrait semi-translucent configuration, scattered radiation promoted similar PAR levels on both sides of the plant rows, resulting in a

comparatively homogeneous light environment. Conversely, the landscape opaque configuration produced broad, persistent shading on the SE side of the rows, while the NW side remained largely exposed to direct radiation. Similar effects have been reported in photovoltaic greenhouses, where checkerboard layouts improved lateral light penetration and spatial homogeneity compared to continuous row arrangements (Yano et al., 2010).

Overall, the modeled results are in reasonable agreement with the PAR measurements, except for the landscape configuration in Lierop. The large difference observed in this landscape configuration is likely due to non-uniform light distribution (Figure 2B), where PAR sensors may have been located in areas with above-average light levels, which could lead to an

overestimation of the mean PAR. Minor discrepancies for other configurations likely arise because the model by Willockx et al. (2022) does not account for the PV support structure or canopy development, potentially causing a slight underestimation of shading. Beyond these model-measurement differences, the results also highlight site- and configuration-specific variation in light transmission. For instance, part of the difference between the Lierop and Someren controls can be explained by the use of PE plastic hoop covers in Lierop versus open field conditions in Someren, which inherently reduce PAR transmission (Sangpradit, 2014). Further variation may have arisen from differences in canopy development stage and sensor positioning relative to the canopy top, which affect the amount of intercepted and measured light.

4.2 Light environment drives microclimate outcomes

In our experiments, the different light conditions induced distinct microclimatic responses beneath the covers. While average daily temperatures differed only slightly between AV and control sites (Figures 4A, B), pronounced differences emerged during hot and cold periods and differences in diurnal patterns revealed a relation to the PV cover type (Figure 4). Opaque panels, implemented in the landscape configuration in Lierop and the portrait configuration in Someren, consistently produced daytime cooling (Figures 4A, B), with effects most pronounced on high-radiation days, reaching peak temperature reductions of approximately 0.7–0.8°C. In contrast, semi-translucent panels, used in the portrait configuration in Lierop, showed warming in the first half of the day (07:00–15:00) (0.4°C) on high-radiation days (Figure 4A), an effect not observed under low-radiation conditions. Despite differences in site location, panel orientation, ground coverage ratio (38 % vs. 66 %), control treatment (open air vs. PE plastic hoop cover), and cultivar between Lierop and Someren, the microclimatic responses under opaque panels was remarkably similar. Semi-translucent panels, however, displayed a distinctly different pattern, indicating that panel type and material properties strongly influence microclimate, likely due to radiometric differences affecting the energy balance of the covered environment (Vox et al., 2010). Although temperature differences during warm and cold days at maximum or minimum temperature windows were consistently significant in statistical tests (Figures 5, 6), their absolute magnitudes were often small, approaching the accuracy limits of the sensors.

4.3 Cover transmissivity governs canopy energy flux

4.3.1 Energy balance and GCR

The distinct thermal patterns observed among different cover types may be explained by variations in the soil-plant energy balance and net radiation (R_n) in combination with the (effective) GCR.

R_n , defined as the difference between incoming and reflected shortwave radiation (sunlight) and incoming and outgoing

longwave radiation (heat radiation), is the primary driver of energy distribution in the soil-plant system (Rana et al., 2004). The energy supplied by R_n is partitioned into latent heat flux (energy used for evaporation and transpiration), sensible heat flux (energy that warms the air), and ground heat flux (energy conducted into or out of the soil). The net radiation balance (R_n , Equation 5) (Allen et al., 1998) is defined as:

$$R_n = (SW \downarrow - SW \uparrow) + (LW \downarrow - LW \uparrow) \quad (5)$$

where $SW \downarrow$ and $SW \uparrow$ are incoming and reflected shortwave radiation, and $LW \downarrow$ and $LW \uparrow$ are incoming and outgoing longwave radiation. Each term is influenced by radiometric properties of the cover materials (the way a material absorbs, reflects, or transmits radiation) as well as by the fraction of the surface that is covered (GCR).

Following Dupraz (2024), the unadjusted GCR represents the physical fraction of land covered by solar panels. For semi-translucent panels, Dupraz introduced an adjusted GCR to account for partial transmission of shortwave radiation, by multiplying the coverage by $(1 - \text{shortwave transmittance})$. This adjustment reflects the effective shading for solar radiation.

