



Climatic and design tipping points in agrivoltaic crop production systems. A meta-analysis

Wei Zhang¹ · Pieter-Willem Hendriks² · Mark Uchanski³ · Shannon Page⁴ · Alan Renwick¹ · Thomas Maxwell² · Clive Kaiser² · Jinpeng Dong⁵ · Wim de Koning¹

Received: 10 March 2025 / Accepted: 11 September 2025
© The Author(s) 2025

Abstract

Amidst global climate change, increasing food demand, and land-use competition between agriculture and energy production, agrivoltaic systems are emerging as a potential solution energy. However, the spatial heterogeneity of existing physical research infrastructure limits the generalizability of plant growth and growth conditions findings across diverse climate zones. This study aims to address this gap by conducting a comprehensive meta-analysis across 20 countries. Unlike previous work, our approach integrates key variables, including photovoltaic system design parameters, crop yield responses, and microclimate changes, into a unified analytical framework. It further maps the empirical evidence onto a global climate context. The analysis reveals several novel insights. First, distinct design patterns were observed in photovoltaic system deployment: small-scale installations (<1000 m²) are often associated with increased mounting heights (3.05 m vs. 2.57 m), which alters ground-level conditions. At the same time, photovoltaic installation characteristics (e.g., panel height and array size) also vary across different climate zones, reflecting differences in installation objectives (e.g., energy optimization vs. experimental). Second, we identified a previously undocumented “tipping point” in system size (~2 ha), beyond which microclimate temperature effects reverse. Third, crop yield responses under shading vary by crop physiology and climatic zone; for example, lettuce showed tolerance to increased shading under certain environmental conditions. In addition, we suggest that a potential trade-off point may exist between crop yield and photovoltaic shading, which could enable a balance between maintaining agricultural productivity and achieving effective energy generation. These findings demonstrate that the performance of agrivoltaic systems is highly climate- and crop-dependent. Therefore, region-specific and plant-centered design principles should be central to future agrivoltaic innovations and policy frameworks. By presenting the first global climate-integrated map of agrivoltaic study locations, this work provides a foundational evidence base to guide climate-smart agrivoltaic planning and implementation.

Keywords Agrivoltaics · Microclimate · Microenvironment · Shading · Crop performance · Dual land-use

✉ Wim de Koning
wim.dekoning@lincoln.ac.nz

- ¹ Centre of Excellence in Transformative Agribusiness, Faculty of Agribusiness and Commerce, Lincoln University, Lincoln, New Zealand
- ² Centre of Excellence in Transformative Agribusiness, Faculty of Agriculture and Life Sciences, Lincoln University, Lincoln, New Zealand
- ³ College of Agricultural Sciences, Colorado State University, Fort Collins, CO, USA
- ⁴ Centre of Excellence in Transformative Agribusiness, Faculty of Environment, Society and Design, Lincoln University, Lincoln, New Zealand
- ⁵ College of Finance and Economics, Shandong University of Science and Technology, Tai'an, Shandong, China

1 Introduction

The rapid rise in global temperature due to climate change combined with a booming population, is placing unprecedented stress on global food systems (FAO 2009; van Dijk et al 2021; IPCC 2021). Scarcity of land and water resources further intensifies this pressure and threaten the sustainability of agriculture (Osman et al 2022; Chartres and Noble 2015). To mitigate further climate change, actions have been taken to explore clean energy alternatives and innovative agricultural models to break the dependence on conventional energy sources and alleviate the strain on food production (Time et al 2024; IEA 2023a). Agrivoltaics, arises as an innovative approach

integrating solar power with agricultural production, offering renewable energy while maximizing land use functionality (Fig. 1) (Giri and Mohanty 2022). Mirroring the growing interest in solar technology, global photovoltaic (PV) capacity surpassed 1.6 TW at the end of 2023 (IEA 2024). The 2023 PV accounted for three-quarters of the global growth in clean energy (e.g., wind, bioenergy, geothermal, and tidal energy) capacity (IEA 2023a, b). Similarly, the growing global agrivoltaics market is estimated to reach over USD 11.14 billion in the coming decade (IRENA 2024; Precedence Research 2023).

By occupying agricultural or marginal lands, large-scale PV installations may alter original land-use patterns and induce local climate effects, such as changes in rainfall distribution or temperature regimes (Muñoz-García et al 2024). Although these installations have a relatively low environmental footprint, they can still be disruptive to local ecosystems by reshaping landscapes and habitats, for example, disturbing native vegetation and impacting local wildlife (Wu et al 2023; Szabadi et al 2023). Agrivoltaics on the other hand offer a balanced solution by alleviating the competition through a dual land use (Lu et al 2022; Barron-Gafford, et al., 2019). The land equivalent ratio (LER) has been commonly applied to assess the efficiency of agrivoltaic systems, as it captures both agricultural and energy yields (Dupraz et al 2011; Pelczar 2025). While a LER greater than 1 suggests improved land productivity, it does not reflect changes in crop quality, which may affect marketability. Numerous studies have shown that agrivoltaic systems can enhance land productivity by enabling the dual use of land for energy and food production (Elamri et al 2018; Reher et al 2024; Valle et al 2017; Willockx et al 2024). The greatest potential for agrivoltaics is generally considered to lie in semi-arid and arid regions, where the shade provided by solar panels can produce synergistic benefits such as reduced

evapotranspiration and improved microclimates (Marrou et al 2013a; Barron-Gafford et al 2025; Ravi et al 2016).

With crop production, there is a direct relationship between light intercepted and biomass production (Sinclair and Muchow 1999). With all other factors non-limiting, radiation use efficiency provides a direct relationship between the light available and the biomass produced (Monteith 1977). Also, a reduction in solar radiation (shading) is expected to be a major abiotic stress factor for plant production under agrivoltaics (Weselek et al 2021a, b).

Shade tolerance, an ecological concept, is the capacity of a given plant to tolerate or even thrive in low light levels (Valladares and Niinemets 2008). The crop responses to shading vary widely; for example, shade-tolerant leafy vegetables and grass species tend to perform better under reduced light conditions (Randle-Boggis et al 2025; Carreño-Ortega et al 2021; Kannenberg et al 2023). Tolerance to shading has been studied more intensively in forest conditions (Gravel et al 2010). There is limited availability of crop-specific data under agrivoltaics conditions, many studies have relied on controlled shading experiments to assess crop sensitivity to partial or full shade (Weselek et al 2019). Efforts have been made to classify crops into shade-sensitive, shade-neutral, and shade-tolerant categories. For example, Beck et al (2012) found maize, wheat, and many horticultural crops to be shade-sensitive, rape, rye, and oats to be relatively shade-neutral, and crops like potatoes, lettuce, and spinach to benefit from moderate shading (up to 50%).

Therefore, not all crops will thrive under the panels, potentially resulting in slowed growth, yield reduction, and nutrient loss (Marrou et al 2013b; Weselek et al 2021a, b; Choi et al 2020). This is largely determined by the design of the PV system. Parameters such as panel tilt angle, spacing, mounting height, and whether the system is fixed or tracking directly influence the spatial distribution of shade and light

Figure 1 Conceptual design of the upcoming agrivoltaic research farm at Lincoln University, New Zealand. Photo-credit: Dr Shannon Page.



intensity on the ground, as well as surface reflectance and soil moisture evaporation (Yang et al 2017; Ramos-Fuentes et al 2023). These factors in turn alter the microclimatic conditions beneath or between the PV panels, typically resulting in reduced temperature (Thum et al 2025), increased humidity (Sun et al 2025), and decreased wind speed (Hassanpour Adeh et al 2018). Such environmental changes potentially have significant effects on crop physiological processes (Randle-Boggis et al 2025; Carreño-Ortega et al 2021; Kanenberg et al 2023). Several countries have developed regulatory guidelines that include minimum yield thresholds to ensure continued agricultural productivity (e.g., 66%–80% of the yield without PV) (ADEME 2021; Gazzetta Ufficiale 2022; MAFF (2015); Elborg 2017; Fraunhofer 2024). With appropriate design, field planning (e.g., low panel density), management and crop selection (e.g., shade-tolerant species), losses may be minimized and crop productivity may be stabilized or even increased (Potenza et al 2022; Weselek et al 2021a, b; Sarr et al 2024).

Innovative designs are emerging to enhance agricultural efficiency. Such changes may improve field management and yield (Willockx et al 2022). For example, elevated solar panels can be installed to increase sunlight exposure for crops, maintain crop growth levels similar to non-agrivoltaic systems and improving access for agricultural machinery and labor (Willockx et al 2022). Other layout strategies, such as vertical agrivoltaics, checkerboard patterns, semi-transparency and the addition of LED supplemental lighting have also been employed to lessen the shading impact on crops (Cho et al 2020; Willockx et al 2024; Zheng et al 2021; Uchanski et al 2023; Thompson et al 2020a, b; Patel et al 2024; Willockx 2020; Riaz et al 2021).

Existing studies have explored the potential of agrivoltaic systems to enhance land-use efficiency and support both food and energy production, with a focus on economic performance, crop yield evaluation, and power generation (Dinesh and Pearce 2016; Widmer et al 2024; Thomas et al 2023; Hassanpour Adeh et al 2019; Mamun et al 2022). However, agrivoltaic systems have been widely studied in the Northern Hemisphere, particularly in North America, Europe, and East Asia. Limited attention has been given to system design and crop suitability in the Southern Hemisphere. Key questions remain regarding which crop types are most compatible with agrivoltaic conditions, what shading levels are optimal, and how solar panel configurations should be adapted to specific agricultural and environmental contexts. In particular, how agrivoltaics can be effectively applied across different climate zones remains largely unknown. This study builds a large-scale dataset based on all available empirical studies on agrivoltaic systems worldwide, encompassing a wide range of climate zones, crop types, and system configurations. Using a meta-analytic approach, it systematically evaluates crop yield responses

under different agrivoltaic conditions, while accounting for factors such as PV system design (e.g., array size, panel height), microclimatic changes, shading intensity, and climatic context. Compared with existing studies, this work offers significant advantages in both the breadth of data coverage and the depth of quantitative synthesis, providing a robust empirical foundation for the optimization and broader adoption of agrivoltaic systems.

2 Methods

The literature review was conducted on 8th May 2025 using Scopus with keywords including “agrivoltaic,” “solar farm,” “solar farming,” “agrophotovoltaics,” “agro-PV,” “agrisolar,” “agri-voltaic,” “photovoltaic farm,” and “PV agriculture.” These keywords were selected to encompass the diverse topics of research concerning the integration of PV systems with agricultural systems or the environment. To avoid including articles focused on greenhouse solar energy, exclusion keywords such as “greenhouse,” “glass-house,” “glass-house,” and “green-house” were used. Peer-reviewed English articles specifically focused on open-field agrivoltaic systems were identified according to inclusion criteria. Conference papers, review articles, notes, and publications that were not written in English were excluded. Initially, 1274 articles were obtained through searches, which were then screened in three steps. The review process first involved checking titles and keywords to exclude studies not related to the subject. Second, abstracts were screened to exclude those studying the non-relevant fields including but not limited to the area of computer science, energy, material science, or modelling only studies. Lastly, full-text reading was performed to remove literature that didn't contain experimental data, or those articles focusing mainly on energy generation, financial results, and economic profits. Relevant literature cited in the selected articles was also reviewed to identify additional studies. In total, 90 articles met the inclusion criteria, focusing on agrivoltaic/photovoltaic research related to crops, and their (micro-) environmental conditions. Open-field agrivoltaics, unlike greenhouse or indoor systems, are significantly influenced by natural factors such as sunlight exposure, temperature, precipitation, and wind. Thus, photovoltaic greenhouses were excluded. The detailed screening procedure is illustrated in Fig. 2.

Data from 320 experiments conducted on 111 solar farms, referenced across articles, were analyzed. These data include 115 records of PV shading rates, 107 farm size measurements, 106 records of PV system types, and 98 measurements of panel heights. A total of 234 experiments involved crop performance (with 260 providing yield data, 115 recording changes in plant morphology, and 56 capturing changes in plant biochemical indicators), and 91 records of

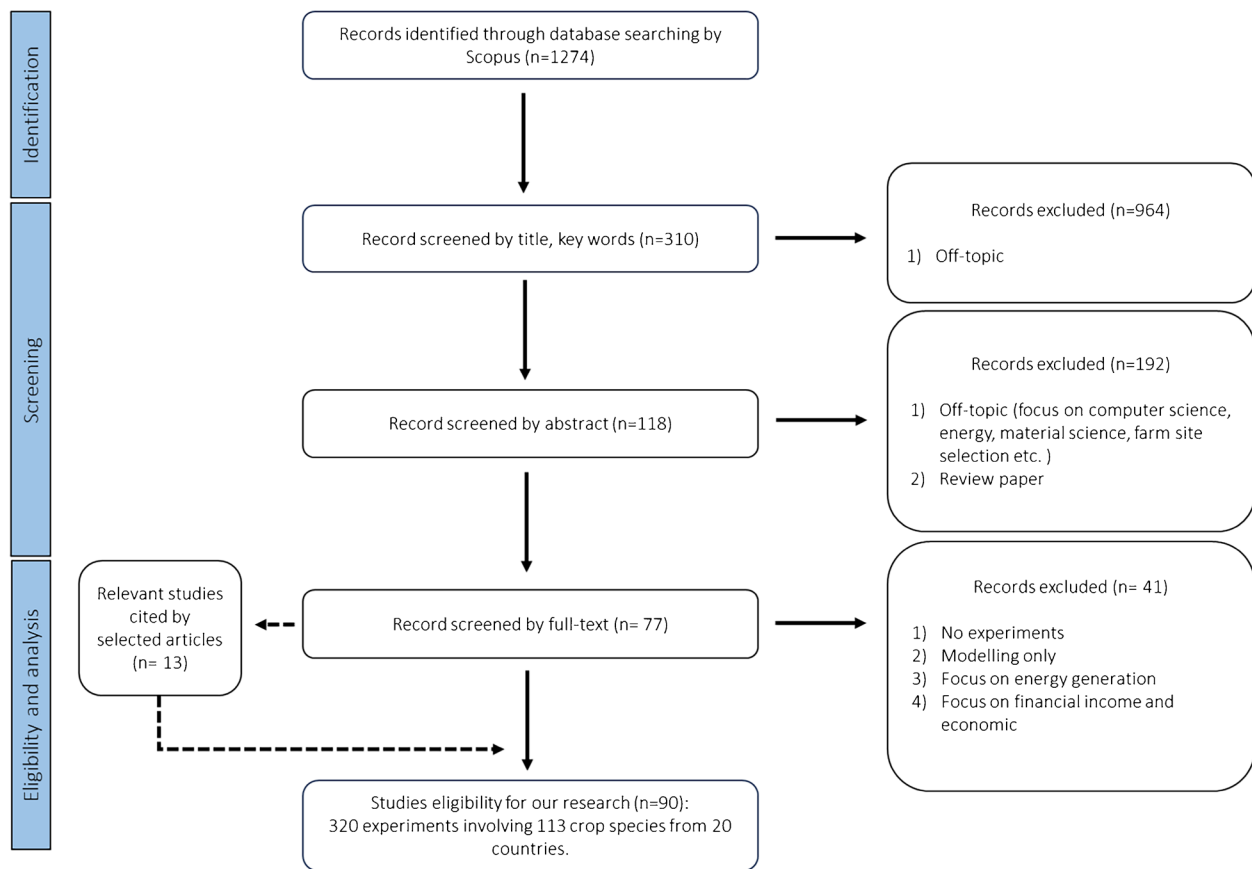


Figure 2 PRISMA flow diagram for literature search and study selection.

climate conditioning were also obtained. It also contains 36 air temperature, 32 soil temperature, 20 air humidity, and 20 soil moisture measurements (i.e., microclimates). Whenever available data points were missing (e.g., PV panel height or scale), they were interpolated/extrapolated based on available public resources, e.g., websites, Google Earth and visual references, but the number of estimated data points remained minimal, and most analyses were based on reported data. The climate type data in this paper were categorized based on the experimental locations provided in the studies, using the Köppen climate classification system. Crops were first categorized into seven groups based on their use and into three groups according to their light sensitivity. For further analysis, three representative crop categories—corn, beans, and lettuce—were selected based on their differing shade tolerance levels (sensitive, partial, and tolerant, respectively) and their relatively large sample sizes. To investigate the effects of key agrivoltaic system design parameters on crop yield response, we performed both linear regression analysis and analysis of variance (ANOVA). Specifically, we used multiple linear regression models to quantify the relationship between shading intensity (%), panel height (m), and system scale (m²) as predictor variables, and crop yield

change (%) as the response variable. Additionally, one-way ANOVA was applied to assess differences in PV system design characteristics (e.g., panel height and area) across different climatic zones. All statistical analyses in this article and data visualizations were conducted using Minitab 22 and R version 4.3.2.

