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Impact of Agrivoltaics Irrigation and Soil Moisture Dynamics- A review

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Abstract: Agrivoltaics systems, which combine solar photovoltaic (PV) energy generation with agricultural production on the same land, are emerging as a promising solution to the intertwined challenges of food, energy, and water security. This review synthesizes recent research on the impacts of agrivoltaics on soil moisture dynamics and irrigation requirements, with a focus on how microclimate modifications induced by PV structures enhance water use efficiency. Evidence indicates that agrivoltaics shading consistently lowers soil and air temperatures, reduces evapotranspiration, and increases soil moisture retention across diverse climates and cropping systems. These effects translate to significant reductions in irrigation needs-often by 20–40%-and improved water use efficiency, especially for shade-tolerant crops and in arid environments. The review also highlights the roles of panel type, installation design, crop selection, and soil texture in optimizing agrivoltaics performance. While agrivoltaics can increase late-season soil moisture by up to 29% and water use efficiency by over 300% compared to conventional systems, spatial variability in shading and soil moisture remains a design challenge. Overall, agrivoltaics offer a synergistic pathway to enhance agricultural resilience, conserve water, and support sustainable energy production, but further research is needed to refine system configurations for diverse agroecological contexts.

***Keywords* - Agrivoltaics, soil moisture, water use efficiency, irrigation, microclimate modification, solar panels.**

I. INTRODUCTION

Agrivoltaics is an innovative approach that integrates solar photovoltaic (PV) energy generation with agricultural production on the same parcel of land. This dual-use strategy addresses the urgent challenge of balancing land for both food and energy, a concern that is intensifying as the global population rises and climate change accelerates (Pascaris *et al*., 2021). By enabling renewable energy generation and crop cultivation to occur simultaneously, agrivoltaics systems eliminate the need to choose between these essential land uses. Typically, solar panels are elevated or strategically positioned to ensure crops beneath receive adequate sunlight, creating a unique microclimate that benefits crops, especially in regions with extreme weather or water scarcity. The shade provided by the panels conserves soil moisture and reduces heat stress, supporting healthier plant growth and improving water use efficiency (Ashraf *et al*., 2021). Beyond these agricultural benefits, agrivoltaics promotes environmental sustainability by lowering greenhouse gas emissions, optimizing land use, and supporting long-term productivity (Gomez-Casanovas *et al*., 2023). As resource pressures grow, agrivoltaics offers a practical, resource-efficient strategy for producing both food and clean energy (Mamun *et al*., 2022).

A key advantage of agrivoltaics is its ability to address the interconnected challenges of food, energy, and water security, which is especially critical in regions facing intensifying water scarcity and unpredictable climate conditions. Traditional farming, often reliant on high water volumes, is increasingly threatened by rising temperatures, erratic rainfall, and prolonged droughts. In these vulnerable areas, the need for resilient, water-efficient farming systems is paramount (Barron‐Gafford *et al*., 2019). Agrivoltaics systems help conserve water by reducing evaporation and improving microclimatic conditions, thereby supporting healthier crop growth and higher yields while promoting sustainable water use. Shading from PV panels alleviates drought stress, reduces irrigation needs, and improves crop survivability during heat and water deficits (Mahto *et al*., 2021; E. Warmann *et al*., 2024b). Studies have shown that agrivoltaics systems can reduce irrigation requirements by up to 40%, significantly boosting water conservation in regions facing chronic water scarcity (Ramos-Fuentes *et al*., 2023).

Traditional irrigation methods, such as furrow or flood irrigation, are often inefficient and result in considerable water loss, especially in water-limited areas (Zhuo & Hoekstra, 2017). These techniques do not always account for the specific water needs of different crops, leading to over- or under-irrigation that can harm crop health and degrade the environment (Li *et al*., 2021). Even with more efficient methods like drip irrigation, optimizing water use across diverse crops and climates remains challenging. Agrivoltaics systems offer a natural solution by providing shade that reduces evaporation, lowers soil temperatures, and helps maintain soil moisture, leading to more efficient water use (S. Chopdar, 2024; Elamri *et al*., 2018a). They can reduce irrigation needs by 20–40%, a significant improvement in drought-prone areas (Elamri *et al*., 2018a; E. Warmann *et al*., 2024b).

In addition to improving water efficiency, agrivoltaics help counteract the effects of climate change on agriculture. The shade from PV panels creates a cooler, more stable environment for crops, reducing heat stress and slowing soil moisture loss (S. Jiang *et al*., 2022; I. Ramos-Fuentes *et al*., 2023). Shading also lowers both air and soil temperatures and increases relative humidity, further decreasing irrigation needs (S. Jung, 2024; I. Ramos-Fuentes *et al*., 2023). PV panels can also act as partial windbreaks, further limiting moisture loss from soil and plants (Barron‐Gafford *et al*., 2019). As a result, agrivoltaics can reduce evapotranspiration by up to 31%, demonstrating their potential to reduce crop water requirements and conserve water resources (S. Jung, 2024; I. Ramos-Fuentes *et al*., 2023).