In the framework presented by Dupraz (2024), no explicit distinction is made between shortwave and longwave radiation. Because the GCR concept is used as a proxy for potential crop productivity, we assume that it implicitly refers to the photosynthetically active shortwave spectrum. However, longwave radiation governs thermal exchange and thus strongly affects heat retention beneath crop covers, making this distinction critical for interpreting microclimate effects in agrivoltaic and mixed-cover systems. Crucially, the transmittance of covering materials differs substantially between shortwave and longwave radiation. Photovoltaic modules with glass covers (semi-translucent) are partially transparent to shortwave radiation but effectively opaque to longwave radiation (Florence et al., 1953), whereas polyethylene (PE) plastic hoop covers transmit a substantial fraction of shortwave radiation while also partially transmitting longwave radiation (Balocco et al., 2018).

To account for this difference in longwave transmittance, we propose an extension to the Dupraz approach which applies the concept of adjusted GCR to both shortwave and longwave radiation separately. For each cover type, we determined two adjusted GCR values: one for shortwave radiation (accounting for solar light transmission) and one for longwave radiation (accounting for thermal radiation escape) (Appendix 2). Although still a simplification, this dual approach may provide a more accurate representation of how different cover materials modify the net radiation balance and, consequently, the microclimate beneath the cover.

4.3.2 Early-morning warming under semi-translucent panels

For shortwave radiation, PE plastic hoop covers transmit about 90% of incoming solar radiation (Sangpradit, 2014; Balocco et al., 2018), while semi-translucent panels transmit approximately 50%. This results in a very low adjusted shortwave GCR for PE plastic

hoop covers (8%, Appendix 2) and a substantially higher value for semi-translucent panels (41%, Appendix 2). For longwave radiation, PV panels are effectively opaque, so their longwave-relevant GCR equals the unadjusted GCR. Semi-translucent panels therefore have a high effective longwave GCR (81%, Appendix 2). In contrast, PE plastic hoop covers transmit about 40% of longwave radiation, reducing their effective longwave GCR to 46% (Appendix 2).

These different transmission fractions of short- and longwave radiation may help explain the observed diurnal temperature dynamics for Lierop (Figure 4A). On sunny days, air temperatures under semi-translucent panels are higher than under the control with PE plastic hoop covers during the early morning hours (until approximately 10–11 h, Figure 4A), despite their lower shortwave GCR compared to PE plastic hoop covers. Given that shortwave radiation dominates the daytime net radiation budget, this pattern may initially appear counterintuitive. However, we hypothesize that the longwave GCR is also playing an important role.

Although less solar radiation reaches the soil directly under semi-translucent panels, the absorbed energy could warm the panels and underlying surfaces, which may subsequently emit longwave radiation. Because semi-translucent panels are nearly opaque to longwave radiation and have a high effective longwave GCR, this thermal energy is likely trapped and may accumulate within the covered system. In contrast, PE plastic hoop covers allow a larger fraction of longwave radiation to escape, potentially reducing heat retention, resulting in lower early-morning air temperatures. As the day progresses, the cumulative net radiation under PE plastic hoop covers increases due to their much higher shortwave transmissivity. Eventually, this increased solar input may compensate for the greater longwave losses, and temperature differences between cover types may diminish as R_n becomes increasingly dominated by shortwave energy input during the day. Additionally, it is possible that these effects are further modulated by panel heating and atmospheric conditions. Semi-translucent panels absorb a substantial fraction of incoming solar radiation; while part of this energy is converted into electricity, the remainder heats the panel itself. According to the Stefan-Boltzmann law, warmer panels emit greater amounts of longwave radiation, which can contribute significantly to warming beneath the panels on high-radiation days (Meraj and Khan, 2019).

Importantly, we observed this warming effect during daytime only under low-wind conditions. In Figure 5, periods with higher temperatures beneath semi-translucent panels consistently coincide with high solar radiation and very low wind speeds. Under windy conditions or when solar radiation is low, enhanced convective heat exchange likely prevents early morning heat accumulation, and the temperature differences between cover types disappear.

4.3.3 Lack of warming under opaque panels

Building on the previous reasoning, the absence of early-morning warming beneath opaque panels in Lierop during the first half of sunny days further suggests that the combined effect of

short- and longwave GCR is critical in determining the effective energy input to the soil-plant system.