3 Results

3.1 Photovoltaic panel parameters and climate

The size of solar farms analyzed in these studies range widely from just 6.5m² (Leroy et al 2025b, a) to 1000 ha (Muñoz-García et al 2024), highlighting the various contexts — from research to utility scale. 76% of the solar arrays included in this study were fixed at angles between 5° and 45° (Vertical systems 76% of the solar arrays included in this study were fixed at angles between 5° to 45° (Vertical systems are fixed at 90°, $n = 3$). In contrast, 24% employed tracking systems designed to optimize solar energy capture by rotating panels. The ground clearance — the height of the lowest panel edge — was specified in 127 studies. This

ranged from just 35 cm (Uchanski et al 2023) to 8.67 m (Al Mamun et al 2023). The average ground clearance of fixed panels is 2.62 m, and 3.50 m for the solar tracking ones, and heights of 2.5, 4, and 5 m are the most common. With elevated panels, agricultural machinery can easily operate underneath. An increase in PV installed area is correlated ($p < 0.05$) with a decrease in installation height (Fig. 3). Analysis revealed a significant tipping point at 1000 m², where there is a shift in installation height behavior: smaller farms (<1000 m²) tend to have higher installation heights (~3.05 m), whereas larger farms (>1000 m²) showed the

opposite trend (~2.57 m). Humid subtropical and Mediterranean climates are the most prevalent climatic conditions in which agrivoltaics have been studied, with a limited number of studies conducted in Cold Desert (Bwk) and Subtropical Highland Climates (Cwb) (Fig. 4). Under different climatic conditions, the installation height and area of PV panels also varied slightly. Analysis of variance (ANOVA, Fisher LSD test, 95% CI) revealed that in the Cold Semi-arid climate (BSk), the installation scale of PV systems was significantly larger than in other climate zones ($p < 0.001$). PV panel installation heights also differed significantly across climate zones. In Hot-summer Mediterranean (Csa), Monsoonal Humid Continental (Dwa), Temperate Oceanic (Cfb), and Humid Subtropical (Cfa) climates, the average installation heights all exceeded 3 m (3.93 m, 3.61 m, 3.45 m, and 3.25 m, respectively), and were statistically higher than those observed in other climate types. For instance, in Tropical Rainforest (Af), Cold Semi-arid (BSk), Warm-summer Mediterranean (Csb), and Tropical Savanna (Aw), the mean heights were notably lower at 1.68 m, 1.54 m, 1.32 m, and 1.04 m, respectively. Notably, the installation height in the Hot Semi-arid (BSh) climate (2.68 m) is intermediate, being lower than the four temperate and subtropical climate types mentioned above, but significantly higher than those observed in tropical and cold arid climate zones. These results indicate that PV systems tend to be installed at significantly greater heights in temperate and subtropical climates compared to tropical and semi-arid regions.

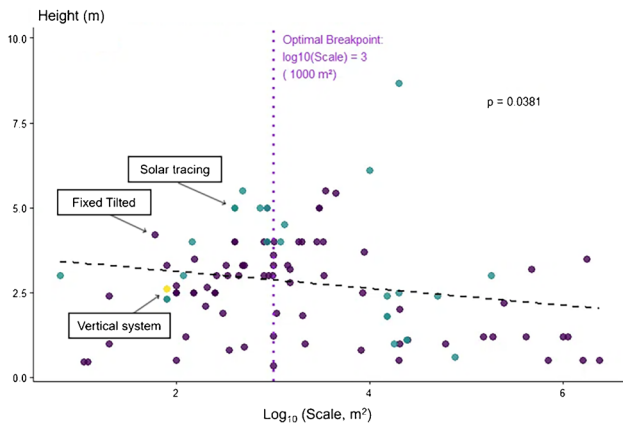


Figure 3 Linear regression and breakpoint analysis: Height vs. Log10 (Scale).

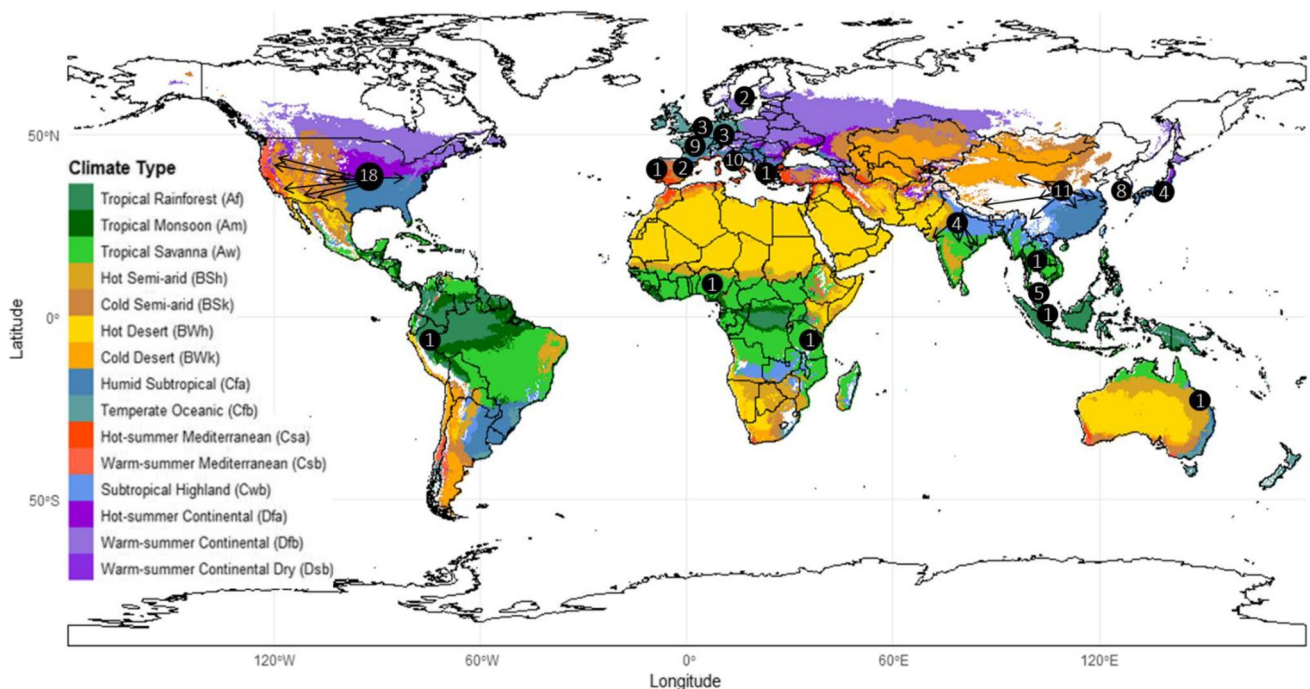


Figure 4 Global photovoltaic experimental research and its climatic environment distribution patterns: a spatial visualization analysis. Note: numbers in black circles indicate experiment counts in this country; arrows show experiment distribution.

3.2 Microclimate under the solar panels

The influence of PV panels on air temperature was inconsistent among studies (ranging from -2.5°C (Al-agele, et al., 2021) to $+2.4^{\circ}\text{C}$ (Barron-Gafford, et al., 2016), as some reported lower temperatures, others observed no significant changes, while a few even reported higher temperatures relative to open-field conditions (Fig. 5). Nearly all studies consistently report a reduction in soil temperature under PV shading (Fig. 5). Of those that quantified the change, the range was from -0.5°C (Moon and Ku 2022b, a) to -5.6°C (Al-agele et al (Al-agele, et al., 2021)). Air humidity and, even more so, soil moisture levels generally increased under the panels compared to open-field conditions (Fig. 5) by up to 14% (Juillion et al 2022) and 21% (Luo et al 2024), respectively. We further analyzed air temperature data using a linear regression, which indicated a significant positive effect of the scale of PV deployment on temperature ($p < 0.01$). This suggests that with scale being the only factor in consideration, an increase in localized temperature is tied to an increase in PV panel area. However, in the multiple regression analysis, the effect of the scale of PV on temperature change was not significant ($p = 0.076$). The absence of any statistically significant effects for other variables, such as panel height ($p > 0.05$) and climate conditions ($p > 0.05$), suggests that such variables might be confounding or influenced by other variables not directly examined in this analysis.

The shading rates range from 9% to 80%, with nearly three-quarters of studies focusing on rates below 50% and a shading rate of around 30% being the most commonly evaluated.

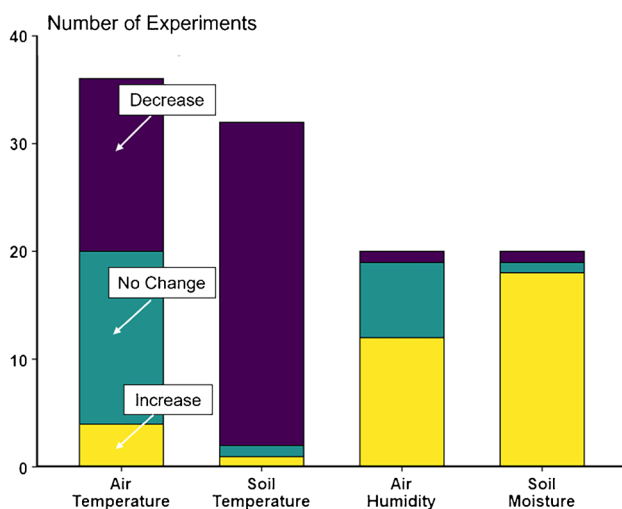


Figure 5 Summary of experimental microclimate results. Note: For soil and air temperature changes within the range of $\pm 0.5^{\circ}\text{C}$, they are categorized as no change, unless the results in the article indicate a statistically significant difference.

3.3 Plant selection and performance under PV systems across various climates

Many different crops have been studied in agrivoltaic conditions. These crops are primarily categorized into vegetables, legumes, grassland/pasture species, fruits, cereals, oilseeds, and herbs (Fig. 6a). Among these, pasture species, and horticultural crops like lettuce and beans were the most frequently assessed species (See Supplementary Table 1 for a detailed list). Of the studies with yield or biomass data reported ($n = 264$), 34 found a positive yield response, 72 a neutral response, and 158 a negative yield under solar panel installations (Fig. 6b). Among 123 experiments reporting morphological change, 49 showed increases in plant height, leaf area, or leaf numbers when compared to control areas without PV panels.

Plants are classified as sensitive, partially-tolerant, or tolerant to shading. Overall, both shade-tolerance species and shade-sensitive species showed a downward yield trend, and partial shade-tolerance species showed a steady and upward trend with increasing shading (Fig. 7a). However, in specific climate zones, shade-tolerant species and partial shade-tolerant species generally maintain minimum yield loss to shade across nearly all climate types (Fig. 7b, c, d), whereas shade-sensitive crops are more likely to be affected under high shading rates.

Notably, in temperate oceanic and warm-summer continental climates, all suffered minimal yield penalty ($< 10\%$) with no further reductions as shading increased (Fig. 7d, e). The yield of beans and corn gradually decreases as shading increases, whereas the shade-tolerant lettuce maintains a stable yield under shaded conditions (Fig. 8). Additionally, some variability is present in the climate conditions of the studies reporting yield increase, but in summary, the climates share some main features: hot summers, limited precipitation and (semi-) arid conditions (Fig. 9).

A linear regression analysis between shading levels and yield confirmed a non-significant ($p > 0.05$) negative correlation between the level of shading crop yield (Fig. 10). Results from segmented regression lines revealed that at shading rates below 20%, crop yield shows no statistically significant difference from the control group ($p = 0.084$), suggesting that moderate shading does not have a marked effect on crop growth. In the shading scale between 20% and 30% (which does not significantly change the microclimate), lower yield is observed ($p < 0.01$). There is a positive trend in yield observed with shading at 30 to 40% ($p \approx 0.05$) presumably due to microclimate changes. Shading at 40 to 50% leads to a slight and non-significant reduction in yield ($p > 0.05$). Shading between 50% and 60% markedly suppresses crop productivity ($p < 0.05$). Shading above 60% further inhibits crop productivity ($p < 0.01$). Importantly, the sensitivity to shading conditions

differed significantly among the plant species (See Supplementary Fig. 1), suggesting the need to choose suitable (i.e., shade tolerant) crops for agrivoltaic systems.

4 Discussion

4.1 Variation in PV panel height and system scale

The variation in PV installation height and coverage area reflects the combined influence of environmental, economic, and practical considerations. Results show that smaller-scale systems and those located in temperate climates tend to have higher average installation heights (above 3 m). This could be because elevated panels would allow for the passage of agricultural machinery.

Higher installation structures are also more common in small-scale projects (<1000 m²), possibly because the additional cost of elevation is more manageable when applied to limited areas. In contrast, large-scale farms are often more sensitive to structural costs, and lower installation heights help reduce investment per unit area. These patterns highlight the need to balance agronomic functionality and economic feasibility when designing agrivoltaic systems.