Despite these benefits, challenges remain. Much of the research on agrivoltaics is limited to specific locations, crops, or climates, and there is a lack of long-term, large-scale field data to fully understand broader impacts (Al-Agele *et al*., 2021). The effects of shading intensity, panel configuration, and other structural variables on soil moisture and crop performance are not yet fully understood. The interactions between shading, microclimate, and soil moisture are complex, and current models often fail to capture these dynamics accurately (Semeraro *et al*., 2024; Warmann *et al*., 2024). Further research is needed to determine how different panel configurations-such as height, tilt, and spacing-affect microclimate and water use efficiency (S. Jiang *et al*., 2022; Zainali *et al*., 2022). The objective of this review is to provide a comprehensive assessment of the impact of agrivoltaics systems on irrigation requirements and soil moisture dynamics, with a focus on how microclimate modifications induced by PV panel structures enhance water use efficiency.

II. Methodology

To ensure a comprehensive synthesis of current research on agrivoltaics systems and their impacts on soil moisture and irrigation, an extensive literature search was conducted using major academic databases, including Scopus, Web of Science, AGRIS, and CAB Abstracts. The search strategy incorporated relevant keywords and Boolean operators-such as "agrivoltaics AND soil moisture," "agrivoltaics AND irrigation," "solar panels AND water use efficiency," "impact of agrivoltaics on water conservation," and "crop performance AND agrivoltaics"-to capture studies examining the interactions between agrivoltaics installations, microclimate modification, and water management. The review prioritized peer-reviewed journal articles and conference papers published in English, with particular attention to research conducted in arid and semi-arid regions or areas facing water scarcity. Both experimental, observational, and modeling studies were considered to provide a balanced perspective on agrivoltaics performance across diverse agroecological contexts. For each selected study, key data were systematically extracted, including soil moisture metrics (such as soil moisture content and evaporation rates), irrigation requirements and water use efficiency (WUE), types of solar panels employed (e.g., bifacial, transparent, conventional), crop types and climate zones (arid, semi-arid, temperate), and details of installation techniques and system designs (such as fixed, tracking, or integrated systems). This rigorous methodology ensured that the review provides an up-to-date, global, and nuanced understanding of how agrivoltaics systems influence soil moisture dynamics and irrigation needs.

III. Descriptive Overview of Included Studies

3.1 Types of Solar Panels in Agrivoltaics

The choice of solar panel technology significantly influences agrivoltaics system performance. Different panel types affect light transmission, temperature regulation, and energy production, all of which impact crop growth and water use. For example, semi-transparent thin-film panels such as CdTe (cadmium telluride) allow more photosynthetically active radiation (PAR) to reach crops without significantly increasing temperature, benefiting shade-tolerant crops and improving soil moisture retention (Ali *et al*., 2023; Uchanski *et al*., 2023). Bifacial panels capture sunlight on both sides, increasing energy production and enhancing light distribution under the panels, which benefits crops that require moderate shading (Ali Khan Niazi & Victoria, 2023a; Costa *et al*., 2023). Dual-axis tracking systems optimize solar irradiance capture, maximize energy production, and allow dynamic shading patterns tailored to crop needs, especially effective in regions with varying solar angles (Rapella *et al*., 2024; Zhang *et al*., 2023). Thin-film and flexible panels, being lightweight and adaptable, are suitable for agrivoltaics systems where structural flexibility is critical, especially in arid and semi-arid regions to reduce soil temperature and retain moisture (A. Sarr *et al*., 2023b). These differences are summarized in Table 3.1.

Table 3.1: Types of Solar Panels and Their Effects in Agrivoltaics

Panel Type	**Key Features & Benefits**	**References**
Semi-transparent thin-film	High PAR transmission, lower temp, good for shade-tolerant crops	(Uchanski *et al*., 2023; Zhang *et al*., 2023)
Bifacial	Sunlight capture on both sides, moderate shading, increased energy output	(Ali Khan Niazi & Victoria, 2023b; Costa *et al*., 2023)
Dual-axis tracking	Maximizes irradiance, dynamic shading, tailored for variable climates	(Rapella *et al*., 2024; Zhang *et al*., 2023)
Thin-film/flexible	Lightweight, adaptable, reduces soil temp, good for arid regions	(J. Sarr, 2023; Uchanski *et al*., 2023)

3.2 Installation Techniques for Agrivoltaics

The installation of solar panels is critical for balancing energy production and agricultural productivity. Raising panels allows more sunlight to reach crops, improving yield while maintaining energy production, though excessive height may reduce shading benefits for soil moisture retention (Diassé Sarr *et al*., 2024; J. Sarr, 2023). Wider spacing increases light availability for crops but may reduce energy production, with optimal spacing depending on crop type and local climate (Miljkovic, Du, Solecki, Jahidul, *et al*., 2024). The tilt angle affects light distribution and energy production; steeper tilts may reduce light transmission to crops but improve energy generation in winter (Costa *et al*., 2023; A. Sarr *et al*., 2023a). East-west orientation is often preferred for more uniform shading throughout the day, reducing temperature fluctuations (Ali Khan Niazi & Victoria, 2023b; Miljkovic *et al*., 2024). Single- and dual-axis tracking systems dynamically adjust panel angles to maximize energy production and control shading patterns, especially effective in regions with high solar variability (Rapella *et al*., 2024; Zhang *et al*., 2023). These factors are summarized in Table 3.2.