Although the adjusted shortwave is similar for semi-translucent and opaque panels in Lierop (41% versus 38%, Appendix 2), no warming effect is observed beneath opaque panels, suggesting that the differences in longwave energy retention may play again a role. The semi-translucent panels in Lierop exhibit a high effective longwave GCR (81%, Appendix 2), which may facilitate the trapping and accumulation of thermal radiation beneath the canopy. In contrast, the opaque panels in Lierop have a much lower longwave-relevant GCR (38%, Appendix 2), likely limiting their capacity to retain emitted thermal energy. While the longwave GCR of opaque panels and the control with PE plastic hoop covers is relatively similar (38% and 46%, respectively; Appendix 2), the control exhibits higher daytime temperatures. This observation supports the interpretation that shortwave radiation input dominates the daytime net radiation balance, as the control has a much lower shortwave GCR (8%) compared to opaque panels (38%).

Importantly, beyond GCR alone, additional factors may further modulate these radiative interactions. Panel height, for example, influences the redistribution of shortwave radiation within agrivoltaic systems, with consequences for both canopy light availability and thermal load, canopy energy balance and crop response (Zhang et al., 2025a). Panel orientation may also be important: although semi-translucent and opaque panels exhibit similar shortwave GCR values, semi-translucent panels still transmit approximately 50% of incoming shortwave radiation, whereas opaque panels transmit none. As a result, semi-translucent panels may allow solar energy to intermittently reach and warm the soil and vegetation below, while opaque panels impose more persistent shading during periods that depend on panel orientation and solar angle.

4.4 Wind diminishes canopy contrasts

As noted above, radiation alone does not explain all microclimate patterns. Airflow also plays a critical role by redistributing heat through convective processes. The localized warming observed under semi-translucent panels during periods of high-radiation and low wind is not directly visible in Figure 8. This is because Figure 8 shows daily average temperatures, which obscure diurnal temperature variations and overnight cooling effects. Nonetheless, our analysis indicates that in highly ventilated setups, air masses tend to equilibrate, and convective movements promote homogenization of air properties that depend on panel height, spacing, and orientation relative to prevailing wind directions (Vernier et al., 2025b). Marrou et al. (2013b) reported that wind did not significantly influence temperature differences on windy days. In contrast, our data, particularly from the relatively exposed Someren site, show that under low wind conditions, cooling beneath AV structures was enhanced, but during windy days this effect disappeared. This observation is consistent with the principles of convective heat transfer: reduced air mixing allows localized temperature gradients to persist, whereas higher wind

speeds promote homogenization of canopy temperatures (Jacobs et al., 1992).

While radiation has been the dominant factor considered in most previous AV studies, our results suggest that wind also influences microclimate formation beneath panel structures. Convective mixing can reduce localized warming or cooling effects caused by the modules, and although our evidence is limited, this mechanism has so far received little attention in AV research. Acknowledging the role of airflow therefore adds an additional perspective to the interpretation of our findings. VPD patterns largely tracked temperature across treatments, and no consistent differences were observed between configurations, consistent with earlier observations that shading-induced humidity responses are often minor compared to temperature effects (Marrou et al., 2013b). At the same time, the view-factor approach used here captures configuration-specific differences in radiation transmission and spatial heterogeneity but does not explicitly resolve airflow, turbulence, or coupled heat and moisture exchanges (Vernier et al., 2025a). Future work could therefore build on recent computational fluid dynamics studies (Vernier et al., 2025b) or more comprehensive energy balance and soil-plant-atmosphere continuum models to mechanistically link radiation, convection, temperature, humidity, and vapor pressure deficit, albeit with higher computational demands and currently limited spatial or temporal applicability (Vernier et al., 2026).

4.4.1 Agrivoltaic design dictates microclimate outcomes

This study quantified microclimate responses under contrasting agrivoltaic and conventional shelter designs during a limited summer monitoring window within a single growing season. Accordingly, the results reflect within-season responses under conditions of full canopy development and high evaporative demand, and do not capture spring or autumn transition periods or interannual variability. The magnitude and direction of the observed microclimate effects should therefore not be extrapolated beyond summer conditions without additional multi-season observations. Nevertheless, these data provide targeted, within-season insights into how agrivoltaic panel configuration interacts with prevailing weather conditions to shape the canopy microclimate, which forms the basis for the following discussion on design-dependent microclimate mechanisms and their agronomic relevance.