4.2 Microclimates

4.2.1 Shading

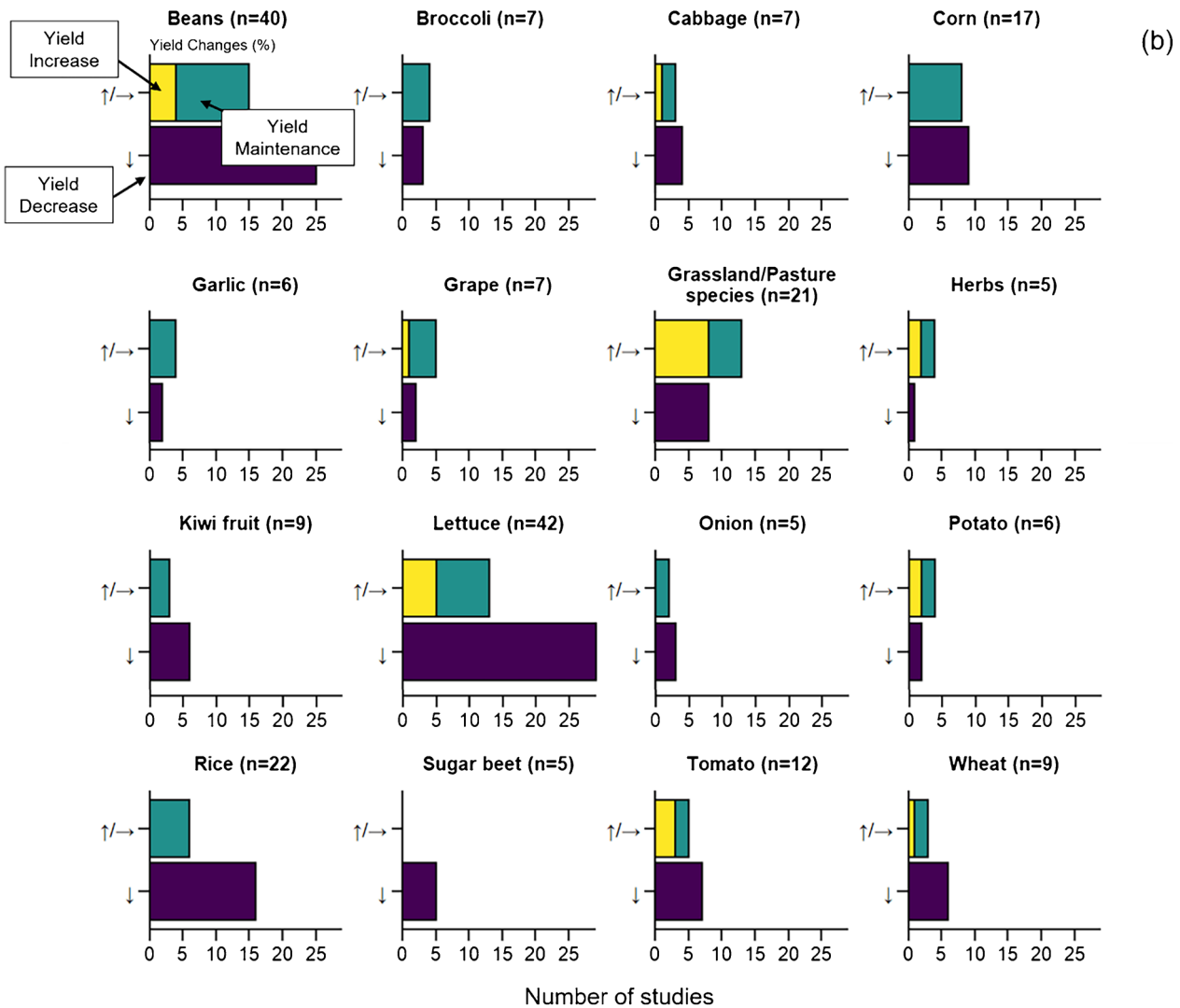
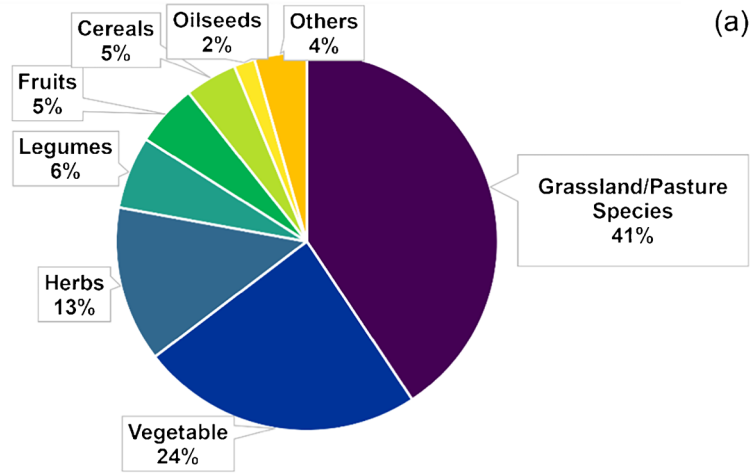
There are a number of solar arrays design parameters, such as panel angle, orientation, height and spacing, that defines the light available to crops. For fixed tilt arrays, the angle and orientation depend on the solar farm's latitude. This angle determines the shading pattern, for instance, a steeper angle casts a longer and more defined shadow, whereas a flatter angle creates a more even shade pattern throughout the year (Santra 2017). In general, fixed-tilt systems create shaded areas whose shape and coverage change throughout the day, but the distribution pattern remains relatively consistent. In contrast, single-axis tracking systems (north-south orientated PV rows) cast long shadows at specific times of day, such as in the morning and late afternoon (Santra 2017; Tahir and Butt 2022). Compared to fixed tilt panels, single-axis tracking systems result in more uniform sunlight on crops (Al Mamun et al 2023). New designs, such as vertical agrivoltaic systems, offer better land-use efficiency and reduce crop shading. These systems cast fixed, concentrated shadows that diminish as the sun approaches solar noon (Willockx et al 2023; Campana et al 2021).

4.2.2 Ambient temperature

Temperatures beneath solar panels usually decrease due to shading, particularly during the middle of the day (Uchanski et al 2023). Shading reduces the evaporative cooling effect of the soil/vegetation (Feng et al 2014). Lower temperatures are usually accompanied by a lower evaporation rate, further decreasing the amount of heat carried away by evaporating water (Wu et al 2023; Jiang et al 2022; Ramos-Fuentes et al 2023). These contrasting patterns highlight the complexity of evaporative cooling dynamics in agrivoltaic systems. The effect is influenced by multiple factors, including wind penetration (which depends heavily on panel height), panel temperature and associated longwave radiation, and the convective exchanges of latent and sensible heat that affect the vertical thermal gradient beneath and between panels (Ali 2024; Shepard et al 2022; Willockx et al 2024). These components should be considered when interpreting the overall heat and energy exchange processes under PV installations.

However, in four studies, the daily air temperature was found to be elevated between 0.7°C and 2.4°C compared with open spaces (Yang et al 2017; Broadbent et al 2019; Barron-Gafford, et al 2016; Sun et al 2025). All these studies were conducted in desert or semi-arid climates with sparse vegetation; all were large-scale (between 67 and 237 ha) and had a low ground clearance of ~0.5 m. In one such in the Gobi region found that the soil and surface materials beneath the panels had a high heat capacity and thermal conductivity, which absorbed and stored more heat, transferring it to the surrounding environment (Yang et al 2017). They may reduce ambient air circulation near the PV installation and create hot spots under conditions which favor high temperatures. PV panels themselves are often 20°C to 30°C hotter than ambient temperatures (Yang et al 2017; Fthenakis and Yu 2013), and this heat is gradually released primarily through longwave radiation to the surrounding environment. With the number of PV panels increasing, shading and heat absorption becomes more intense. A study showed that the heat tends to diminish with increasing distance and height from the system (Fthenakis and Yu 2013). Furthermore, measurement time and proximity to the panels may also affect temperature readings (Fig. 11).

The above finding prompted us to explore temperature variation patterns further by conducting a segmented regression analysis to quantify the effects of increasing PV scale (m²). Our analysis (Fig. 10) identified a breakpoint at around 2 ha. Below this scale, temperature changes remained relatively stable, but a growing temperature trend was noted as the scale increased. Above this 2-ha threshold, temperatures showed an upward trend, indicating that heat accumulation from shading starts to exceed its cooling benefits as the installation scale grows. This shift likely results from a combination of factors, including shading, heat conduction,



◀**Figure 6** Summary of crop diversity (a) and changes in yield (b) in selected agrivoltaic experiments. Note: All listed plant species have a sample size of 5 or more. The x-axis represents the frequency of crops at different yield change levels (i.e., the number of studies); The y-axis represents yield change levels: ↓ indicates a decrease in yield, → indicates no significant change (yield changes within $\pm 10\%$ are considered stable unless the article indicates a significant difference), and ↑ indicates an increase in yield.

reduced evaporation and wind (Broadbent et al 2019). Reduced evaporation further limits ground cooling, contributing to temperature increases (Teng et al 2022). Regression analysis confirmed a significant relationship between PV system scale and temperature variation ($p < 0.05$). And results also showed that for every tenfold increase in area, the temperature rises by approximately 0.4°C ($p < 0.01$).

Additionally, three studies found elevated nighttime temperatures (maximum difference of $+3.5^{\circ}\text{C}$) under solar panels (Barron-Gafford et al 2016, 2019; Yang et al 2017), primarily due to the panels blocking radiative cooling (Barron-Gafford et al 2016). This effect was found to be especially pronounced in large-scale installations in a desert region (Yang et al 2017). Also, large-scale PV systems may influence local microclimates in ways similar to urban heat island effects; however, the extent of these impacts depends on various factors such as panel material, installation density, configuration, and surface albedo (Muñoz-García et al 2024; Barron-Gafford et al 2016). This kind of effect diminishes with increasing distance from the solar farm and height above the panels, and it may be mitigated or even nullified in areas with ground vegetation cover (Muñoz-García et al 2024; Fthenakis and Yu 2013; Barron-Gafford et al 2016).

4.2.3 Soil temperature

Soil temperature measurements under solar panels are conducted from the surface soil to a depth of up to 180 cm. Almost all studies found soil temperature became cooler. Generally, shading reduces soil temperature. Solar panels may slow the inflow of cold air, and the heat conduction through the solar panel pillars may cause localized increases in soil temperature, especially near the pillars (Cho et al 2020). Shallow soil layers exhibit greater diurnal temperature fluctuations, and distinct temperature differences are observed across different soil depths (Gong et al 2025; Yang et al 2017).

4.2.4 Air humidity and soil moisture

Full sunlight exposure can lead to faster depletion of water than under more moderated growth conditions, potentially limiting biomass production (Al Mamun et al 2023). PV systems can be an effective method for improving water use efficiency and promoting plant growth (Andrew, et al.,

2024). Increased array heights may provide longer and broader shading, which can more effectively decrease soil temperature and reduce moisture evaporation (Sturchio et al 2022). Most studies have found that air humidity under PV panels is generally higher than in open fields. This is because shading slows evaporation, thus helping to retain moisture in soil, plants, and the surrounding air (Hide 1954; Möller and Assouline 2006). As a result, humidity tends to increase with greater PV shading (Jiang et al 2022).

PV panels suppress soil moisture evaporation through shading, and this effect can lead to higher overall soil moisture beneath the panels (Marrou et al 2013a; Hassanpour Adeg et al 2018). This advantage is particularly evident in semi-arid regions, where crops grown under PV panels can use water more efficiently than those grown in open fields (Ferrara et al 2023; Al-agele et al 2021; Jiang et al 2022; Ramos-Fuentes et al 2023; Marrou et al 2013a; Elamri et al 2018). While shading conditions may improve water use efficiency, water productivity does not show a consistent increase with increasing shading intensity, indicating a possible threshold effect or crop-specific response (Jiang et al 2022).

However, it is worth noting that PV panels can also affect the spatial distribution of rainfall at the same time, concentrating water at the panel edges and leading to uneven soil moisture distribution (Sturchio et al 2022; Kannenberg et al 2023). As a result, soil moisture in some areas beneath the panels may be lower than in open fields after rainfall (Wu et al 2023; Choi et al 2020), with the rainwater being concentrated under the edge of the panels and locally. This may also pose potential risks to crops.

4.2.5 Crop growth, development, yield quantity and quality and under various climatic conditions

Agrivoltaic systems have been extensively studied across a diverse range of crops, encompassing species from temperate to tropical regions. Insufficient sunlight under PV panels reduces photosynthesis, primarily leading to decreased crop yields; as shading increases, available light decreases, resulting in a corresponding drop in yields (Sekiyama and Nagashima 2019). This impacts more crops that are considered “shade intolerant” (Yang and Li 2017). However, some studies found that certain shade-intolerant crops, through effective management, can still be successfully integrated into an agrivoltaic system (Gonocruz et al 2021).

In general, higher levels of shading, mainly resulting from artificial structures such as shade cloths and nets, as well as intercropping systems, are associated with reduced crop yields, although the relationship is complex and not perfectly linear (Laub et al 2022). After analyzing all the data of yield response to shade, a slight negative correlation between crop yield and shading intensity was found, but

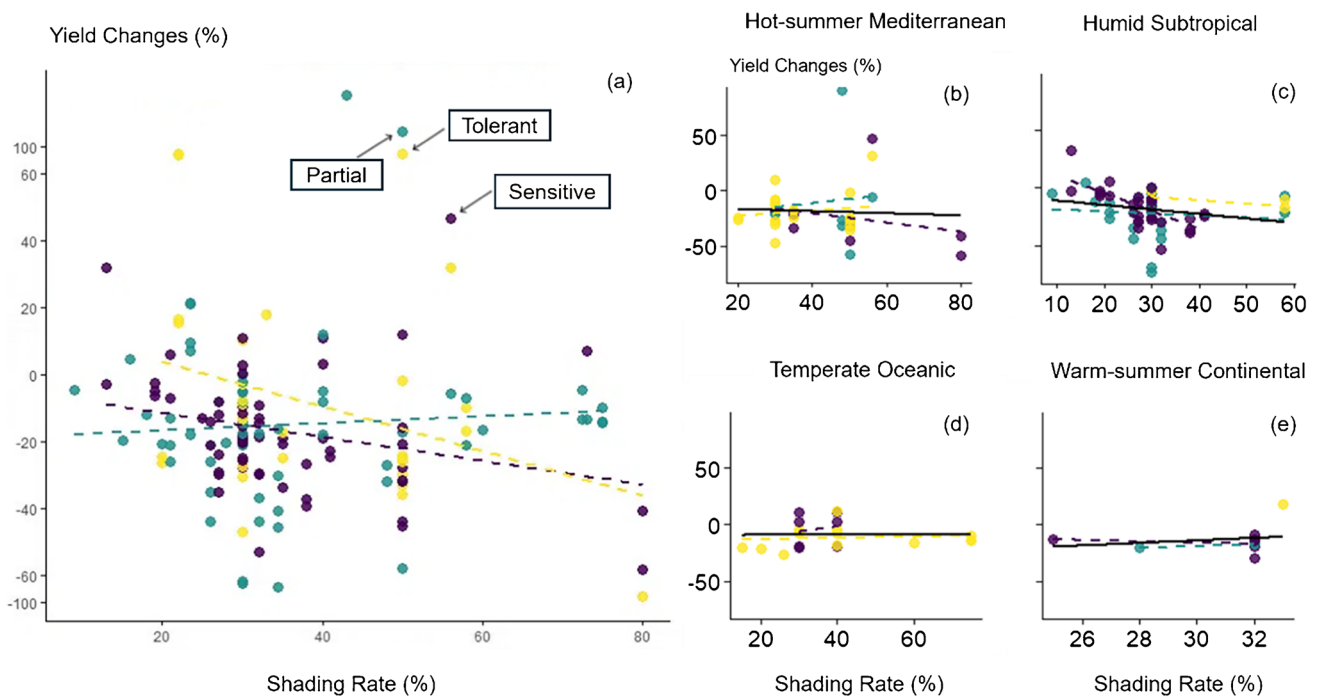


Figure 7 Overall plant shading response regression (a) and climate-specific shade response regression (b, c, d, e). Note: The dashed lines represent trend lines for different shade responses, while the solid line

represents the overall crop shade response trend line. The intercept and slope values represent the overall crop response.