Table 3.2: Installation Variables and Their Effects

Variable	Modification/Configuration	Impact on Crop & System Performance	References
Panel Height	High-mounted panels	Increases light, supports shade-intolerant crops	(J. Sarr, 2023; Sekiyama & Nagashima, 2019a)
	Low-mounted panels	Cooler, humid microclimate, good for hot climates	(A. Sarr *et al*., 2023a)
Panel Spacing	Wider spacing	More light for crops, less energy output	(Ali Khan Niazi & Victoria, 2023b)
Panel Tilt	Steeper tilt	Optimizes light/energy, reduces excessive shading	(P. E. Campana *et al*., 2021)
Panel Orientation	East-west	Uniform shading, stabilizes microclimate	(J. Sarr, 2023)
Tracking System	Adjustable/dual-axis	Dynamic shade, optimized crop and energy efficiency	(Rapella *et al*., 2024; Zhang *et al*., 2023)

3.3. Agrivoltaics and Microclimate Modification

3.3.1 Shading Effects on Soil Temperature and Evaporation

Agrivoltaics systems create a moderated microclimate by providing shade, which reduces soil surface temperatures and alleviates plant stress. For example, research in Chile found that shading from AV panels lowered soil temperatures, improving microclimate conditions and reducing heat stress for crops (J. Jung *et al*., 2024). In grapevines, AV systems decreased both air and soil maximum temperatures by 1–2°C, reducing midday heat stress (Ferrara *et al*., 2023). Similarly, sheep-grazed AV systems in France maintained soils 2.6–3.4°C cooler than unshaded areas (Madej *et al*., 2024). Shading also significantly reduces evaporation and increases soil moisture. In Chile, AV systems reduced evapotranspiration by 31% and increased soil moisture by 29% (D. Jung *et al*., 2024). Kiwifruit grown under AV panels experienced up to 40% less soil evaporation, resulting in improved water productivity under moderate shading (S. Jiang *et al*., 2022). Controlled experiments have confirmed that transient shading sharply decreases evaporation rates by lowering soil temperatures (Cho & Hillel, 1983). AV systems further enhance water efficiency by conserving moisture and improving overall water use efficiency. For instance, in maize, shading improved water balance and drought tolerance by reducing soil temperature and conserving moisture (Amaducci *et al*., 2018a).

3.3.2 Quantitative Outcomes on Microclimate Variables

AV shading consistently reduces incident solar radiation. A study in Malaysia reported significant decreases in both light intensity and photosynthetically active radiation (PAR) under panels (Noor & Reeza, 2022). Similar reductions (85–95%) have been observed under tree-like shading structures, serving as analogues for AV systems (Feng *et al*., 2023). While daily average air temperature often shows minimal change, some AV setups report localized reductions. In France, air temperature under panels was similar to full-sun conditions (Marrou, Dufour, & Wery, 2013), but greenhouse-based AV systems with smart ventilation maintained optimal internal temperatures even at 51% shading (Minanda *et al*., 2021). Shading under AV increases relative humidity, with rises of 3–20% observed in urban tree canopy analogues (Feng *et al*., 2023). In AV systems, humidity increases are more subtle but still present. PV panels reduce wind speed beneath them, as consistently reported in both AV and tree-canopy studies (Feng *et al*., 2023; Noor & Reeza, 2022). A summary of key microclimate changes observed in different climates is provided in Table 3.3.

3.4. Impacts on Irrigation Water Use

3.4.1 Irrigation Volume Reductions

Agrivoltaics systems significantly reduce irrigation requirements across crops and climates. For example, irrigated lettuce required 20% less water (Elamri *et al*., 2018a), and maize grown under AV systems saw up to a 47% reduction in water demand depending on shading and water stress (Ramos-Fuentes, 2023). In arid regions, water savings of 30–40% are common due to reduced evapotranspiration and more efficient water application (E. Warmann *et al*., 2024a). Soil evaporation also declines under panel coverage, with reductions of 14–33% (Omer *et al*., 2022). Shade-tolerant crops like lettuce and tomatoes require up to 30% less water under partial shading (Al-Agele *et al*., 2021; Marrou, Dufour, Wery, *et al*., 2013). These savings are achieved as shading lowers soil temperature and limits direct sunlight, suppressing soil evaporation. Plant transpiration also decreases due to reduced stomatal conductance, while the cooler, less windy microclimate further conserves moisture (S. Chopdar, 2024). Dynamic AV systems can optimize these effects by adjusting panel angles to match crop water needs (P. E. Campana *et al*., 2021). The greatest water conservation is observed in hot, arid environments and for shade-tolerant crops. Panel height, row spacing, and system type (fixed or dynamic) also influence both light availability and water-saving potential (P. Campana *et al*., 2021; Elamri *et al*., 2017).