Clear contrasts between opaque and semi-translucent panels emerged, illustrating the broader design trade-off in agrivoltaics: whether to prioritize microclimate buffering or uniform light distribution, depending on crop type and regional climate. The implications extend beyond the physical environment to plant physiological responses. These environmental shifts also carry physiological consequences for crops, as changes in light intensity and dynamics directly shape photosynthesis and growth. Transient light patterns under semi-translucent panels resemble sunflecks in natural canopies, where shifting patches of light influence how efficiently leaves use available energy (Pearcy et al., 2006; Retkute et al., 2015). Plant growth is also guided by the spatial distribution

of light, with shoots and leaves orienting toward brighter zones. Agrivoltaic systems can help by lowering midday radiation peaks, which in turn reduces the risk of light and heat stress during sunny periods (Barron-Gafford et al., 2025).

These mechanisms are particularly relevant for raspberry cultivation, where periods of high radiation combined with low wind and high temperatures increase fruit susceptibility to physiological disorders, sunburn, and quality loss. While our results suggest that AV structures can buffer these stress conditions at canopy level, effects on fruit production outcomes remain to be evaluated. Shown here for raspberry crops, the balance between buffering and light distribution remains a key consideration across all horticultural AV applications.

5 Conclusions and future perspectives

This study provides within-season evidence that agrivoltaic panel layout and material modify raspberry canopy light environment and microclimate during the summer of 2021. Although both sites had comparable canopy volumes, differences in panel orientation, ground coverage ratio (GCR), shelter design, and cultivar complicate direct comparisons. Furthermore, key variables such as longwave radiation, canopy energy fluxes, and leaf temperatures were not explicitly measured, which constrains mechanistic interpretation of ΔT and ΔVPD .

However, taken together, our results indicate that differences in panel material, layout, and ground coverage ratio were associated with distinct radiation regimes and measurable temperature and vapor pressure deficit responses, which were most pronounced during specific diurnal periods under high radiation and low wind conditions. Opaque AV configurations provided microclimate buffering in a manner similar to or stronger than PE tunnels, highlighting their potential as replacements for plastic covers in horticultural production while enabling electricity generation. Semi-translucent panels improved light distribution but were associated with localized warming under high-radiation, low-wind conditions, highlighting a trade-off between thermal buffering and light homogeneity.

Contrasting responses under opaque and semi-translucent panels point to differences in how these structures interact with incoming and outgoing radiation. The observed patterns are consistent with differences in shortwave transmission and longwave heat retention, suggesting that combined radiative effects may play a role in shaping canopy temperature dynamics. Beyond radiation and shading, airflow emerged as a critical modulator of microclimate expression. Panel height, spacing, and orientation will influence convective heat exchange and humidity build-up. Optimizing agrivoltaic performance therefore requires integrated consideration of radiative properties and airflow in relation to prevailing wind conditions.

To validate and generalize these findings, future research should extend monitoring across full growing seasons and multiple years, explicitly quantify changes in canopy energy balance under different agrivoltaic array types, with dedicated measurement of shortwave

and longwave radiation components to better explain the observed temperature patterns. Collecting these data would not only clarify the mechanistic basis of how agrivoltaic systems redistribute energy within the canopy and alter latent versus sensible heat fluxes but also provide the empirical foundation for modeling canopy processes such as evapotranspiration.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: <https://doi.org/10.48804/FLUHT1>.

Author contributions

ZS: Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. JM: Conceptualization, Data curation, Project administration, Resources, Supervision, Writing – review & editing. CL: Formal analysis, Visualization, Writing – review & editing. JC: Supervision, Writing – review & editing. SS: Funding acquisition, Resources, Supervision, Writing – review & editing. JD: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. BP: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. TR: Conceptualization, Methodology, Project administration, Supervision, Writing – original draft.

Funding

The author(s) declared that financial support was received for this work and/or its publication. Funding for this research was provided by ENGIE Research & Innovation as well as by the European Union's Horizon 2020 research and innovation program project "HyPERFarm" (grant number 101000828); a Flanders Innovation and Entrepreneurship (VLAIO) TETRA grant project "Agrivoltaics" (grant number HBC.2019.2049); and a VLAIO LA-traject grant "Agri-PV: Gecombineerd fruit en groene stroom produceren" (grant number HBC.2022.0920).