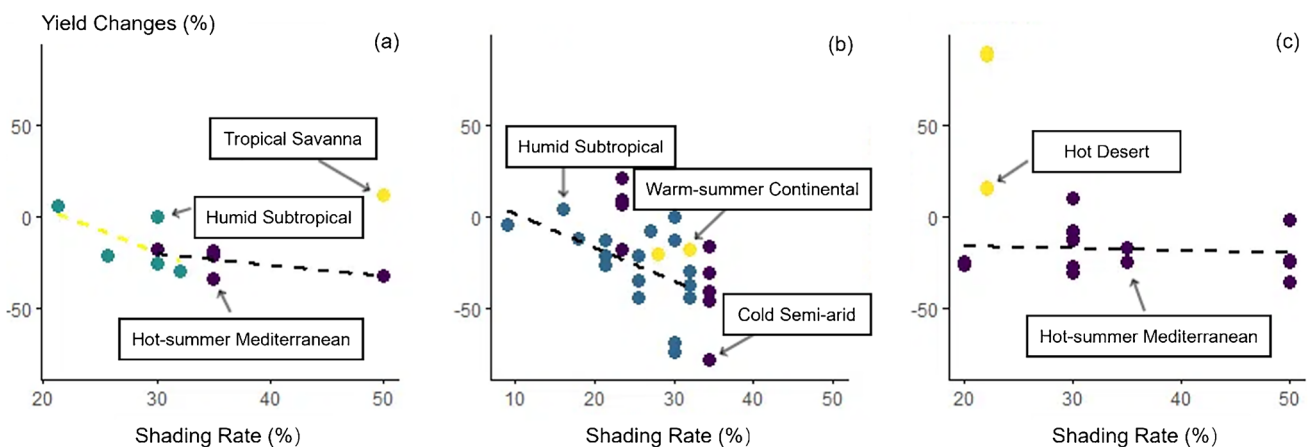


Figure 8 Linear regression analysis of shading rate and yield change in crops (a: Corn, b: Beans, c: Lettuce) under various climate.

results were not statistically significant (Fig. 10). The studies analyzed resulted in no overall effects on yield for shading proportions lower than 20%. Therefore, one could suggest that at these lower levels of shading, the shading effect is weak, such that light is not a limiting factor and PV structures do not significantly interfere with photosynthesis or growth. Additionally, other beneficial physiological changes and/or microclimate effects may help compensate for any minor yield reductions caused by shading. Indeed, studies concluded that under moderate shading certain physiological

traits such as chlorophyll content and NDVI can be enhanced (Min et al 2022; Moon and Ku 2023).

In the shading range of 20–30%, the decreased yield may be ascribed to the direct effects of shading, and the compensation advantages from the control of the microenvironment are no longer enough to make up the yield loss. Remarkably, although the results of the shading range from 30% to 40% was not statistically significant ($p = 0.058$), but it suggests that there may be a favorable trade-off zone between sunlight exposure and shading, which does not

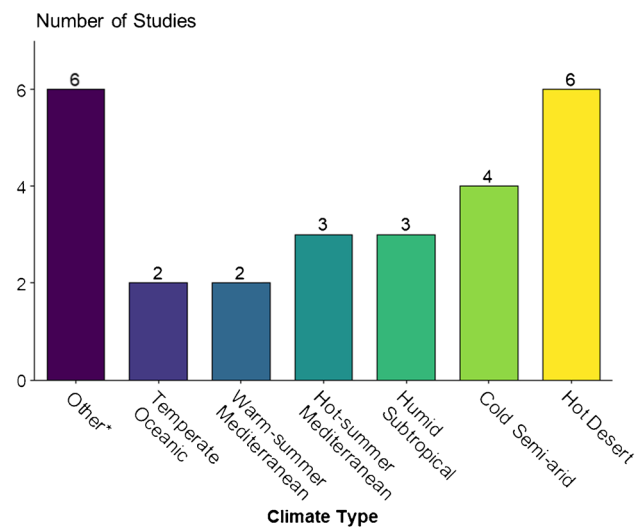


Figure 9 Number of studies reporting yield increases across different climate types. Note: Other classifications include Hot Semi-arid, Hot-summer Mediterranean, Tropical Rainforest, Tropical Savanna, Warm-summer Continental Climate.

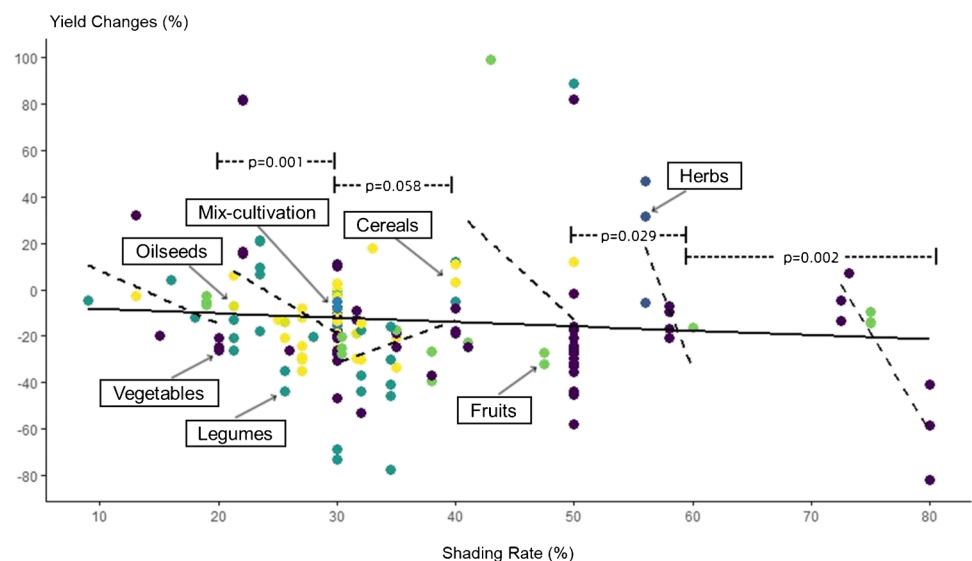
affect excessive sunlight but remains a protected area that encourages growing plants with micro-climate. In the shading range of 40–50%, crops still maintained photosynthetic activity; however, a decreasing trend in yield was observed, although this decline was not statistically significant ($p > 0.05$). Above 50% shading, crop output drops significantly due to reduced photosynthesis and growth. To reduce the impact on the growth of crops, the shading caused by PV systems should preferably not exceed 20%, but such a strategy might sacrifice energy generation per unit of land. In order to maximize dual land use, a shading rate of 30%–40% may balance the power yield of the PV system with the yield

of the crops, as this shading rate also modifying microclimatic conditions, such as temperature, humidity, and soil moisture in ways that are favorable for crop growth.

Less light availability conditions can induce morphological changes in plants (Juillion et al 2022). It may contribute to compensatory growth responses, such as stem elongation and leaf expansion, which are likely adaptive strategies to enhance light capture in shaded environments (Armarego-Marriott et al 2020). For example, leaves tend to become thinner and larger under these conditions thus increasing their specific leaf area (Al-agele et al 2021; Potenza et al 2022; Juillion et al 2022). A few studies, besides assessing the above-ground aspects, also investigated root system growth under solar arrays (Thompson et al 2020a, b; Carreño-Ortega et al 2021; Mohammadi et al 2023b, a). The results are mixed reporting increases in lettuce root biomass under the panels (Carreño-Ortega et al 2021), a decrease in basil and spinach root biomass (Thompson et al 2020a, b), and the absence of significant differences for tomato root systems (Mohammadi et al 2023b, a).

Apart from focusing on above-ground aspects, a few studies have investigated root system responses; Carreño-Ortega, et al. (2021) reported an increase in lettuce root biomass under PV panels (Carreño-Ortega et al 2021), while Thompson, et al. (2020a, b) observed a decrease in root biomass for basil and spinach (Thompson et al 2020a, b). And Mohammadi, et al. (2023b, a) found no significant changes in tomato root systems (Mohammadi et al 2023b, a). The limited number of results suggests the need for further investigations under more standardized conditions to be able to compare studies amongst each other. Plants adjust their physiological mechanisms (e.g., chlorophyll) to adapt to the limited light (Shi et al 2022). For instance, plants may develop shade-adapted leaves with higher chlorophyll content per unit area

Figure 10 Impact of shading rate on crop yield across categories with overall and segmented regression analyses (n= 155). Note: the solid line represents the overall regression, while the dashed line represents the segmented regression. Y-axis shows the percentage change in yield and values exceeding $\pm 80\%$ were visually compressed to improve readability.



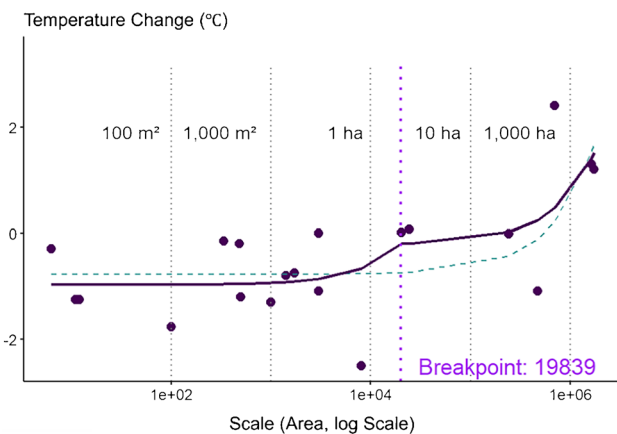


Figure 11 Effect of PV system scale and height on temperature change with identified breakpoint. The green dashed line represents the initial regression line, the purple solid line represents the segmented regression fitted line, and the purple vertical dashed line represents the breakpoint marker.

than those fully exposed to sunlight to improve light capture efficiency, such as kimchi cabbage and broccoli grown which demonstrated increased chlorophyll content under PV systems (Min et al 2022; Moon and Ku 2023). On the other hand, other crops, such as corn, kiwi fruit, Chinese cabbage, soybean, and Chinese kale, exhibited no significant difference in chlorophyll content compared to open-field condition (Marrou et al 2013c; Jiang et al 2022; Lee et al 2022; Grubbs et al 2024; Reeza et al 2024; Potenza et al 2022). Conversely, reductions in chlorophyll were observed in chicory, okra, eggplant, green spinach, Brazilian spinach, and Chinese kale (Reeza et al 2024; Semeraro et al 2024). A study on sugar beet indicated a reduction of nearly 7.3% in chlorophyll content under PV panels (Reher et al 2024). Nevertheless, shading can mitigate moisture stress effects on chlorophyll content to a certain extent, suggesting that PV systems may benefit plants in water-limited environments (Semeraro et al 2024). Although the changes in chlorophyll levels vary among crops, they are generally influenced by several factors, including the degree of shading, its spatial homogeneity or heterogeneity, the spatio-temporal distribution of light, the type of crop, and its growth stage. Moreover, leaf senescence processes were found to be delayed, contributing to extended functional leaf lifespan (Kannenberg et al 2023; Gonocruz et al 2021).

Furthermore, several studies report modified plant phenology in agrivoltaic conditions compared to open field conditions. Indeed, delayed flowering and slowed growth have been observed in plants growing under solar panels (Graham et al 2021; Marrou et al 2013b; Ramos-Fuentes et al 2023).

In addition, many studies have reported impacts on crop quality. For example, the titratable acidity of tomatoes was reported to increase (Mohammedi et al 2023b, a), and the

ratio of sugar to acid in apples decreases (Juillion et al 2024). Similarly, the content of amino acids in broccoli is reported to increase, grapes show higher total acidity, but the content of sugar, soluble solids, polyphenols, and anthocyanin were reduced (Cho et al 2020; Ferrara et al 2023). In addition, the polyphenolic content of chicory has also been reported to increase (Semeraro et al 2024). In contrast, studies on the quality of forage indicate that plants grown under PV panels have better quality fodder (Kampherbeek et al 2023; Sturchio et al 2024), with improved protein content of the plants inside. Similar findings were reported in research on wheat, rice, basil, and spinach (Thompson et al 2020a, b; Gonocruz et al 2021; Dal Prà et al 2024). Additionally, in sensory evaluations of agricultural products under PV systems, it was noted that broccoli exhibited a greener color, which are more attractive to consumer visual preferences (Moon and Ku 2023; Chae et al 2022). On the other hand, other studies show no significant differences between the quality of plants grown under PV systems or open field conditions (Chae et al 2022; Ko et al 2023). While grape coloration was slower than grows in open areas; however, no significant difference was observed between final color (Cho et al 2020). Furthermore, participants to blind tastings did not perceive significant differences in the color, aroma, and taste ratings of juice made from agrivoltaic products (Malu et al 2017).

Based on our analysis the climate seems to play a crucial role in agrivoltaics systems, influencing crop responses to shading and later affecting yield variations (Fig. 7). The shade-tolerant crops exhibited a yield reduction in the overall regression analysis, but they still outperform shade-intolerant and partially shade-tolerant crops when shading levels are above approximately 45%. The potential reason for the yield decline in shade-tolerant crops is that when shading exceeds a certain threshold, their photosynthetic capacity approaches or falls below the light compensation point (Givnish 1988), making it difficult to sustain normal growth, and ultimately leading to yield reduction. For example, Beck et al., (2012) identified 50% shading as a threshold for shade tolerant crops such as lettuce and potatoes, to start losing yield. In a climate with hot summers, shading has a positive impact on shade-tolerant and partially shade-tolerant plants. On the one hand, it meets the minimum light compensation point required by the crops, and on the other, it alleviates heat stress. The results from this meta-analysis show that in a temperate oceanic climate and warm-summer continental climate, crop yields do not decrease with increased shading but remain stable (Fig. 7). This phenomenon may be related to climatic characteristics, such as temperatures, precipitation distribution, and solar radiation. Under such conditions, the microclimate regulation effect of the photovoltaic system may be minimal and thus may not significantly influence crop growth. The global distribution of Agrivoltaics research

is heavily skewed toward temperate and subtropical climates. Although agrivoltaic studies span 15 different climate types, the number of studies across these climates is highly uneven.

4.3 The challenge and future design of agrivoltaics

Despite the growing interest in agrivoltaics, its practical deployment remains constrained by several pressing challenges. Large-scale PV systems often occupy large areas of land, which can lead to the loss of natural habitats, land use conflicts (Graham et al 2021) and alter local rainfall patterns (Barron-Gafford et al 2016). Construction activities can alter soil properties (e.g., increasing bulk density) and remove existing vegetation (Choi et al 2020; Willockx et al 2023; Hassanpour Adeh et al 2018). Long-term shading may disrupt plant diversity, as some species lose regenerative capacity or disappear entirely beneath solar panels (Wu et al 2023; Muñoz-García et al 2024; Hassanpour Adeh et al 2018).

Beyond environmental impacts, agronomic challenges arise from shading effects and structural constraints. Crop yields are highly sensitive to species-specific light requirements, and excessive shading can lead to significant reductions when light availability drops below the photosynthetic compensation point. Fixed panel heights and rigid layouts can hinder mechanization and obstruct farming operations. The microclimate under PV arrays, characterized by changes in temperature, humidity, and airflow, introduces further complexity and remains insufficiently understood due to limited studies across diverse climates and farming systems. Moreover, crops are often passively selected, as farmers tend to select shade-tolerant or low-stature species compatible with PV setups. This reduced crop diversity hinders sustainable farming, for example by limiting crop rotation options vital for soil health and pest control, thereby posing long-term challenges to agroecosystem resilience.

Operational and maintenance issues also affect system performance. Weed control is essential, as uncontrolled weeds can compete with crops and reduce yields (Oerke 2005). In poorly managed systems, weeds may cover low-mounted PV panels, impairing energy generation (Willockx et al 2023). Extreme temperatures, high humidity and low rainfall can affect the performance of PV modules by hastening component ageing, reducing power generation efficiency and increasing dust adhesion onto the modules (Smith et al 2022; Williams et al. 2023). These environmental factors, when combined, can have even more pronounced effects (Said et al. 2018). Moreover, with the rapid growth of PV deployment, the reuse of decommissioned or refurbished PV modules is attracting increasing attention, particularly in agrivoltaic systems where sustainability and cost-efficiency are key priorities (Nieto-Morone et al 2025).

These challenges underscore the need for thoughtful system design, which is now being increasingly tailored to

crop types, land use, and local climate conditions. Accordingly, distinct agrivoltaic farm configurations have emerged to suit specific production systems and landscapes. Grasslands and pasture-based solar farms, for instance, typically cover large areas and incorporate livestock, while vegetable and fruit solar farms are generally smaller in scale. Experimental PV systems may vary in size, often taking up only a few square meters to reflect specific research goals and geographic contexts. Larger farms tend to prioritize energy output in high-radiation zones, while smaller experimental farms provide more controlled environments.