Table 3.3: Microclimate Changes Across Different Climates

Study Location	Climate Type	Key Microclimate Changes	Quantitative Data	Citation
Santiago, Chile	Semi-arid	Lower radiation, reduced evapotranspiration, cooler soil	↓42% radiation, ↓31% PET, ↑29% soil moisture	(D. Jung *et al*., 2024)
SW Germany	Temperate	Lower soil temp, less light, altered rain distribution	↓30% PAR, ↑11% yield (potato) during heat	(Weselek, 2019)

Malaysia (UiTM)	Tropical	Lower PAR, lower wind speed, no air temp change	Significant drop in radiation, reduced wind	(Noor & Reeza, 2022)
Malaysia (A. paniculata)	Tropical	Cooler, more humid, better soil moisture	↓6% air temp, ↑8.9% RH, ↑soil moisture	(J. Abidin, 2024)
USA (Simulation)	Variable	Cooler PV modules due to evapotranspiration	↓10°C PV temp at 4m height with crops	(Williams *et al*., 2023)
India (Okra)	Semi-arid	Lower light/temp, higher soil moisture	↓40% light, ↓2.5°C air temp, ↑2–8% soil moisture	(Islam *et al*., 2025)

3.4.2 Irrigation Method Performance in Agrivoltaics

Among irrigation methods, drip irrigation is most compatible with AV systems, offering up to 41% water savings due to precise delivery and reduced evaporation under shade (Raza *et al*., 2022). Drip irrigation is best suited for high-value or water-sensitive crops in arid climates. Sprinkler irrigation also benefits from AV microclimates, but wind drift and uneven shade can reduce efficiency, making it suitable for grains and moderate water-need crops in temperate climates (M. A. Z. Abidin *et al*., 2021). Flood irrigation, while panel shading reduces evaporation, remains inefficient and can cause waterlogging in shaded areas, making it less suitable for AV systems (Barron‐Gafford *et al*., 2019). Drip irrigation paired with AV maximizes water productivity, even if yields are slightly reduced due to lower light. The impact on yield depends on crop species and light requirements, with shade-tolerant crops performing best (Amaducci *et al*., 2018a). These comparisons are shown in Table 3.4.

Table 3.4: Irrigation Method Performance in AV Systems

Method	Water Savings	Suitability in AV	Crop Types	References
Drip	Up to 41%	Highly compatible	High-value, water-sensitive	(Ramos-Fuentes et al., 2023; Raza et al., 2022)
Sprinkler	Moderate	Some benefit, less precise	Grains, moderate water-need	(M. A. Z. Abidin et al., 2021)
Flood	Low	Not recommended	Not recommended	(Barron-Gafford et al., 2019; Omer et al., 2022)

3.4.3 Water Use Efficiency (WUE) Metrics

Water use efficiency (WUE) is typically measured as yield per unit water input. In AV systems, WUE can also include land equivalent ratio (LER) and water productivity, accounting for both crop and energy outputs (R. K. Chopdar *et al*., 2024). Empirical studies show AV systems outperform open-field agriculture in WUE. For instance, irrigated lettuce under AV required 20% less water with only a 10% yield reduction, resulting in higher WUE (Elamri *et al*., 2017). Maize and tomato production under AV saw up to 30% water savings without yield loss under moderate shading (Marrou *et al*., 2013; Riaz *et al*., 2021). Shade-tolerant crops such as lettuce and maize maintain stable yields under AV, while light-demanding crops may need adaptive management. WUE gains are most pronounced in hot, dry climates where AV shading reduces both evaporation and transpiration. System design-including panel height, spacing, tilt, and adjustability-also affects WUE. Elevated or vertically aligned panels allow better light and air flow, mitigating excessive shading while saving water (R. K. Chopdar *et al*., 2024). Beyond water savings, AV systems enhance farm resilience to climate variability and reduce dependence on fossil-fuel-based irrigation by integrating solar energy (Bhandari *et al*., 2021b).

3.5 Soil Moisture Dynamics under Agrivoltaics

3.5.1 Effects on Soil Moisture Retention and Depletion

Agrivoltaics systems consistently enhance soil moisture retention and reduce depletion rates when compared to conventional open-field agriculture. This improvement is primarily attributed to reduced soil evaporation, moderated microclimatic conditions, and spatial variability in shading intensity across the field. Shading from solar panels lowers surface temperatures and limits direct solar radiation, reducing evaporative losses by 15–40%. Additionally, AV systems moderate wind speed and increase relative humidity under the panels, further supporting moisture conservation. Moisture distribution is often heterogeneous within AV setups, with zones directly under the panel center-termed the shaded fenced center (SFC)-retaining 20–40% more soil moisture than open-field or peripheral zones (shaded fenced open, SFO). For instance, in a temperate pasture system in Oregon, SFC zones maintained approximately 0.30 vol/vol moisture at 60 cm depth late in the season, while adjacent open zones declined to 0.20 vol/vol (Hassanpour Adeh *et al*., 2018). Similarly, in semi-arid Chile, grapevines grown under AV panels retained 29% more soil moisture than control plots (J. Jung *et al*., 2024). In tropical India, shading in maize fields on clay soils reduced daily soil moisture depletion to 2.3%, compared to 6.7% in sandy soils under similar conditions, emphasizing the role of both shading and soil texture in moisture dynamics (Rout & Arulmozhiselvan, 2019). However, some AV systems have reported anomalously lower moisture retention beneath panels, such as in Heggelbach, Germany, possibly due to altered root dynamics, local hydrology, or drainage patterns that were not fully accounted for.