Acknowledgments

We would like to thank Thwan Van Gennip, Sander Koenen, Jos Filippini, and Emiel Kuijpers for their support and input in

managing the orchard. Thanks to Erik Van Nieuwenhuijzen, Rob Kursten and Sergi Gispert Samarra for technical support. Thanks to Brech Willockx for discussions during the design phase. Thanks to Stijn Roden and Julie Vercruysse for helping with data collection.

Conflict of interest

Two of the co-authors, SS and JM, are affiliated with ENGIE Research & Innovation, an organization that funded this research. The study was conducted using a scientifically rigorous and objective methodology.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. During the preparation of this work the author(s) used OpenAI's ChatGPT 4 and 5 in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fhort.2026.1716398/full#supplementary-material>

References

Ali Abaker Omer, A., Li, M., Zhang, F., Hassaan, M. M. E., El Kolaly, W., Zhang, X., et al. (2025). Impacts of agrivoltaic systems on microclimate, water use efficiency, and

crop yield: A systematic review. *Renewable Sustain. Energy Rev.* 221, 115930. doi: 10.1016/j.rser.2025.115930

- Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements* (Rome, Italy: FAO).
- Asa'a, S., Reher, T., Rongé, J., Diels, J., Poortmans, J., Radhakrishnan, H. S., et al. (2024). A multidisciplinary view on agrivoltaics: Future of energy and agriculture. *Renewable Sustain. Energy Rev.* 200, 114515. doi: 10.1016/j.rser.2024.114515
- Balocco, C., Mercatelli, L., Azzali, N., Meucci, M., and Grazzini, G. (2018). Experimental transmittance of polyethylene films in the solar and infrared wavelengths. *Solar Energy* 165, 199–205. doi: 10.1016/j.solener.2018.03.011
- Barron-Gafford, G. A., Murphy, P., Salazar, A., Lepley, K., Rouini, N., Barnett-Moreno, I., et al. (2025). Agrivoltaics as a climate-smart and resilient solution for midday depression in photosynthesis in dryland regions. *NPJ Sustain. Agric.* 3, 32. doi: 10.1038/s44264-025-00073-1
- Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., et al. (2019). Agrivoltaics provide mutual benefits across the food-energy-water nexus in drylands. *Nat. Sustain.* 2, 848–855. doi: 10.1038/s41893-019-0364-5
- Beck, H. E., McVicar, T. R., Vergopolan, N., Berg, A., Lutsko, N. J., Dufour, A., et al. (2023). High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections. *Sci. Data* 10, 724. doi: 10.1038/s41597-023-02549-6
- Bernacchi, C. J., Ruiz-Vera, U. M., Siebers, M. H., DeLucia, N. J., and Ort, D. R. (2023). Short- and long-term warming events on photosynthetic physiology, growth, and yields of field grown crops. *Biochem. J.* 480, 999–1014. doi: 10.1042/BCJ20220433
- Deuster, C., Kajander, N., Muench, S., Natale, F., Nedee, A., Scapolo, F., et al. (2023). Demography and climate change, EUR 31512 EN, Publications Office of the European Union, Luxembourg, doi: 10.2760/26411, JRC133580
- Dupraz, C. (2024). Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity. *Agroforestry Syst.* 98, 2679–2696. doi: 10.1007/s10457-023-00906-3
- Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., and Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renew. Energy* 36, 2725–2732. doi: 10.1016/j.renene.2011.03.005
- Elamri, Y., Cheviron, B., Lopez, J.-M., Dejean, C., and Belaud, G. (2018a). Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. *Agric. Water Manage.* 208, 440–453. doi: 10.1016/j.agwat.2018.07.001
- Elamri, Y., Cheviron, B., Mange, A., Dejean, C., Liron, F., and Belaud, G. (2018b). Rain concentration and sheltering effect of solar panels on cultivated plots. *Hydrol. Earth Syst. Sci.* 22, 1285–1298. doi: 10.5194/hess-22-1285-2018
- Erbs, D. G., Klein, S. A., and Duffie, J. A. (1982). Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy* 28, 293–302. doi: 10.1016/0038-092X(82)90302-4