Orientation maximizes sunlight capture. For regions with a high latitude, north-south orientation is most favorable, where in the northern hemisphere they will face south, and in the southern hemisphere, they will face north (Mouhib et al 2024; Ruan et al 2024). In contrast, an east-west orientation is more effective in equatorial and low-latitude regions. Single-axis or dual-axis solar tracking systems further enhance sunlight capture efficiency (Al Mamun et al 2023). Wind direction should also be considered to enhance heat dissipation and system efficiency (Vasel and Iakovidis 2017).

PV panels with adjustable angles could provide a more practical solution - at early stages like sowing and seed germination, plants require little to no light (Frankland 1983), allowing the system to focus on maximizing solar energy capture. However, during key growth periods such as flowering and fruiting, the system can sacrifice some captured solar energy to compensate for the plants' increased light demands (Wang 2020).

Our analysis suggests that shading rates between 30% and 40% may support plant growth while maintaining reasonable solar output. Shading above 50% is not ideal from a crop standpoint, as it often reduces net photosynthesis. Since shading tolerance varies by species and climate, shading design should be based on crop physiological traits.

Elevated PV structures provide better light penetration, ventilation, and growing space, but also raise installation costs (Smith et al 2022). Notably, heat island effects may emerge in PV installations over 2 ha, raising temperatures beneath panels. Although shading reduces evapotranspiration, higher temperatures may induce greater transpiration for cooling, thereby diverting water from biomass production (Yang et al 2023). Thus, system designers must carefully balance shading, panel height, and spatial scale to meet both energy and agricultural goals.

Finally, crop layout also matters. Crops planted between rows of PV panels generally perform better than those placed directly beneath them (Luo et al 2024; Reeza et al 2024). Furthermore, changes in rainfall distribution caused by PV structures can benefit crops at the panel edges, enhancing water-use efficiency, especially during summer and under limited water availability (Reeza et al 2024; Sturchio et al 2024, 2022).

5 Conclusion

This study is the first to apply meta-analysis to evaluate agrivoltaic systems from the perspective of crop yield responses to shading, microclimatic changes, and climatic context. By compiling a global empirical dataset covering diverse system designs, crop types, and climate zones, it offers the most comprehensive synthesis to date of crop performance under agrivoltaic conditions. The results revealed key patterns in the interactions between agrivoltaic system design, environmental conditions, and crop responses, including: (1) differentiated deployment patterns in PV systems; (2) reversal of microclimatic temperature effects induced by large-scale PV systems; (3) crop yield responses varying with physiological traits and climate zones; and (4) a potential trade-off threshold between PV-induced shading and crop productivity. These findings provide valuable insights into the future potential and site-specific optimization of agrivoltaic applications.

However, current agrivoltaic research is still largely experimental. Data availability is uneven across regions and crop types. For example, the geographic distribution of PV studies is not balanced, even in areas with high solar potential (Fig. 4), such as parts of Africa, the Middle East, the Tibetan Plateau, Mongolia, and Australia. Most existing studies are concentrated in the Northern Hemisphere, with limited investigation in the Southern Hemisphere and other climate zones. This reduces the representativeness and broader applicability of current findings. More large-scale and long-term field studies are needed to assess the scalability of agrivoltaics. Plus, the performance of agrivoltaics under different climatic conditions appears to be site-specific, leading to diverse in crop responses. This refers to variation across both geographic locations (spatial) and time periods or growing seasons (temporal), depending on local climate, crop type, and system design. Thus, the existing studies remain limited.

Additionally, most existing research has involved identifying or testing suitable target crops within existing PV systems, putting PV in a passive position without being customized to the specific needs of different crops, and limiting its potential to enhance crop yield and quality. Current PV system success is often at the expense of crop yield and quality, but environmental and management factors are critical. Customizing systems based on regional climates, crop needs, and energy optimization, along with incorporating adjustable PV features (such as height and angle), can enhance productivity and efficiency, enabling farmers to proactively manage diverse challenges and adapt more flexibly to crop requirements, resilience and efficiency in the face of climate change.

Microclimates under PV systems generally provide decreased soil temperature and increased air and soil humidity, with air temperature remaining stable or decreasing, changes

that improve growing conditions for crops in arid regions and high-temperature environments. Notably, in severe weather conditions (e.g., frost, strong winds, hail), PV panels exert a protective effect and mitigate direct damage to plants (Dal Prà et al 2024; Juillion et al 2022).

The future of agrivoltaic systems will no longer follow a “one-size-fits-all” approach, but will instead evolve into a highly customized, ecologically adaptive, agriculture-centered system that also maximizes energy yield. It will deeply integrate crop physiology, climatology, engineering design, and ecological conservation, serving as a critical pillar for climate-resilient agriculture and the transition to sustainable energy. As data accumulates and predictive models improve, agrivoltaics is expected to offer an innovative pathway for sustainable agriculture, providing more stable and efficient options for agricultural production in the face of current and future challenges.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13593-025-01060-z>.

Acknowledgements We thank the Centre of Excellence in Transformative Agribusiness at Lincoln University for supporting this research. We are also grateful to Dr. Tiffany McIntyre and Riikka Kokko for their insightful discussions and constructive feedback on this research.

Authors' contributions Wei Zhang performed data analysis and drafted the original manuscript. Pieter-Willem Hendriks, Mark Uchanski, Shannon Page, Alan Renwick, Thomas Maxwell, Clive Kaiser, Jinpeng Dong, and Wim de Koning contributed to writing, reviewing, and editing. Wim de Koning and Alan Renwick provided supervision and guidance.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Data availability The data and materials used in this study are available upon reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication All authors have agreed to the submission and publication of this manuscript.

Conflict of interest The authors declare that they have no conflicts of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in

the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Agence de la transition écologique (ADEME) (2021) Characterize photovoltaic projects on agricultural land and agrivoltaics. The French Agency for Ecological Transition. <https://digital-energy.eu/en/etudes/caracteriser-les-projets-photovoltaiques-sur-terres-agricoles-et-lagrivoltaisme>. Accessed 25th June 2024
- Al Mamun MA, Garba II, Campbell S, Dargusch P, deVoil P, Aziz AA (2023) Biomass production of a sub-tropical grass under different photovoltaic installations using different grazing strategies. *Agric Syst* 208:103662. <https://doi.org/10.1016/j.agsy.2023.103662>
- Al-agele HA, Proctor K, Murthy G, Higgins C (2021) A case study of tomato (*Solanum lycopersicon* var. Legend) production and water productivity in agrivoltaic systems. *Sustainability* 13(5):2850. <https://doi.org/10.3390/su13052850>
- Ali N (2024) Agrivoltaic system success: a review of parameters that matter. *J Renewable Sustainable Energy*. <https://doi.org/10.1063/5.0197775>
- Andrew AC, Higgins CW, Smallman MA, Prado-Tarango DE, Rosati A, Ghajar S, Graham M, Ates S (2024) Herbage and sheep production from simple, diverse, and legume pastures established in an agrivoltaic production system. *Grass Forage Sci* 79(2):294–307. <https://doi.org/10.1111/gfs.12653>
- Armarego-Marriott T, Sandoval-Ibanez O, Kowalewska L (2020) Beyond the darkness: recent lessons from etiolation and de-etiolation studies. *J Exp Bot* 71(4):1215–1225. <https://doi.org/10.1093/jxb/erz496>
- Barron-Gafford GA, Minor RL, Allen NA, Cronin AD, Brooks AE, Pavao-Zuckerman MA (2016) The photovoltaic heat island effect: larger solar power plants increase local temperatures. *Sci Rep* 6:35070. <https://doi.org/10.1038/srep35070>
- Barron-Gafford GA, Pavao-Zuckerman MA, Minor RL, Sutter LF, Barnett-Moreno I, Blackett DT, Thompson M, Dimond K, Gerlak AK, Nabhan GP, Macknick JE (2019) Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat Sustain* 2(9):848–855. <https://doi.org/10.1038/s41893-019-0364-5>
- Barron-Gafford GA, Murphy P, Salazar A, Lepley K, Rouini N, Barnett-Moreno I, Macknick JE (2025) Agrivoltaics as a climate-smart and resilient solution for midday depression in photosynthesis in dryland regions. *Npj Sustain Agric* 3(1):32. <https://doi.org/10.1038/s44264-025-00073-1>
- Beck M, Bopp G, Goetzberger A, Obergfell T, Reise C, Schindele S (2012) Combining PV and food crops to agrophotovoltaic—optimization of orientation and harvest. 27th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC, Frankfurt, Germany. <https://publica-rest.fraunhofer.de/server/api/core/bitstreams/d853a27b-d675-4639-9f4f-07c5744c7557/content>. Accessed 20th June 2024
- Broadbent AM, Krayenhoff ES, Georgescu M, Sailor DJ (2019) The observed effects of utility-scale photovoltaics on near-surface air temperature and energy balance. *J Appl Meteorol Climatol* 58(5):989–1006. <https://doi.org/10.1175/jamc-d-18-0271.1>
- Campana PE, Stridh B, Amaducci S, Colauzzi M (2021) Optimisation of vertically mounted agrivoltaic systems. *J Clean Prod* 325:129091. <https://doi.org/10.1016/j.jclepro.2021.129091>
- Carreño-Ortega A, do Paço TA, Díaz-Pérez M, Gómez-Galán M (2021) Lettuce production under mini-PV modules arranged in patterned designs. *Agronomy* 11(12):2554. <https://doi.org/10.3390/agronomy11122554>
- Chae S-H, Kim HJ, Moon H-W, Kim YH, Ku K-M (2022) Agrivoltaic systems enhance farmers' profits through broccoli visual quality and electricity production without dramatic changes in yield, antioxidant capacity, and glucosinolates. *Agronomy* 12(6):1415. <https://doi.org/10.3390/agronomy12061415>
- Chartres CJ, Noble A (2015) Sustainable intensification: overcoming land and water constraints on food production. *Food Secur* 7(2):235–245. <https://doi.org/10.1007/s12571-015-0425-1>
- Cho J, Park SM, Park AR, Lee OC, Nam G, Ra I-H (2020) Application of photovoltaic systems for agriculture: a study on the relationship between power generation and farming for the improvement of photovoltaic applications in agriculture. *Energies* 13(18):4815. <https://doi.org/10.3390/en13184815>
- Choi CS, Cagle AE, Macknick J, Bloom DE, Caplan JS, Ravi S (2020) Effects of revegetation on soil physical and chemical properties in solar photovoltaic infrastructure. *Front Environ Sci* 8:140. <https://doi.org/10.3389/fenvs.2020.00140>
- Dal Prà A, Miglietta F, Genesio L, Lanini GM, Bozzi R, Morè N, Greco A, Fabbri MC (2024) Determination of feed yield and quality parameters of whole crop durum wheat (*Triticum durum* Desf.) biomass under agrivoltaic system. *Agroforest Syst* 98(8):2861–2873. <https://doi.org/10.1007/s10457-024-00979-8>
- Dinesh H, Pearce JM (2016) The potential of agrivoltaic systems. *Renew Sustain Energy Rev* 54:299–308. <https://doi.org/10.1016/j.rser.2015.10.024>
- Dupraz C, Marrou H, Talbot G, Dufour L, Nogier A, Ferard Y (2011) Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes. *Renew Energy* 36(10):2725–2732. <https://doi.org/10.1016/j.renene.2011.03.005>
- Elamri Y, Cheviron B, Lopez JM, Dejean C, Belaud G (2018) Water budget and crop modelling for agrivoltaic systems: application to irrigated lettuces. *Agric Water Manag* 208:440–453. <https://doi.org/10.1016/j.agwat.2018.07.001>
- Elborg M (2017) Reducing land competition for agriculture and photovoltaic energy generation—a comparison of two agro-photovoltaic plants in Japan. *Int J Sci Res* 3:5. <https://doi.org/10.3389/fendo.2023.1081704>
- FAO (2009) How to feed the world in 2050. https://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf. Accessed 25th June 2024
- Feng Y, Qiu GY, Zhang Q (2014) Determination of canopy-shadow-affected area in sparse steppes and its effects on evaporation and evapotranspiration. *Ecohydrol* 7(6):1589–1603. <https://doi.org/10.1002/eco.1482>
- Ferrara G, Boselli M, Palasciano M, 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. <https://doi.org/10.1016/j.scienta.2022.111595>
- Frankland B, Taylorson, R. (1983) Light control of seed germination. In: Shropshire, W., Mohr, H. (eds) *Photomorphogenesis*, vol 16. *Encyclopedia of Plant Physiology*. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-68918-5_17
- Fraunhofer (2024) Agrivoltaics: opportunities for agriculture and the energy transition. <https://www.ise.fraunhofer.de/en/publications/studies/agrivoltaics-opportunities-for-agriculture-and-the-energy-transition.html>. Accessed 25th June 2024
- Fthenakis V, Yu Y (2013) Analysis of the potential for a Heat Island Effect in large solar farms. In 2013 IEEE 39th photovoltaic specialists conference (PVSC). IEEE. <https://legalelectric.org/f/2021/02/Ex.-Grant-County-Intervenors-Frear-5.pdf>. Accessed 28th June 2024
- Gazzetta Ufficiale (2022) Urgent measures to contain the costs of electricity and natural gas, for the development of renewable energy