3.5.2 Depth-Specific Moisture Profiles

The impact of AV systems on soil moisture is strongly depth-dependent, with the most pronounced effects occurring in the upper 30 cm of soil where root activity is highest. In these layers, AV shading significantly reduces evaporation, leading to 20–40% higher soil moisture compared to open-field conditions, as demonstrated in studies on lettuce in France and grapevines in Chile (Elamri *et al*., 2018a; S. Jung, 2024). At intermediate depths (30–60 cm), AV systems allow increased percolation due to reduced evapotranspiration, resulting in 15–30% higher moisture retention. In Oregon, near-saturation levels were maintained at 60 cm depth in AV-shaded pasture systems (Adeh *et al*., 2018). Beyond 60 cm, moisture remains relatively stable, as these deeper layers are less affected by surface evaporation and benefit indirectly from overall reductions in water loss. Studies from temperate grasslands in France and the USA further support this observation, highlighting the capacity of AV systems to stabilize deep soil moisture profiles during prolonged dry periods (Madej *et al*., 2024; Marrou *et al*., 2013). Soil texture also plays a crucial role; clay soils, due to their higher water-holding capacity and slower percolation, retain approximately twice the moisture of sandy soils under similar AV conditions (Rout & Arulmozhiselvan, 2019). These findings are summarized in Table 3.5.

Table 3.5: Depth-Specific Soil Moisture Profiles under AV

Depth (cm)	Moisture Trend under AV vs. Control	Key Study & Context	Citation
0–30	+20–40% higher retention in root zone	Lettuce (France), Grapevine (Chile)	(Elamri et al., 2018a; S. Jung, 2024)
30–60	+15–30% retention, near saturation	Pasture (Oregon)	(Adeh et al., 2018)
60+	Stable moisture due to reduced loss	Temperate grasslands (France, USA)	(Madej et al., 2024; Marrou et al., 2013)

3.5.3 Seasonal Trends in Soil Moisture

AV systems influence soil moisture retention throughout the growing season, with the magnitude of effects varying across early, mid, and late phases. In the early season, soil moisture levels are typically uniform across both AV and control plots due to recent rainfall or irrigation inputs. For example, pastures in Oregon began the season with approximately 0.30 vol/vol moisture at all measured depths (Adeh *et al*., 2018). As the season progresses, differences become more evident. During mid-season, open-field plots exhibit more rapid depletion-up to 50% faster than shaded zones-while AV-shaded lettuce fields in France retained 20% more moisture during summer heatwaves (Elamri *et al*., 2018b). By late season, shaded zones (SFC) consistently retain significantly more moisture. In Oregon, for instance, moisture under AV panels remained at ~0.30 vol/vol, compared to ~0.15 vol/vol in unshaded areas (Adeh *et al*., 2018), and in Chile, grapevines maintained a 29% higher moisture content under AV during drought conditions (J. Jung *et al*., 2024). These seasonal patterns also exhibit regional variability. In arid and semi-arid regions, AV systems improve late-season moisture retention by 25–40%, offering critical drought mitigation. In temperate climates, although seasonal rainfall partially offsets the need for shading, SFC zones still show a 15–20% increase in soil moisture. In humid regions, where excessive moisture may accumulate, AV systems require integrated drainage solutions to avoid waterlogging (Z. Z. Abidin *et al*., 2024). Table 3.6 summarizes these seasonal trends.

Table 3.6: Seasonal Trends in Soil Moisture under AV

Climate	Early Season (vol/vol)	Late Season (vol/vol)	% Retention Increase	Citation
Semi-Arid	0.25	0.32 (+29%)	29%	(J. Jung et al., 2024)
Temperate	0.30	0.25 (-17% in control)	20% (SFC vs. SFO)	(Adeh et al., 2018)
Tropical	0.28	0.24 (+8.9%)	8.9%	(Z. Z. Abidin et al., 2024)

3.6 Crop and System Variables Influencing Outcomes

3.6.1 Role of Crop Type and Canopy Structure

The performance of agrivoltaic systems is significantly influenced by crop type and canopy architecture. Crop morphology determines a species' capacity to adapt to altered light regimes and microclimatic conditions under solar panels. Shade-tolerant crops-such as leafy vegetables, forages, and certain fruits-frequently exhibit stable or even improved yields under AV setups. These crops benefit from rapid canopy closure, physiological adaptation to diffused light, and improved water use efficiency (Marrou *et al*., 2013; C. Warmann, 2024). Conversely, light-demanding crops like maize and grain legumes may show yield declines under shaded conditions unless cultivated in hot or drought-prone environments, where the moderated microclimate provided by AV systems-characterized by reduced solar radiation, cooler temperatures, and increased humidity-can partially offset the effects of reduced light availability (Al-Agele *et al*., 2021; Amaducci *et al*., 2018b). Microclimate modification under AV typically reduces incident solar radiation by 25–40%, lowers both soil and air temperatures, and increases relative humidity (Weselek *et al*., 2021). These changes are particularly beneficial in arid and high-temperature agroecosystems. Structural aspects such as panel height, tilt angle, and density play a crucial role in determining the degree of shading. Dense, low-mounted panels can intensify shading and may negatively affect yields of light-sensitive crops, whereas adjustable tracking systems or wider row spacing can enhance the balance between crop and energy production (P. E. Campana *et al*., 2021; S. Chopdar, 2024). Canopy structure further modulates crop responses to AV conditions. Crops with broad, flexible, or vertically inclined canopies are often better suited for diffused light environments, as they can maintain photosynthetic efficiency and adjust their architecture accordingly. Additionally, reduced evapotranspiration rates under partial shade can lower water requirements by 10–40%, particularly in species with dense foliage (E. Warmann *et al*., 2024a). These relationships are detailed in Table 3.7.