- Ferrara, G., Boselli, M., Palasciano, M., and Mazzeo, A. (2023). Effect of shading determined by photovoltaic panels installed above the vines on the performance of cv. Corvina (Vitis vinifera L.). *Sci. Hortic.* 308, 111595. doi: 10.1016/j.scienta.2022.111595
- Ge, S., Smith, R. G., Jacovides, C. P., Kramer, M. G., and Carruthers, R. I. (2011). Dynamics of photosynthetic photon flux density (PPFD) and estimates in coastal northern California. *Theor. Appl. Climatol.* 105, 107–118. doi: 10.1007/s00704-010-0368-6
- Gomez-Casanovas, N., Mwembaze, P., Khanna, M., Branham, B., Time, A., DeLucia, E. H., et al. (2023). Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production. *Cell Rep. Phys. Sci.* 4, 8. doi: 10.1016/j.xcrp.2023.101518
- Grossiord, C., Buckley, T. N., Cernusak, L. A., Novick, K. A., Poulter, B., Siegwolf, R. T. W., et al. (2020). Plant responses to rising vapor pressure deficit. *New Phytol.* 226, 1550–1566. doi: 10.1111/nph.16485
- Gu, L., Baldocchi, D., Verma, S. B., Black, T. A., Vesala, T., Falge, E. M., et al. (2002). Advantages of diffuse radiation for terrestrial ecosystem productivity. *J. Geophysical Res. Atmospheres* 107, ACL 2–1-ACL 2-23. doi: 10.1029/2001jd001242
- Hermelink, M. I., Maestrini, B., and de Ruijter, F. J. (2024). Berry shade tolerance for agrivoltaics systems: A meta-analysis. *Sci. Hortic.* 330, 113062. doi: 10.1016/j.scienta.2024.113062
- Holsteens, K., Moerkens, R., Van de Poel, B., and Vanlommel, W. (2020). The effect of low-haze diffuse glass on greenhouse tomato and bell pepper production and light distribution properties. *Plants* 9, 1–15. doi: 10.3390/plants9070806
- IEA (2021). *Key world energy statistics 2021* (Paris: OECD). doi: 10.1787/2ef8cebc-en
- International Energy Agency (2025). *Global energy review 2025*. Available online at: www.iea.org (Accessed July 23, 2025).
- Jacobs, A. F. G., Van Boxel, J. H., and Shaw, R. H. (1992). Horizontal and vertical distribution of air temperature in a vegetation canopy. *NJAS* 40, 359–372. doi: 10.18174/njas.v40i4.16498
- Juillion, P., Lopez, G., Fumey, D., Lesniak, V., Génard, M., and Vercambre, G. (2022). Shading apple trees with an agrivoltaic system: Impact on water relations, leaf morphophysiological characteristics and yield determinants. *Sci. Hortic.* 306, 111434. doi: 10.1016/j.scienta.2022.111434
- Laub, M., Pataczek, L., Feuerbacher, A., Zikeli, S., and Högy, P. (2022). Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis. *Agron. Sustain. Dev.* 42, 51. doi: 10.1007/s13593-022-00783-7
- Magarelli, A., Mazzeo, A., and Ferrara, G. (2024). Fruit crop species with agrivoltaic systems: A critical review. *Agronomy* 14, 722. doi: 10.3390/agronomy14040722
- Magarelli, A., Mazzeo, A., and Ferrara, G. (2025). Exploring the grape agrivoltaic system: climate modulation and vine benefits in the puglia region, southeastern Italy. *Horticulturae* 11, 160. doi: 10.3390/horticulturae11020160
- Majumdar, D., and Pasqualetti, M. J. (2018). Dual use of agricultural land: Introducing 'agrivoltaics' in Phoenix Metropolitan Statistical Area, USA. *Landsc. Urban Plan.* 170, 150–168. doi: 10.1016/j.landurbplan.2017.10.011
- Ma Lu, S., Amaducci, S., Gorjian, S., Haworth, M., Hägglund, C., Ma, T., et al. (2024). Wavelength-selective solar photovoltaic systems to enhance spectral sharing of sunlight in agrivoltaics. *Joule* 8, 2483–2522. doi: 10.1016/j.joule.2024.08.006
- Marrou, H., Dufour, L., and Wery, J. (2013a). How does a shelter of solar panels influence water flows in a soil-crop system? *Eur. J. Agron.* 50, 38–51. doi: 10.1016/j.eja.2013.05.004
- Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., and Wery, J. (2013b). Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? *Agric. For. Meteorol.* 177, 117–132. doi: 10.1016/j.agrformet.2013.04.012