- and for the relaunch of industrial policies. Italian Official Journal. <https://www.gazzettaufficiale.it/>. Accessed 30th June
- Giri NC, Mohanty RC (2022) Design of agrivoltaic system to optimize land use for clean energy-food production: a socio-economic and environmental assessment. *Clean Technol Environ Policy* 24(8):2595–2606. <https://doi.org/10.1007/s10098-022-02337-7>
- Givnish TJ (1988) Adaptation to sun and shade: a whole-plant perspective. *Funct Plant Biol* 15:63–92. <https://doi.org/10.1071/PP9880063>
- Gong W, Zhang L, Gong J, Geng X, Wang L, Deng L, Wu C, Bao E (2025) Regulatory effect of agriphotovoltaic systems with different panel heights on the thermal environment. *Sci Rep* 15(1):11196. <https://doi.org/10.1038/s41598-025-96166-5>
- Gonocruz RA, Nakamura R, Yoshino K, Homma M, Doi T, Yoshida Y, Tani A (2021) Analysis of the rice yield under an agrivoltaic system: a case study in Japan. *Environments* 8(7):65. <https://doi.org/10.3390/environments8070065>
- Graham M, Ates S, Melathopoulos AP, Moldenke AR, DeBano SJ, Best LR, Higgins CW (2021) Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. *Sci Rep* 11(1):7452. <https://doi.org/10.1038/s41598-021-86756-4>
- Gravel D, Canham CD, Beaudet M, Messier C (2010) Shade tolerance, canopy gaps and mechanisms of coexistence of forest trees. *Oikos* 119(3):475–484. <https://doi.org/10.1111/j.1600-0706.2009.17441.x>
- Grubbs EK, Gruss SM, Schull VZ, Gosney MJ, Mickelbart MV, Brouder S, Gitau MW, Bermel P, Tuinstra MR, Agrawal R (2024) Optimized agrivoltaic tracking for nearly-full commodity crop and energy production. *Renew Sustain Energy Rev* 191:114018. <https://doi.org/10.1016/j.rser.2023.114018>
- Hassanpour Adeb E, Selker JS, Higgins CW (2018) Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS ONE* 13(11):e0203256. <https://doi.org/10.1371/journal.pone.0203256>
- Hassanpour Adeb E, Good SP, Calaf M, Higgins CW (2019) Solar PV power potential is greatest over croplands. *Sci Rep* 9(1):11442. <https://doi.org/10.1038/s41598-019-47803-3>
- Hide JC (1954) Observations on factors influencing the evaporation of soil moisture. *Soil Sci Soc Am J* 18(3):234–239. <https://doi.org/10.2136/sssaj1954.03615995001800030002x>
- International Energy Agency (IEA) (2023a) Renewables 2023 analysis and forecast to 2028. https://iea.blob.core.windows.net/assets/96d66a8b-d502-476b-ba94-54ffda84cf72/Renewables_2023.pdf. Accessed 25th June 2024
- International Energy Agency (IEA) (2023b) World energy outlook 2023. <https://www.iea.org/reports/world-energy-outlook-2023>. Accessed 25th June 2024
- International Energy Agency (IEA) (2024) Snapshot of global PV markets 2024. International Energy Agency, <https://iea-pvps.org/wp-content/uploads/2024/04/Snapshot-of-Global-PV-Markets-1.pdf>. Accessed 30th June 2024
- International Renewable Energy Agency (IRENA) (2024) Renewable energy capacity statistics 2024. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Mar/IRENA_RE_Capacity_Statistics_2024.pdf. Accessed 28th June 2024
- IPCC (2021) Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/>. Accessed 28th June 2024
- Jiang S, Tang D, Zhao L, Liang C, Cui N, Gong D, Wang Y, Feng Y, Hu X, Peng Y (2022) Effects of different photovoltaic shading levels on kiwifruit growth, yield and water productivity under “agrivoltaic” system in Southwest China. *Agric Water Manag* 269:107675. <https://doi.org/10.1016/j.agwat.2022.107675>
- Juillion P, Lopez G, Fumey D, Lesniak V, Génard M, Vercambre G (2022) Shading apple trees with an agrivoltaic system: impact on water relations, leaf morphophysiological characteristics and yield determinants. *Sci Hortic* 306:111434. <https://doi.org/10.1016/j.scienta.2022.111434>
- Juillion P, Lopez G, Fumey D, Lesniak V, Génard M, Vercambre G (2024) Combining field experiments under an agrivoltaic system and a kinetic fruit model to understand the impact of shading on apple carbohydrate metabolism and quality. *Agroforest Syst* 98(8):2829–2846. <https://doi.org/10.1007/s10457-024-00965-0>
- Kampherbeek EW, Webb LE, Reynolds BJ, Sistla SA, Horney MR, Ripoll-Bosch R, Dubowsky JP, McFarlane ZD (2023) A preliminary investigation of the effect of solar panels and rotation frequency on the grazing behavior of sheep (*Ovis aries*) grazing dormant pasture. *Appl Anim Behav Sci* 258:105799. <https://doi.org/10.1016/j.applanim.2022.105799>
- Kannenber SA, Sturchio MA, Venturas MD, Knapp AK (2023) Grassland carbon-water cycling is minimally impacted by a photovoltaic array. *Commun Earth Environ* 4(1):238. <https://doi.org/10.1038/s43247-023-00904-4>
- Ko D-Y, Chae S-H, Moon H-W, Kim H, Seong J, Lee M-S, Ku K-M (2023) Agrivoltaic farming insights: a case study on the cultivation and quality of kimchi cabbage and garlic. *Agronomy* 13(10):2625. <https://doi.org/10.3390/agronomy13102625>
- Laub M, Pataczek L, Feuerbacher A, Zikeli S, 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(3):51. <https://doi.org/10.1007/s13593-022-00783-7>
- Lee HJ, Park HH, Kim YO, Kuk YI (2022) Crop cultivation underneath agro-photovoltaic systems and its effects on crop growth, yield, and photosynthetic efficiency. *Agronomy* 12(8):1842. <https://doi.org/10.3390/agronomy12081842>
- Leroy V, Decocq G, Noirot-Cosson P-E, Marrec R (2025a) Impacts of punctual solar trackers on soil biodiversity in agricultural lands. *Geoderma* 453:117147. <https://doi.org/10.1016/j.geoderma.2024.117147>
- Lu L, Effendy Ya’acob M, Shamsul Anuar M, Nazim Mohtar M (2022) Comprehensive review on the application of inorganic and organic photovoltaics as greenhouse shading materials. *Sustain Energy Technol Assess* 52:101077. <https://doi.org/10.1016/j.seta.2022.102077>
- Luo J, Luo Z, Li W, Shi X, Sui X (2024) The early effects of an agrivoltaic system within a different crop cultivation on soil quality in dry-hot valley eco-fragile areas. *Agronomy* 14(3):584. <https://doi.org/10.3390/agronomy14030584>
- Malu PR, Sharma US, Pearce JM (2017) Agrivoltaic potential on grape farms in India. *Sustain Energy Technol Assess* 23:104–110. <https://doi.org/10.1016/j.seta.2017.08.004>
- Mamun MAA, Dargusch P, Wadley D, Zulkarnain NA, Aziz AA (2022) A review of research on agrivoltaic systems. *Renew Sustain Energy Rev* 161:112351. <https://doi.org/10.1016/j.rser.2022.112351>
- Marrou H, Dufour L, Wery J (2013a) How does a shelter of solar panels influence water flows in a soil-crop system? *Eur J Agron* 50:38–51. <https://doi.org/10.1016/j.eja.2013.05.004>
- Marrou H, Guillioni L, Dufour L, Dupraz C, 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. <https://doi.org/10.1016/j.agrformet.2013.04.012>
- Marrou H, Wery J, Dufour L, Dupraz C (2013c) Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. *Eur J Agron* 44:54–66. <https://doi.org/10.1016/j.eja.2012.08.003>
- Min SY, Kim BM, Yun HK, Jung JH, Oh W (2022) Effects of environmental changes by an agrivoltaic system on growth and

- quality characteristics of kimchi cabbage. *J People Plants Environ* 25(6):659–667. <https://doi.org/10.11628/ksppe.2022.25.6.659>
- Ministry of Agriculture, Forestry and Fisheries (MAFF)(2015) FY2014 annual report on food, agriculture and rural areas in Japan Summary. Tokyo, Japan. <https://www.maff.go.jp/e/pdf/fy2014.pdf>. Accessed 25th June 2024
- Mohammedi S, Dragonetti G, Admane N, Fouial A (2023a) The impact of agrivoltaic systems on tomato crop: a case study in southern Italy. *Processes* 11(12):3370. <https://doi.org/10.3390/pr11123370>
- Möller M, Assouline S (2006) Effects of a shading screen on microclimate and crop water requirements. *Irrig Sci* 25(2):171–181. <https://doi.org/10.1007/s00271-006-0045-9>
- Monteith JL (1977) Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London b, Biol Sci* 281(980):277–294
- Moon H-W, Ku K-M (2022a) Impact of an agriphotovoltaic system on metabolites and the sensorial quality of cabbage (*Brassica oleracea* var. *capitata*) and its high-temperature-extracted juice. *Foods* 11(4):3370. <https://doi.org/10.3390/foods11040498>
- Moon H-W, Ku KM (2023) The effect of additional shading utilizing agriphotovoltaic structures on the visual qualities and metabolites of broccoli. *Front Plant Sci* 14:1111069. <https://doi.org/10.3389/fpls.2023.1111069>
- Mouhib E, Fernández-Solas Á, Pérez-Higueras PJ, Fernández-Ocaña AM, Micheli L, Almonacid F, Fernández EF (2024) Enhancing land use: integrating bifacial PV and olive trees in agrivoltaic systems. *Appl Energy* 359:122660. <https://doi.org/10.1016/j.apenergy.2024.122660>
- Muñoz-García M-Á, Fialho L, Moreda GP, Baptista F (2024) Assessment of the impact of utility-scale photovoltaics on the surrounding environment in the Iberian Peninsula. Alternatives for the coexistence with agriculture. *Sol Energy* 271:112446. <https://doi.org/10.1016/j.solener.2024.112446>
- Nieto-Morone M-B, Muñoz-García M-Á, Pérez López D, Bernal-Basurco C, García Rosillo F, Alonso-García MdC (2025) Agrivoltaics: integration of reused PV modules. *Agronomy* 15(3):730. <https://doi.org/10.3390/agronomy15030730>
- Oerke EC (2006) Crop losses to pests. *J Agric Sci* 144(1):31–43. <https://doi.org/10.1017/s0021859605005708>
- Osman AI, Chen L, Yang M, Msigwa G, Farghali M, Fawzy S, Rooney DW, Yap P-S (2022) Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. *Environ Chem Lett* 21(2):741–764. <https://doi.org/10.1007/s10311-022-01532-8>
- Patel UR, Gadhya GA, Chauhan PM (2024) Techno-economic analysis of agrivoltaic system for affordable and clean energy with food production in India. *Clean Technol Environ Policy* 26(7):2117–2135. <https://doi.org/10.1007/s10098-023-02690-1>
- Pelczar S (2025) Is the Land Equivalent Ratio (LER) a sufficient indicator to describe the efficiency of agrivoltaic system? Insights to better understanding the interpretation of ler and the development of additional coefficients. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5185197. Accessed 25th June 2024
- Potenza E, Croci M, Colauzzi M, Amaducci S (2022) Agrivoltaic system and modelling simulation: a case study of soybean (*Glycine max* L.) in Italy. *Horticulturae* 8(12):1160. <https://doi.org/10.3390/horticulturae8121160>
- Precedence Research (2023) Agrivoltaics market- global industry analysis, size, share, growth, trends, regional outlook, and forecast 2023-2032. Precedence Research. <https://www.precedenceresearch.com/agrivoltaics-market>. Accessed 25th June 2024
- Ramos-Fuentes IA, Elamri Y, Cheviron B, Dejean C, Belaud G, Fumey D (2023) Effects of shade and deficit irrigation on maize growth and development in fixed and dynamic AgriVoltaic systems. *Agric Water Manag* 280:108187. <https://doi.org/10.1016/j.agwat.2023.108187>
- Randle-Boggis RJ, Barron-Gafford GA, Kimaro AA, Lamanna C, Macharia C, Maro J, Mbele A, Hartley SE (2025) Harvesting the sun twice: energy, food and water benefits from agrivoltaics in East Africa. *Renew Sustain Energy Rev* 208:115066. <https://doi.org/10.1016/j.rser.2024.115066>
- Ravi S, Macknick J, Lobell D, Field C, Ganesan K, Jain R, Elchinger M, Stoltenberg B (2016) Colocation opportunities for large solar infrastructures and agriculture in drylands. *Appl Energy* 165:383–392. <https://doi.org/10.1016/j.apenergy.2015.12.078>
- Reeza AA, Noor NFM, Ahmed OH, Masuri MA (2024) Shading effect of photovoltaic panels on growth of selected tropical vegetable crops. *Sci Hortic* 324:112574. <https://doi.org/10.1016/j.scienta.2023.112574>
- Reher T, Lavaert C, Willockx B, Huyghe Y, Bisschop J, Martens JA, Diels J, Cappelle J, Van de Poel B (2024) Potential of sugar beet (*Beta vulgaris*) and wheat (*Triticum aestivum*) production in vertical bifacial, tracked, or elevated agrivoltaic systems in Belgium. *Appl Energy* 359:122679. <https://doi.org/10.1016/j.apenergy.2024.122679>
- Riaz MH, Imran H, Younas R, Butt NZ (2021) The optimization of vertical bifacial photovoltaic farms for efficient agrivoltaic systems. *Sol Energy* 230:1004–1012. <https://doi.org/10.1016/j.solener.2021.10.051>
- Ruan T, Wang F, Topel M, Laumert B, Wang W (2024) A new optimal PV installation angle model in high-latitude cold regions based on historical weather big data. *Appl Energy* 359:122690. <https://doi.org/10.1016/j.apenergy.2024.122690>
- Said SAM, Hassan G, Walwil HM, Al-Aqeeli N (2018) The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies. *Renew Sustain Energy Rev* 82:743–760. <https://doi.org/10.1016/j.rser.2017.09.042>
- Santra P (2017) Agri-voltaics or solar farming: the concept of integrating solar PV based electricity generation and crop production in a single land use system. *Int J Renew Energy Res* 7(2):694–699. <https://doi.org/10.20508/ijrer.v7i2.5582.g7049>
- Sarr A, Soro YM, Tossa AK, Diop L (2024) A new approach for modelling photovoltaic panel configuration maximizing crop yield and photovoltaic array outputs in agrivoltaics systems. *Energy Convers Manag* 309:118436. <https://doi.org/10.1016/j.enconman.2024.118436>
- Sekiyama T, Nagashima A (2019) Solar sharing for both food and clean energy production: performance of agrivoltaic systems for corn, a typical shade-intolerant crop. *Environments* 6(6):65. <https://doi.org/10.3390/environments6060065>
- Semeraro T, Scarano A, Curci LM, Leggieri A, Lenucci M, Basset A, Santino A, Piro G, De Caroli M (2024) Shading effects in agrivoltaic systems can make the difference in boosting food security in climate change. *Appl Energy* 358:122565. <https://doi.org/10.1016/j.apenergy.2023.122565>
- Shepard LA, Higgins CW, Proctor KW (2022) Agrivoltaics: modeling the relative importance of longwave radiation from solar panels. *PLoS ONE* 17(10):e0273119. <https://doi.org/10.1371/journal.pone.0273119>
- Shi Y, Ke X, Yang X, Liu Y, Hou X (2022) Plants response to light stress. *J Genet Genomics* 49(8):735–747. <https://doi.org/10.1016/j.jgg.2022.04.017>
- Sinclair TR, Muchow RC (1999) Radiation use efficiency. *Adv Agron* 65:215–265. [https://doi.org/10.1016/s0065-2113\(08\)60914-1](https://doi.org/10.1016/s0065-2113(08)60914-1)
- Smith SE, Viggiano B, Ali N, Silverman TJ, Obligado M, Calaf M, Cal RB (2022) Increased panel height enhances cooling for photovoltaic solar farms. *Appl Energy* 325:119819. <https://doi.org/10.1016/j.apenergy.2022.119819>