Table 3.7: Crop Type, Canopy Modifications, and Yield/Water Use Impact in AV

Crop Type	Example Crops	Canopy/Structural Modifications	Yield/Water Use Impact	Supporting Citation(s)
Shade-tolerant	Lettuce, spinach, kale	High panel density (60–75% RSR), partial shading, adjust row orientation	Maintained or improved yield, up to 30% yield increase in arid regions	(E. Warmann et al., 2024a)
Moderately shade-tolerant	Potato, tomato, carrot	Moderate panel spacing (30–50% RSR), elevated panels, dynamic tilt	Variable yield: e.g., potato +11% in cool, –18% in dense shade	(Emmott & al., 2023; Weselek et al., 2021)
Shade-intolerant	Maize, soybean, rice	Low panel density (<30% RSR), wide row spacing, east-west orientation	Yield reduction under dense shade; possible yield gain in low-density AV in drought-prone regions	(Amaducci et al., 2018a; Sekiyama & Nagashima, 2020)

Broad/flexible canopy	Cabbage, broccoli, radish	Select for broad/flexible canopies	Maintained photosynthesis, reduced water demand by 10–40%	(E. Warmann et al., 2024a)

3.6.2 Influence of Structural Variables on AV Performance

The structural configuration of agrivoltaic systems-specifically panel height, tilt, density, and orientation-plays a critical role in determining both microclimatic conditions and crop productivity. High-mounted panels enhance air flow and allow greater solar penetration, which is advantageous for shade-intolerant crops. Conversely, low-mounted panels create cooler and more humid microclimates, which are suitable for shade-tolerant crops or for mitigating heat stress in arid climates (J. Sarr, 2023; Sekiyama & Nagashima, 2019b). Panel tilt angles modify the daily distribution of light, with steeper tilts optimizing light distribution and energy output while reducing excessive shading (P. Campana *et al*., 2021). Panel density, or spacing between arrays, represents a trade-off: denser configurations increase energy yield but can reduce crop productivity due to increased shading, while wider spacing allows better light penetration but reduces land-use efficiency for electricity generation (R. K. Chopdar *et al*., 2024). The orientation of panels also matters. An east-west configuration offers more consistent shading throughout the day, which can moderate temperature swings and stabilize the microclimate (A. Sarr *et al*., 2023a). Finally, dynamic or tracking systems-which adjust tilt or orientation in real time-enable flexible shade management across seasons, offering a promising approach for optimizing both energy output and crop yield (P. Campana *et al*., 2021; A. Sarr *et al*., 2023a). These factors are summarized in Table 3.8.

Table 3.8. Structural Variables and Their Impact on AV Performance

Structural Variable	Modification/Configuration	Impact on Crop & System Performance	Supporting Citation(s)
Panel Height	High-mounted panels	Increases light penetration and air circulation; supports shade-intolerant crops	(J. Sarr, 2023; Sekiyama & Nagashima, 2019b)
	Low-mounted panels	Creates cooler, more humid microclimate; suitable for hot climates and shade-tolerant crops	(J. Sarr, 2023)
Panel Tilt	Steeper tilt angles	Optimizes light distribution and energy output; can reduce excessive shading	(P. Campana et al., 2021)
Panel Density/Spacing	Closer spacing (higher density)	Maximizes energy output but increases shading; may reduce yields for light-sensitive crops	(R. K. Chopdar et al., 2024; J. Sarr, 2023)
	Wider spacing (lower density)	Increases light availability for crops; may reduce total energy output	(R. K. Chopdar et al., 2024)
Panel Orientation	East-west orientation	Provides more uniform shading throughout the day; stabilizes microclimate	(A. Sarr et al., 2023a)
Tracking/Dynamic Systems	Adjustable tilt or tracking panels	Allows real-time shade management; optimizes both crop and energy efficiency	(P. Campana et al., 2021; A. Sarr et al., 2023a)