- Meraj, M., and Khan, M. E. (2019). Thermal modeling of opaque and semi-transparent photovoltaic (PV) module. *Int. J. Innovative Technol. Exploring Eng.* 8, 3271–3276. doi: 10.35940/ijitee.L3616.1081219
- Moore, C. E., Meacham-Hensold, K., Lemonnier, P., Slattery, R. A., Benjamin, C., Bernacchi, C. J., et al. (2021). The effect of increasing temperature on crop photosynthesis: From enzymes to ecosystems. *J. Exp. Bot.* 72, 2822–2844. doi: 10.1093/jxb/erab090
- Muir, R., Kushwaha, P., Barron-Gafford, G. A., and Babst-Kostecka, A. (2026). Enhancing climate-smart crop performance in arid agrivoltaics systems: effects of photovoltaic shading and soil amendments on tepary bean growth, yield, and associated soil microbiome. *Plant Soil*. doi: 10.1007/s11104-025-08247-z
- Pandey, G., Lyden, S., Franklin, E., and Harrison, M. T. (2025). Agrivoltaics as an SDG enabler: Trade-offs and co-benefits for food security, energy generation and emissions mitigation. *Resources Environ. Sustainability* 19, 100186. doi: 10.1016/j.resenv.2024.100186
- Pearcy, R. W., Krall, J. P., and Sassenrath-Cole, G. F. (2006). Photosynthesis in fluctuating light environments. *Photosynthesis Environ.* 321–346. doi: 10.1007/0-306-48135-9_13
- Rahimi Jahangirlou, M., Pullens, J. W. M., Lindhardt, M. K. K., El Khoury, Y. V., Antoniu, V., Manevski, K., et al. (2026). Agrivoltaic systems: Trade-offs on microclimate, physiology, yield and canopy thermal-spectral maps. *Agric. Syst.* 232, 104557. doi: 10.1016/j.agry.2025.104557
- Rana, G., Katerji, N., Introna, M., and Hammami, A. (2004). Microclimate and plant water relationship of the “overhead” table grape vineyard managed with three different covering techniques. *Sci. Hortic.* 102, 105–120. doi: 10.1016/j.scienta.2003.12.008
- Rapella, L., Viovy, N., Faranda, D., and Drobinski, P. (2026). Optimizing fertilizer use for sustainable crops with Agrivoltaics in Mediterranean climates. *NPJ Sustain. Agric.* 4, 3. doi: 10.1038/s44264-025-00112-x
- Reher, T., Willockx, B., Schenk, A., Bisschop, J., Huyghe, Y., Nicolai, B. M., et al. (2025). Agrivoltaic cultivation of pears under semi-transparent panels reduces yield consistently and maintains fruit quality in Belgium. *Agron. Sustain. Dev.* 45, 25. doi: 10.1007/s13593-025-01019-0
- Retkute, R., Smith-Unna, S. E., Smith, R. W., Burgess, A. J., Jensen, O. E., Johnson, G. N., et al. (2015). Exploiting heterogeneous environments: Does photosynthetic acclimation optimize carbon gain in fluctuating light? *J. Exp. Bot.* 66, 2437–2447. doi: 10.1093/jxb/erv055
- Rongé, J., Bosserez, T., Huguenin, L., Dumortier, M., Haussener, S., and Martens, J. A. (2015). Solar hydrogen reaching maturity. *Oil Gas Sci. Technol. - Rev. d'IFP Energies nouvelles* 70, 863–876. doi: 10.2516/ogst/2014061
- Sangpradit, K. (2014). “Study of the solar transmissivity of plastic cladding materials and influence of dust and dirt on greenhouse cultivations,” in *Energy procedia* (Elsevier Ltd) 56, 566–573. doi: 10.1016/j.egypro.2014.07.194
- Thaler, S., Berger, K., Eitzinger, J., Mahnaz, A., Shala-Mayrhofer, V., Zamini, S., et al. (2024). Radiation limits the yield potential of main crops under selected agrivoltaic designs—A case study of a new shading simulation method. *Agronomy* 14, 11. doi: 10.3390/agronomy14112511
- Touil, S., Richa, A., Fizir, M., and Bingwa, B. (2021). Shading effect of photovoltaic panels on horticulture crops production: a mini review. *Rev. Environ. Sci. Biotechnol.* 20, 281–296. doi: 10.1007/s11157-021-09572-2
- van Dijk, M., Morley, T., Rau, M. L., and Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nat. Food* 2, 494–501. doi: 10.1038/s43016-021-00322-9
- Vernier, J., Amiot, B., Edouard, S., Dupont, E., Ferrand, M., Combes, D., et al. (2025a). *How to model wind flows in vegetative canopies and plant-air convective heat exchanges? A special focus on agrivoltaics 2*. Available online at: https://ssrn.com/abstract=5761642.