- Sturchio MA, Macknick JE, Barron-Gafford GA, Chen A, Alderfer C, Condon K, Hajek OL, Miller B, Pauletto B, Siggers JA, Slette IJ, Knapp AK (2022) Grassland productivity responds unexpectedly to dynamic light and soil water environments induced by photovoltaic arrays. *Ecosphere* 13(12):e4334. <https://doi.org/10.1002/ecs2.4334>
- Sturchio MA, Kannenberg SA, Knapp AK (2024) Agrivoltaic arrays can maintain semi-arid grassland productivity and extend the seasonality of forage quality. *Appl Energy* 356:122418. <https://doi.org/10.1016/j.apenergy.2023.122418>
- Sun J, Cui W, Wang W, Yang X (2025) The microclimatic and eco-hydrological effects of photovoltaic facilities in arid/semi-arid regions of China: an integrated modeling study. *J Environ Manage* 382:125395. <https://doi.org/10.1016/j.jenvman.2025.125395>
- Szabadi KL, Kurali A, Rahman NAA, Froidevaux JSP, Tinsley E, Jones G, Görföl T, Estók P, Zsebők S (2023) The use of solar farms by bats in mosaic landscapes: implications for conservation. *Glob Ecol Conserv* 44:e02481. <https://doi.org/10.1016/j.gecco.2023.e02481>
- Tahir Z, Butt NZ (2022) Implications of spatial-temporal shading in agrivoltaics under fixed tilt & tracking bifacial photovoltaic panels. *Renew Energy* 190:167–176. <https://doi.org/10.1016/j.renene.2022.03.078>
- Teng JWC, Soh CB, Devihosur SC, Tay RHS, Jusuf SK (2022) Effects of agrivoltaic systems on the surrounding rooftop microclimate. *Sustainability* 14(12):7089. <https://doi.org/10.3390/su14127089>
- Thomas SJ, Thomas S, Sahoo SS, G AK, Awad MM (2023) Solar parks: a review on impacts, mitigation mechanism through agrivoltaics and techno-economic analysis. *Energy Nexus* 11:100220. <https://doi.org/10.1016/j.nexus.2023.100220>
- Thompson EP, Bombelli EL, Shubham S, Watson H, Everard A, D'Ardes V, Schievano A, Bocchi S, Zand N, Howe CJ, Bombelli P (2020a) Tinted semi-transparent solar panels allow concurrent production of crops and electricity on the same cropland. *Adv Energy Mater* 10(35):2001189. <https://doi.org/10.1002/aenm.202001189>
- Thum CH, Okada K, Yamasaki Y, Kato Y (2025) Impacts of agrivoltaic systems on microclimate, grain yield, and quality of lowland rice under a temperate climate. *Field Crops Res* 326:109877. <https://doi.org/10.1016/j.fcr.2025.109877>
- Time A, Gomez-Casanovas N, Mwebaze P, Apollon W, Khanna M, DeLucia EH, Bernacchi CJ (2024) Conservation agrivoltaics for sustainable food-energy production. *Plants People Planet* 6(3):558–569. <https://doi.org/10.1002/ppp3.10481>
- Uchanski M, Hickey T, Bousselot J, Barth KL (2023) Characterization of agrivoltaic crop environment conditions using opaque and thin-film semi-transparent modules. *Energies* 16(7):3012. <https://doi.org/10.3390/en16073012>
- Valladares F, Niinemets Ü (2008) Shade tolerance, a key plant feature of complex nature and consequences. *Annu Rev Ecol Evol Syst* 39(1):237–257. <https://doi.org/10.1146/annurev.ecolsys.39.110707.173506>
- Valle B, Simonneau T, Sourd F, Pechier P, Hamard P, Frisson T, Ryckewaert M, Christophe A (2017) Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Appl Energy* 206:1495–1507. <https://doi.org/10.1016/j.apenergy.2017.09.113>
- van Dijk M, Morley T, Rau ML, 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(7):494–501. <https://doi.org/10.1038/s43016-021-00322-9>
- Vasel A, Iakovidis F (2017) The effect of wind direction on the performance of solar PV plants. *Energy Convers Manag* 153:455–461. <https://doi.org/10.1016/j.enconman.2017.09.077>
- Wang R, Eguchi M, Gui Y, Iwasaki Y (2020) Evaluating the effect of light intensity on flower development uniformity in strawberry (*Fragaria xananassa*) under early induction conditions in forcing culture. *HortScience* 55(5):670–675. <https://doi.org/10.21273/HORTSCI14917-20>
- Weselek A, Ehmann A, Zikeli S, Lewandowski I, Schindele S, Högy P (2019) Agrophotovoltaic systems: applications, challenges, and opportunities. A review. *Agron Sustain Dev* 39(4):35. <https://doi.org/10.1007/s13593-019-0581-3>
- Weselek A, Bauerle A, Hartung J, Zikeli S, Lewandowski I, Högy P (2021a) Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agron Sustain Dev* 41(5):59. <https://doi.org/10.1007/s13593-021-00714-y>
- Widmer J, Christ B, Grenz J, Norgrove L (2024) Agrivoltaics, a promising new tool for electricity and food production: a systematic review. *Renew Sustain Energy Rev* 192:114277. <https://doi.org/10.1016/j.rser.2023.114277>
- Williams HJ, Hashad K, Wang H, Max Zhang K (2023) The potential for agrivoltaics to enhance solar farm cooling. *Appl Energy* 332:120478. <https://doi.org/10.1016/j.apenergy.2022.120478>
- Willockx B (2020) Combining photovoltaic modules and food crops: first agrivoltaic prototype in Belgium. *Renew Energy Power Qual J* 18. <https://doi.org/10.24084/repqj18.291>
- Willockx B, Lavaert C, 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. <https://doi.org/10.1016/j.egy.2022.06.076>
- Willockx B, Lavaert C, Cappelle J (2023) Performance evaluation of vertical bifacial and single-axis tracked agrivoltaic systems on arable land. *Renew Energy* 217:119181. <https://doi.org/10.1016/j.renene.2023.119181>
- Willockx B, Reher T, Lavaert C, Herteleer B, Van de Poel B, Cappelle J (2024) Design and evaluation of an agrivoltaic system for a pear orchard. *Appl Energy* 353. <https://doi.org/10.1016/j.apenergy.2023.122166>
- Wu C, Liu H, Yu Y, Zhao W, Guo L, Liu J, Yetemen O (2023) Ecohydrological insight: solar farms facilitate carbon sink enhancement in drylands. *J Environ Manage* 342:118304. <https://doi.org/10.1016/j.jenvman.2023.118304>
- Yang C, Li L (2017) Hormonal regulation in shade avoidance. *Front Plant Sci* 8:1527. <https://doi.org/10.3389/fpls.2017.01527>
- Yang L, Gao X, Lv F, Hui X, Ma L, Hou X (2017) Study on the local climatic effects of large photovoltaic solar farms in desert areas. *Solar Energy* 144:244–253. <https://doi.org/10.1016/j.solener.2017.01.015>
- Yang Z, Jiang Y, Qiu R, Gong X, Agathokleous E, Hu W, Clothier B (2023) Heat stress decreased transpiration but increased evapotranspiration in gerbera. *Front Plant Sci* 14:1119076. <https://doi.org/10.3389/fpls.2023.1119076>
- Zheng J, Meng S, Zhang X, Zhao H, Ning X, Chen F, Abaker Omer AA, Ingenhoff J, Liu W (2021) Increasing the comprehensive economic benefits of farmland with even-lighting agrivoltaic systems. *PLoS ONE* 16(7):e0254482. <https://doi.org/10.1371/journal.pone.0254482>

References for the meta-analysis

- Adolfo R, Kyle P, Azad D, Maggie G, Serkan A, Kirschten HM, Higgins CW (2023) Agroforestry versus agrivoltaic: spectral composition of transmitted radiation and implications for understory crops. *Agroforest Syst* 8:98. <https://doi.org/10.1007/s10457-023-00914-3>
- Al Mamun MA, Garba II, Campbell S, Dargusch P, deVoil P, Aziz AA (2023) Biomass production of a sub-tropical grass under different

- photovoltaic installations using different grazing strategies. *Agric Syst* 208:103662. <https://doi.org/10.1016/j.agsy.2023.103662>
- Al-agele HA, Proctor K, Murthy G, Higgins C (2021) A case study of tomato (*Solanum lycopersicon* var. Legend) production and water productivity in agrivoltaic systems. *Sustainability* 13(5):2850. <https://doi.org/10.3390/su13052850>
- Andrew AC, Higgins CW, Smallman MA, Graham M, Ates S (2021) Herbage yield, lamb growth and foraging behavior in agrivoltaic production system. *Front Sustain Food Syst* 5:659175. <https://doi.org/10.3389/fsufs.2021.659175>
- Andrew AC, Higgins CW, Smallman MA, Prado-Tarango DE, Rosati A, Ghajar S, Graham M, Ates S (2024) Herbage and sheep production from simple, diverse, and legume pastures established in an agrivoltaic production system. *Grass Forage Sci* 79(2):294–307. <https://doi.org/10.1111/gfs.12653>
- Barron-Gafford GA, Minor RL, Allen NA, Cronin AD, Brooks AE, Pavao-Zuckerman MA (2016) The photovoltaic heat island effect: larger solar power plants increase local temperatures. *Sci Rep* 6:35070. <https://doi.org/10.1038/srep35070>
- Barron-Gafford GA, Pavao-Zuckerman MA, Minor RL, Sutter LF, Barnett-Moreno I, Blackett DT, Thompson M, Dimond K, Gerlak AK, Nabhan GP, Macknick JE (2019) Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat Sustain* 2(9):848–855. <https://doi.org/10.1038/s41893-019-0364-5>
- Broadbent AM, Krayenhoff ES, Georgescu M, Sailor DJ (2019) The observed effects of utility-scale photovoltaics on near-surface air temperature and energy balance. *J Appl Meteorol Climatol* 58(5):989–1006. <https://doi.org/10.1175/jamc-d-18-0271.1>
- Campana PE, Stridh B, Amaducci S, Colauzzi M (2021) Optimisation of vertically mounted agrivoltaic systems. *J Clean Prod* 325:129091. <https://doi.org/10.1016/j.jclepro.2021.129091>
- Carreño-Ortega A, do Paço TA, Díaz-Pérez M, Gómez-Galán M (2021) Lettuce production under mini-PV modules arranged in patterned designs. *Agronomy* 11(12):2554. <https://doi.org/10.3390/agronomy11122554>
- Chae S-H, Kim HJ, Moon H-W, Kim YH, Ku K-M (2022) Agrivoltaic systems enhance farmers' profits through broccoli visual quality and electricity production without dramatic changes in yield, antioxidant capacity, and glucosinolates. *Agronomy* 12(6):1415. <https://doi.org/10.3390/agronomy12061415>
- Cho J, Park SM, Park AR, Lee OC, Nam G, Ra I-H (2020) Application of photovoltaic systems for agriculture: a study on the relationship between power generation and farming for the improvement of photovoltaic applications in agriculture. *Energies* 13(18):4815. <https://doi.org/10.3390/en13184815>
- Choi CS, Cagle AE, Macknick J, Bloom DE, Caplan JS, Ravi S (2020) Effects of revegetation on soil physical and chemical properties in solar photovoltaic infrastructure. *Front Environ Sci* 8:140. <https://doi.org/10.3389/fenvs.2020.00140>
- Dal Prà A, Miglietta F, Genesio L, Lanini GM, Bozzi R, Morè N, Greco A, Fabbri MC (2024) Determination of feed yield and quality parameters of whole crop durum wheat (*Triticum durum* Desf.) biomass under agrivoltaic system. *Agroforest Syst* 98(8):2861–2873. <https://doi.org/10.1007/s10457-024-00979-8>
- Dal Prà A, Dainelli R, Santoni M, Lanini GM, Di Serio A, Zanotti D, Greco A, Ronga D (2025) Impact of different shading conditions on processing tomato yield and quality under organic agrivoltaic systems. *Horticulturae* 11 (3): 0-0. <https://doi.org/10.3390/horticulturae11030319>
- Elamri Y, Cheviron B, Lopez JM, Dejean C, Belaud G (2018) Water budget and crop modelling for agrivoltaic systems: application to irrigated lettuces. *Agric Water Manag* 208:440–453. <https://doi.org/10.1016/j.agwat.2018.07.001>
- Fagnano M, Fiorentino N, Visconti D, Baldi GM, Falce M, Acutis M, Genovese M, Di Blasi M (2024) Effects of a photovoltaic plant on microclimate and crops' growth in a Mediterranean area. *Agronomy* 14(3):466. <https://doi.org/10.3390/agronomy14030466>
- Ferrara G, Boselli M, Palasciano M, 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. <https://doi.org/10.1016/j.scienta.2022.111595>
- Fthenakis V, Yu Y (2013) Analysis of the potential for a Heat Island Effect in large solar farms. In 2013 IEEE 39th photovoltaic specialists conference (PVSC). IEEE. <https://legalelectric.org/f/2021/02/Ex.-Grant-County-Intervenors-Frear-5.pdf>. Accessed 28th June 2024
- Giri NC, Mohanty RC (2022) Design of agrivoltaic system to optimize land use for clean energy-food production: a socio-economic and environmental assessment. *Clean Technol Environ Policy* 24(8):2595–2606. <https://doi.org/10.1007/s10098-022-02337-7>
- Giri NC, Mohanty RC (2024) Turmeric crop farming potential under agrivoltaic system over open field practice in Odisha, India. *Environ Dev Sustain*: 1-19. <https://doi.org/10.1007/s10668-024-05086-3>
- Gonocruz RA, Nakamura R, Yoshino K, Homma M, Doi T, Yoshida Y, Tani A (2021) Analysis of the rice yield under an agrivoltaic system: a case study in Japan. *Environments* 8(7):65. <https://doi.org/10.3390/environments8070065>
- Gosgot Angeles W, Banda Martinez D, Barrena Gurbillón MÁ, Espinoza Canaza FI, Santillan Gomez H, Mori Servan DC, Yalta Chappa M, Huanes Mariños MA, Gamarra-Torres OA, Oliviera-Cruz M (2025) Productivity and morphological adaptation of *Phaseolus vulgaris* L. in agrivoltaic systems with different photovoltaic technologies: a case study in Chachapoyas, Amazonas, Peru. *Agronomy* 15(3):529. <https://doi.org/10.3390/agronomy15030529>
- Graham M, Ates S, Melathopoulos AP, Moldenke AR, DeBano SJ, Best LR, Higgins CW (2021) Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. *Sci Rep* 11(1):7452. <https://doi.org/10.1038/s41598-021-86756-4>
- Grubbs EK, Gruss SM, Schull VZ, Gosney MJ, Mickelbart MV, Brouder S, Gitau MW, Bermel P, Tuinstra MR, Agrawal R (2024) Optimized agrivoltaic tracking for nearly-full commodity crop and energy production. *Renew Sustain Energy Rev* 191:114018. <https://doi.org/10.1016/j.rser.2023.114018>
- Gupta V, Gruss SM, Cammarano D, Brouder SM, Bermel PA, Tuinstra MR, Gitau MW, Agrawal R (2024) Optimizing corn agrivoltaic farming through farm-scale experimentation and modeling. *Cell Rep Sustain* 1(7):100148. <https://doi.org/10.1016/j.crsus.2024.100148>
- Hassanpour Adeg E, Selker JS, Higgins CW (2018) Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS ONE* 13(11):e0203256. <https://doi.org/10.1371/journal.pone.0203256>
- Inghels C, Noirot-Cosson P-E, Riou T, Kichey T, Guiller A (2025) Effect of high biaxial solar trackers on crop yield, application to different design simulations. *Agroforest Syst* 99(2):48. <https://doi.org/10.1007/s10457-025-01144-5>
- Jiang S, Tang D, Zhao L, Liang C, Cui N, Gong D, Wang Y, Feng Y, Hu X, Peng Y (2022) Effects of different photovoltaic shading levels on kiwifruit growth, yield and water productivity under “agrivoltaic” system in Southwest China. *Agric Water Manag* 269:107675. <https://doi.org/10.1016/j.agwat.2022.107675>
- Jo H, Asekova S, Bayat MA, Ali L, Song JT, Ha Y-S, Hong D-H, Lee J-D (2022) Comparison of yield and yield components of several crops grown under agro-photovoltaic system in Korea. *Agriculture* 12(5):619. <https://doi.org/10.3390/agriculture12050619>
- Juillion P, Lopez G, Fumey D, Lesniak V, Génard M, Vercambre G (2022) Shading apple trees with an agrivoltaic system: impact on