3.6.3 Influence of Soil Texture and Field Management

Soil texture plays a crucial role in mediating the effects of agrivoltaics systems on water retention, temperature regulation, and crop performance. Sandy soils, due to their rapid drainage, benefit significantly from AV-induced shading that slows evaporation, but still require careful water management through irrigation and mulching. Loamy soils offer an optimal balance of water retention and drainage, making them well-suited for AV applications. Clay soils, while excellent at retaining water, are more prone to waterlogging under reduced evaporation conditions, necessitating well-planned drainage systems (De Francesco *et al*., 2025). Field management practices must be adapted to AV-specific spatial and microclimatic constraints. Mulching, for example, synergizes with panel-induced shading to further reduce soil evaporation. Tillage practices should minimize compaction, particularly under narrow panel rows, and fertilization strategies must be tailored to the altered light and moisture dynamics. Conservation-oriented techniques, such as cover cropping and reduced tillage, support long-term soil health and complement the AV-induced microclimatic shifts (Emde *et al*., 2021; Time *et al*., 2024). AV system design should be matched to soil characteristics. For example, higher panel mounting is preferable in clay-rich soils to enhance aeration, while denser panel configurations can reduce moisture loss in sandy soils. Precision agriculture technologies, including soil sensors and variable-rate irrigation, can help manage intra-field variability. Notably, soil protection during installation-especially in fine-textured soils vulnerable to compaction-is critical for maintaining long-term soil function (Wild & Schueller, 2024). Table 3.9 summarizes these factors.

Table 3.9: Soil Texture and Field Management Factors in Agrivoltaics Systems

Factor / Variable	Observed Effects in AV Systems	Field Management Recommendations	Supporting Citation(s)
Soil Texture	AV shading increases soil moisture retention; clay holds water well, sandy drains rapidly	Match AV design to soil type: e.g., wider spacing for clay, denser panels for sandy soils	(Barron-Gafford et al., 2019; Hassanpour Adeh et al., 2018)
Spatial Heterogeneity	Uneven moisture distribution under panels (e.g., wetter edges, drier centers) affects crop growth	Employ precision irrigation and adjust planting patterns accordingly	(Emde et al., 2021)

Soil Compaction	Heavy equipment during installation can compact soil, reducing infiltration and root penetration	Use low-pressure tires, minimize machinery, consider subsoiling if needed	(Wild & Schueller, 2024)
Microclimate Effects	Shading lowers soil temperature, increases humidity, boosts resilience in hot/dry climates	Choose climate-adapted crops and adjust irrigation schedules	(Barron-Gafford et al., 2019)
Field Operations	Restricted space under panels complicates operations like spraying and harvesting	Use narrower or foldable machinery, GPS-guided steering, and AV-specific row planning	(Wild & Schueller, 2024)
Soil Fertility	Prolonged shading may alter nutrient cycling and lower topsoil water-holding capacity	Rotate crops, monitor soil fertility trends, apply organic matter as needed	(Y. Jiang et al., 2022)

3.7 Case Studies in Agrivoltaics: Impacts on Irrigation and Soil Moisture

The practical application of agrivoltaics (AV) systems across diverse climates and cropping systems has generated valuable case studies that highlight their effects on irrigation requirements, soil moisture dynamics, and overall agricultural productivity. This section presents selected case studies from recent literature that exemplify the core findings of this review.

3.7.1. Case Study 1: Optimizing Water Availability for Wheat in France

A recent study near Orléans, Central France, explored how AV system design and dynamic panel management influence water availability for wheat. Using microclimate simulations and the AGRISOLEO software, researchers modeled the effects of different AV structure sizings and a panel steering algorithm tailored to wheat phenology. The results demonstrated that AV systems could reduce incoming irradiance by up to 40%, thereby lowering crop water stress by as much as 48%. Notably, by dynamically adjusting the panel rotation angle to maximize light during key wheat development stages, the reduction in irradiance could be moderated to 17%, ensuring both crop growth and water conservation. This case underscores the importance of AV system sizing and dynamic management in protecting crops from water stress while maintaining productivity, and suggests that such approaches can be extended to other crops and climates for optimized agronomic outcomes (Rapella *et al.*, 2024).

3.7.2. Case Study 2: Spectrum-Splitting and Concentrated Agrivoltaics for Peanuts and Soybeans in China

A novel approach to balancing energy production and crop photosynthesis was tested in China using Spectrum-splitting and Concentrated Agrivoltaics (SCAPV) with peanuts and soybeans. This system uses PV panels designed to split the light spectrum, allowing more photosynthetically active radiation to reach crops while generating electricity. The study compared SCAPV plots with conventional open-air controls and found that SCAPV reduced evapotranspiration by 31%, leading to improved physiological traits and higher yields. Peanuts grown under SCAPV showed increases in protein, fat, and linoleic acid content, while soybeans exhibited significant gains in fat, soluble sugar, and essential fatty acids. The average land equivalent ratio (LER) was 1.7, indicating a substantial improvement in land productivity. These findings demonstrate that advanced AV designs like SCAPV can reduce irrigation needs and enhance both crop quality and yield, supporting the dual goals of food and energy production (Ali *et al.*, 2023).

3.7.3. Case Study 3: Agrivoltaics for Tomato Production in Italy

A field study in Italy evaluated the impact of AV systems on tomato crops, focusing on soil moisture and irrigation frequency. The research found that AV structures significantly improved soil moisture retention, especially when irrigation was applied every two days. Under these conditions, soil moisture remained 15% higher compared to conventional open-field plots, allowing for reduced irrigation volumes without compromising yield. This case highlights the potential of AV systems to enhance water use efficiency in horticultural crops, particularly in Mediterranean and semi-arid environments where water scarcity is a pressing concern (Riaz *et al*., 2021).