- Vernier, J., Berlioux, B., Amiot, B., Edouard, S., Ferrand, M., Dupont, E., et al. (2025b). An innovative method based on CFD to simulate the influence of photovoltaic panels on the microclimate in agrivoltaic conditions. *Solar Energy* 297, 113571. doi: 10.1016/j.solener.2025.113571
- Vernier, J., Edouard, S., Amiot, B., Ferrand, M., Tuzet, A., Dupont, E., et al. (2026). A Soil-Plant-Atmosphere Continuum model coupled to CFD to simulate plant energy and water exchanges in heterogeneous microclimates. *Agric. For. Meteorol.* 376, 110906. doi: 10.1016/j.agrformet.2025.110906
- Vox, G., Teitel, M., Pardossi, A., Minuto, A., Tinivella, F., and Schettini, E. (2010). Sustainable greenhouse systems. *Sustainable agriculture: technology, planning and management*. 14, 1–79.
- Weselek, A., Bauerle, A., Hartung, J., Zikeli, S., Lewandowski, I., and Högy, P. (2021). Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agron. Sustain. Dev.* 41, 59. doi: 10.1007/s13593-021-00714-y
- Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., and Högy, P. (2019). Agrophotovoltaic systems: applications, challenges, and opportunities. A review. *Agron. Sustain. Dev.* 39, 35. doi: 10.1007/s13593-019-0581-3
- Willockx, B., Lavaert, C., and Cappelle, J. (2022). Geospatial assessment of elevated agrivoltaics on arable land in Europe to highlight the implications on design, land use and economic level. *Energy Rep.* 8, 8736–8751. doi: 10.1016/j.egy.2022.06.076
- Yano, A., Kadowaki, M., Furue, A., Tamaki, N., Tanaka, T., Hiraki, E., et al. (2010). Shading and electrical features of a photovoltaic array mounted inside the roof of an east-west oriented greenhouse. *Biosyst. Eng.* 106, 367–377. doi: 10.1016/j.biosystemseng.2010.04.007
- Zeddies, H. H., Parlasca, M., and Qaim, M. (2025). Agrivoltaics increases public acceptance of solar energy production on agricultural land. *Land Use Policy* 156, 107604. doi: 10.1016/j.landusepol.2025.107604
- Zhang, L., Gong, J., Yang, Z., Wu, X., Wang, W., Yang, C., et al. (2025a). Evaluating the contribution of decreasing heights of photovoltaic panels on light environment and agricultural production in agrivoltaic systems. *J. Clean. Prod.* 495, 9. doi: 10.1016/j.jclepro.2025.145091
- Zhang, W., Hendriks, P. W., Uchanski, M., Page, S., Renwick, A., Maxwell, T., et al. (2025b). Climatic and design tipping points in agrivoltaic crop production systems. A meta-analysis. *Agron. Sustain. Dev.* 45, 69. doi: 10.1007/s13593-025-01060-z

Glossary

AV	agrivoltaic	PPFD	photosynthetic photon flux density
DHI	diffuse horizontal irradiance	PV	photovoltaic
DLI	daily light integral	RH	relative humidity
DNI	direct normal irradiance	T°	temperature (°C)
GCR	ground coverage ratio	VPD	vapor pressure deficit
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)	ΔT	temperature difference
PAR	photosynthetically active radiation	ΔVPD	vapor pressure deficit difference
PE	polyethylene		