- water relations, leaf morphophysiological characteristics and yield determinants. *Sci Hortic* 306:111434. <https://doi.org/10.1016/j.scienta.2022.111434>
- Juillion P, Lopez G, Fumey D, Lesniak V, Génard M, Vercambre G (2024) Combining field experiments under an agrivoltaic system and a kinetic fruit model to understand the impact of shading on apple carbohydrate metabolism and quality. *Agroforest Syst* 98(8):2829–2846. <https://doi.org/10.1007/s10457-024-00965-0>
- Kampherbeek EW, Webb LE, Reynolds BJ, Sistla SA, Horney MR, Ripoll-Bosch R, Dubowsky JP, McFarlane ZD (2023) A preliminary investigation of the effect of solar panels and rotation frequency on the grazing behavior of sheep (*Ovis aries*) grazing dormant pasture. *Appl Anim Behav Sci* 258:105799. <https://doi.org/10.1016/j.applanim.2022.105799>
- Kannenbergh SA, Sturchio MA, Venturas MD, Knapp AK (2023) Grassland carbon-water cycling is minimally impacted by a photovoltaic array. *Commun Earth Environ* 4(1):238. <https://doi.org/10.1038/s43247-023-00904-4>
- Kim S, Kim S, Yoon C-Y (2021) An efficient structure of an agrivoltaic system in a temperate climate region. *Agronomy* 11(8):1584. <https://doi.org/10.3390/agronomy11081584>
- Ko D-Y, Chae S-H, Moon H-W, Kim H, Seong J, Lee M-S, Ku K-M (2023) Agrivoltaic farming insights: a case study on the cultivation and quality of kimchi cabbage and garlic. *Agronomy* 13(10):2625. <https://doi.org/10.3390/agronomy13102625>
- Kumpanalaisatit M, Setthapun W, Sintuya H, Jansri SN (2022) Efficiency improvement of ground-mounted solar power generation in agrivoltaic system by cultivation of Bok Choy (*Brassica rapa* subsp. *chinensis* L.) under the panels. *Int J Renew Energy Dev* 11(1):103–110. <https://doi.org/10.14710/ijred.2022.41116>
- Lee HJ, Park HH, Kim YO, Kuk YI (2022) Crop cultivation underneath agro-photovoltaic systems and its effects on crop growth, yield, and photosynthetic efficiency. *Agronomy* 12(8):1842. <https://doi.org/10.3390/agronomy12081842>
- Leroy V, Decocq G, Noirot-Cosson P-E, Marrec R (2025b) Impacts of punctual solar trackers on soil biodiversity in agricultural lands. *Geoderma* 453:117147. <https://doi.org/10.1016/j.geoderma.2024.117147>
- Liu Z, Peng T, Ma S, Qi C, Song Y, Zhang C, Li K, Gao N, Pu M, Wang X, Bi Y, Na X (2023) Potential benefits and risks of solar photovoltaic power plants on arid and semi-arid ecosystems: an assessment of soil microbial and plant communities. *Front Microbiol* 14:1190650. <https://doi.org/10.3389/fmicb.2023.1190650>
- Luo J, Luo Z, Li W, Shi W, Sui X (2024) The early effects of an agrivoltaic system within a different crop cultivation on soil quality in dry-hot valley eco-fragile areas. *Agronomy* 14(3):584. <https://doi.org/10.3390/agronomy14030584>
- Ma Lu S, Zainali S, Zidane TEK, Horndahl T, Tekie S, Khosravi A, Guezgouz M, Stridh B, Avelin A, Campana PE (2024) Data on the effects of a vertical agrivoltaic system on crop yield and nutrient content of barley (*Hordeum vulgare* L.) in Sweden. *Data Brief* 57:110990. <https://doi.org/10.1016/j.dib.2024.110990>
- Magarelli A, Mazzeo A, Ferrara G (2025) Exploring the grape agrivoltaic system: climate modulation and vine benefits in the Puglia Region, southeastern Italy. *Horticulturae* 11(2):160. <https://doi.org/10.3390/horticulturae11020160>
- Marrou H, Dufour L, Wery J (2013) How does a shelter of solar panels influence water flows in a soil-crop system? *Eur J Agron* 50:38–51. <https://doi.org/10.1016/j.eja.2013.05.004>
- Marrou H, Guilioni L, Dufour L, Dupraz C, Wery J (2013d) Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? *Agric for Meteorol* 177:117–132. <https://doi.org/10.1016/j.agrformet.2013.04.012>
- Marrou H, Wery J, Dufour L, Dupraz C (2013e) Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. *Eur J Agron* 44:54–66. <https://doi.org/10.1016/j.eja.2012.08.003>
- Min SY, Kim BM, Yun HK, Jung JH, Oh W (2022) Effects of environmental changes by an agrivoltaic system on growth and quality characteristics of kimchi cabbage. *J People Plants Environ* 25(6):659–667. <https://doi.org/10.11628/kspe.2022.25.6.659>
- Modi VV, Patel SK (2024) Performance evaluation of agrivoltaic system for the synergy among greengram (*Vigna radiata* L. Wilczek) production and solar electric power generation. *Energy Sci Eng* 12(12):5385–5397. <https://doi.org/10.1002/ese3.1870>
- Mohammedi S, Dragonetti G, Admane N, Fouial A (2023b) The impact of agrivoltaic systems on tomato crop: a case study in Southern Italy. *Processes* 11(12):3370. <https://doi.org/10.3390/pr11123370>
- Moon H-W, Ku K-M (2022b) Impact of an agrivoltaic system on metabolites and the sensorial quality of cabbage (*Brassica oleracea* var. *capitata*) and its high-temperature-extracted juice. *Foods* 11(4):498. <https://doi.org/10.3390/foods11040498>
- Moon HW, Ku KM (2023) The effect of additional shading utilizing agrivoltaic structures on the visual qualities and metabolites of broccoli. *Front Plant Sci* 14:1111069. <https://doi.org/10.3389/fpls.2023.1111069>
- Muñoz-García M-Á, Fialho L, Moreda GP, Baptista F (2024) Assessment of the impact of utility-scale photovoltaics on the surrounding environment in the Iberian Peninsula. Alternatives for the coexistence with agriculture. *Sol Energy* 271:112446. <https://doi.org/10.1016/j.solener.2024.112446>
- Nasukawa H, Kuwabara Y, Tatsumi K, Tajima R (2025) Rice yield and energy balance in an agrivoltaic system established in Shonai plain, northern Japan. *Sci Total Environ* 959:178315. <https://doi.org/10.1016/j.scitotenv.2024.178315>
- Nieto-Morone M-B, Muñoz-García M-Á, Pérez López D, Bernal-Basurco C, García Rosillo F, Alonso-García MdC (2025) Agrivoltaics: integration of reused PV modules. *Agronomy* 15(3):730. <https://doi.org/10.3390/agronomy15030730>
- Othman NF, Yaacob ME, Mat Su AS, Jaafar JN, Hizam H, Shahidan MF, Jamaluddin AH, Chen G, Jalaludin A (2020) Modeling of stochastic temperature and heat stress directly underneath agrivoltaic conditions with *Orthosiphon stamineus* crop cultivation. *Agronomy* 10(10):1472. <https://doi.org/10.3390/agronomy10101472>
- Othman NF, Ya'acob ME, Lu L, Jamaluddin AH, Mat Su AS, Hizam H, Shamsudin R, Jaafar JN (2023) Advancement in agriculture approaches with agrivoltaics natural cooling in large scale solar PV farms. *Agriculture* 13(4):854. <https://doi.org/10.3390/agriculture13040854>
- Patel UR, Gadhiya GA, Chauhan PM (2024) Techno-economic analysis of agrivoltaic system for affordable and clean energy with food production in India. *Clean Technol Environ Policy* 26(7):2117–2135. <https://doi.org/10.1007/s10098-023-02690-1>
- Potenza E, Croci M, Colauzzi M, Amaducci S (2022) Agrivoltaic system and modelling simulation: a case study of soybean (*Glycine max* L.) in Italy. *Horticulturae* 8(12):1160. <https://doi.org/10.3390/horticulturae8121160>
- Ramos-Fuentes IA, Elamri Y, Cheviron B, Dejean C, Belaud G, Fumey D (2023) Effects of shade and deficit irrigation on maize growth and development in fixed and dynamic AgriVoltaic systems. *Agric Water Manag* 280:108187. <https://doi.org/10.1016/j.agwat.2023.108187>
- Randle-Boggis RJ, Barron-Gafford GA, Kimaro AA, Lamanna C, Macharia C, Maro J, Mbele A, Hartley SE (2025) Harvesting the sun twice: energy, food and water benefits from agrivoltaics in East Africa. *Renew Sustain Energy Rev* 208:115066. <https://doi.org/10.1016/j.rser.2024.115066>
- Reeza AA, Noor NFM, Ahmed OH, Masuri MA (2024) Shading effect of photovoltaic panels on growth of selected tropical vegetable crops. *Sci Hortic* 324:112574. <https://doi.org/10.1016/j.scienta.2023.112574>

- Reher T, Lavaert C, Willockx B, Huyghe Y, Bisschop J, Martens JA, Diels J, Cappelle J, Van de Poel B (2024) Potential of sugar beet (*Beta vulgaris*) and wheat (*Triticum aestivum*) production in vertical bifacial, tracked, or elevated agrivoltaic systems in Belgium. *Appl Energy* 359:122679. <https://doi.org/10.1016/j.apenergy.2024.122679>
- Scarano A, Semeraro T, Calisi A, Aretano R, Rotolo C, Lenucci MS, Santino A, Piro G, De Caroli M (2024) Effects of the agrivoltaic system on crop production: the case of tomato (*Solanum lycopersicum* L.). *Appl Sci* 14(7):3095. <https://doi.org/10.3390/app14073095>
- Sekiyama T, Nagashima A (2019) Solar sharing for both food and clean energy production: performance of agrivoltaic systems for corn, a typical shade-intolerant crop. *Environments* 6(6):65. <https://doi.org/10.3390/environments6060065>
- Semeraro T, Scarano A, Curci LM, Leggieri A, Lenucci M, Basset A, Santino A, Piro G, De Caroli M (2024) Shading effects in agrivoltaic systems can make the difference in boosting food security in climate change. *Appl Energy* 358:122565. <https://doi.org/10.1016/j.apenergy.2023.122565>
- Sturchio MA, Macknick JE, Barron-Gafford GA, Chen A, Alderfer C, Condon K, Hajek OL, Miller B, Pauletto B, Siggers JA, Slette IJ, Knapp AK (2022) Grassland productivity responds unexpectedly to dynamic light and soil water environments induced by photovoltaic arrays. *Ecosphere* 13(12):e4334. <https://doi.org/10.1002/ecs2.4334>
- Sturchio MA, Kannenberg SA, Knapp AK (2024) Agrivoltaic arrays can maintain semi-arid grassland productivity and extend the seasonality of forage quality. *Appl Energy* 356:122418. <https://doi.org/10.1016/j.apenergy.2023.122418>
- Sun J, Cui W, Wang W, Yang X (2025) The microclimatic and eco-hydrological effects of photovoltaic facilities in arid/semi-arid regions of China: an integrated modeling study. *J Environ Manage* 382:125395. <https://doi.org/10.1016/j.jenvman.2025.125395>
- Teng JWC, Soh CB, Devihosur SC, Tay RHS, Jusuf SK (2022) Effects of agrivoltaic systems on the surrounding rooftop microclimate. *Sustainability* 14(12):7089. <https://doi.org/10.3390/su14127089>
- Thompson EP, Bombelli EL, Shubham S, Watson H, Everard A, D'Ardes V, Schievano A, Bocchi S, Zand N, Howe CJ, Bombelli P (2020b) Tinted semi-transparent solar panels allow concurrent production of crops and electricity on the same cropland. *Adv Energy Mater* 10(35):2001189. <https://doi.org/10.1002/aenm.202001189>
- Thum CH, Okada K, Yamasaki Y, Kato Y (2025) Impacts of agrivoltaic systems on microclimate, grain yield, and quality of lowland rice under a temperate climate. *Field Crops Res* 326:109877. <https://doi.org/10.1016/j.fcr.2025.109877>
- Trommsdorff M, Kang J, Reise C, Schindele S, Bopp G, Ehmann A, Weselek A, Högy P, Oberfell T (2021) Combining food and energy production: design of an agrivoltaic system applied in arable and vegetable farming in Germany. *Renew Sustain Energy Rev* 140:110694. <https://doi.org/10.1016/j.rser.2020.110694>
- Uchanski M, Hickey T, Bousselot J, Barth KL (2023) Characterization of agrivoltaic crop environment conditions using opaque and thin-film semi-transparent modules. *Energies* 16(7):3012. <https://doi.org/10.3390/en16073012>
- Ukwu UN, Muller O, Meier-Grull M, Uguru MI (2025) Agrivoltaics shading enhanced the microclimate, photosynthesis, growth and yields of *vigna radiata* genotypes in tropical Nigeria. *Sci Rep* 15(1):1190. <https://doi.org/10.1038/s41598-024-84216-3>
- Valle B, Simonneau T, Sourd F, Pechier P, Hamard P, Frisson T, Ryckewaert M, Christophe A (2017) Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Appl Energy* 206:1495–1507. <https://doi.org/10.1016/j.apenergy.2017.09.113>
- Vervloesem J, Marcheggiani E, Choudhury MDAM, Muys B (2022) Effects of photovoltaic solar farms on microclimate and vegetation diversity. *Sustainability* 14(12):7493. <https://doi.org/10.3390/su14127493>
- Waghmare RM, Jilte R, Joshi S (2023) Performance analysis of agro-photovoltaic systems with *Solanum lycopersicum* crops. *Mater Today Proc* 72:1284–1289. <https://doi.org/10.1016/j.matpr.2022.09.300>
- Weselek A, Bauerle A, Hartung J, Zikeli S, Lewandowski I, 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(5):59. <https://doi.org/10.1007/s13593-021-00714-y>
- Weselek A, Bauerle A, Zikeli S, Lewandowski I, Högy P (2021b) Effects on crop development, yields and chemical composition of celeriac (*Apium graveolens* L. var. rapaceum) cultivated underneath an agrivoltaic system. *Agronomy* 11(4):733. <https://doi.org/10.3390/agronomy11040733>
- Willockx B, Lavaert C, Cappelle J (2023) Performance evaluation of vertical bifacial and single-axis tracked agrivoltaic systems on arable land. *Renew Energy* 217:119181. <https://doi.org/10.1016/j.renene.2023.119181>
- Willockx B, Reher T, Lavaert C, Herteleer B, Van de Poel B, Cappelle J (2024) Design and evaluation of an agrivoltaic system for a pear orchard. *Appl Energy* 353. <https://doi.org/10.1016/j.apenergy.2023.122166>
- Wu C, Liu H, Yu Y, Zhao W, Guo L, Liu J, Yetemen O (2023) Ecohydrological insight: solar farms facilitate carbon sink enhancement in drylands. *J Environ Manage* 342:118304. <https://doi.org/10.1016/j.jenvman.2023.118304>
- Ya'acob ME, Lu L, Nobilly F, Che'Ya NN, Aziz AA, Dupraz C, Yahya MS, Atikah SN, Mamun MAA (2022) Analysis of weed communities in solar farms located in tropical areas—the case of Malaysia. *Agronomy* 12(12):3073. <https://doi.org/10.3390/agronomy12123073>
- Ya'acob ME, Lu L, Zulkifli SA, Roslan N, Ahmad WFHW (2023) Agrivoltaic approach in improving soil resistivity in large scale solar farms for energy sustainability. *Appl Energy* 352:121943. <https://doi.org/10.1016/j.apenergy.2023.121943>
- Yang L, Gao X, Lv F, Hui X, Ma L, Hou X (2017) Study on the local climatic effects of large photovoltaic solar farms in desert areas. *Sol Energy* 144:244–253. <https://doi.org/10.1016/j.solener.2017.01.015>
- Yue S, Wu W, Yuan B, Ye D, Bai W (2025) Large-scale photovoltaic farms significantly change the vegetation diversity and biomass through influencing soil moisture and physiochemical properties. *Vadose Zone J* 24(2):e70002. <https://doi.org/10.1002/vzj2.70002>
- Zhang L, Yang Z, Wu X, Wang W, Yang C, Xu G, Wu C, Bao E (2023) Open-field agrivoltaic system impacts on photothermal environment and light environment simulation analysis in eastern China. *Agronomy* 13(7):1820. <https://doi.org/10.3390/agronomy13071820>