3.7.4. Case Study 4: Agrivoltaics Demonstration in Gujarat, India

India has seen a growing interest in agrivoltaics, with several pilot projects demonstrating their feasibility in diverse agro-climatic zones. One notable example is the Gujarat State Electricity Company Limited (GSECL) project, which implemented a drip irrigation system across an AV plant established on loamy sand soil. The raised PV modules (three meters high) allowed for the cultivation of various crops, including groundnut, soybean, lady fingers, and winter vegetables like tomatoes and cucumbers. Observations indicated that soil moisture was consistently higher under the AV system, supporting healthy crop growth even in a previously uncultivated, sandy site. The integration of efficient irrigation and AV structures proved effective in conserving water and enabling year-round cultivation (S. Chopdar, 2024).

3.7.5. Case Study 5: Integrated Agrivoltaics and Rainwater Harvesting in Tanzania

The "Harvesting the Sun Twice" pilot project in Tanzania exemplifies the multifunctional benefits of AV systems in semi-arid regions. A 35 kWp off-grid AV installation at an agricultural training center in Morogoro incorporated rainwater harvesting and battery storage. The AV system provided a 13.8% reduction in irrigation water use and significantly improved crop yields for beans, Swiss chard, and maize compared to conventional plots. Remarkably, the survival rate of beans under AV was about 60% higher, attributed to the protective microclimate and improved soil moisture. The project achieved a land equivalent ratio of 1.86, reflecting an 86% increase in land productivity, and demonstrated the potential for AV systems to address food, water, and energy security simultaneously in resource-constrained settings (Bhandari *et al*., 2021a).

3.8 Practical Implications

The integration of solar photovoltaic systems into Integrated Farming Systems (IFS) offers a promising strategy to enhance both the economic viability and environmental sustainability of smallholder agriculture. The base model of a diversified IFS

comprising enterprises such as cropping, dairy, poultry, fishery, duckery, fruit production, biogas, and country bean cultivation is adapted from Behera *et al*., (2018), who reported a total net income of ₹3.75 lakh per hectare per year under a well-planned, multi-enterprise farming system (Table 10).
Building upon this model, a hypothetical scenario incorporating a solar energy component has been simulated to assess its financial impact (Tables 3.11–3.13). The solar system, modeled as a 154.8 kWp array of 459 panels with an annual energy generation of 226,008 kWh, is expected to yield ₹7.91 lakh per year at an average feed-in tariff of ₹3.5 per kWh (Table 11). With a total installation cost of ₹26.66 lakh and a government subsidy of ₹15.99 lakh, the effective capital investment stands at ₹10.66 lakh.

Table 3.10: Economic Analysis of Solar Panel Integration in IFS

Enterprise	Area (ha)	Cost of Cultivation (INR)	Net Income (INR)
Cropping system	0.625	72,156	93,198
Dairy (3 cows)	0.025	330,482	161,638
Duckery (35 birds)	0.05	30,679	30,411
Fishery	0.1	53,792	37,288
Poultry (50 birds)	0.1	24,272	28,778
Fruit production	0.05	8,658	11,242
Biogas KVIC (2 m³)	-	4,000	5,000
Country bean (fencing area)	0.05	2,000	8,000
Total	**1**	**5,26,039**	**3,75,555**

Source: Bussa and Behera (2020)

Table 3.11: Solar Panel Parameters (used for simulation)

Parameter	Value
Panel dimensions	1.96 m × 0.99 m × 0.04 m
Panel area (exact)	1.9404 m²
Number of panels	459 panels
Panel rating	335 Wp
Total panel cost	₹ 26.66 lakhs
System capacity	154.8 kWp
Annual energy generation	226,008 kWh
Income (₹3.5/kWh)	**₹ 7.91 lakhs**

Table 3.12. Simulated Calculation (1st Year) for IFS with Solar Panel Integration

Enterprise	Cost of Production (INR)	Subsidy (₹)	Net Expenses (₹)	Gross Income (₹)	Net Income (₹)
Cropping system	72,156	0	72,156	165,354	93,198
Dairy (3 cows)	330,482	0	330,482	492,120	161,638
Duckery (35 birds)	30,679	0	30,679	61,090	30,411

Enterprise	Cost of Production (INR)	Subsidy (₹)	Net Expenses (₹)	Gross Income (₹)	Net Income (₹)
Fishery	53,792	0	53,792	91,080	37,288
Poultry (50 birds)	24,272	0	24,272	53,050	28,778
Fruit production	8,658	0	8,658	19,900	11,242
Biogas KVIC (2 m³)	4,000	0	4,000	9,000	5,000
Country bean (fencing area)	2,000	0	2,000	10,000	8,000
Solar panel	26,66,200	15,99,720	10,66,480	7,91,028	-2,75,452
Loan interest (8%)	85,318.40	0	85,318	0	-85,318
Total	**31,92,239**	**15,99,720**	**16,77,837**	**16,92,622**	**14,785**

3.8.1. Simulated Financial Performance

In the first year of integration, after accounting for loan interest and capital expenses, the net income marginally increases to ₹14,785 (Table 3.12). However, from the second year onward after the amortization of initial costs the net income increases sharply to ₹11.66 lakh (Table 3.13), more than tripling the income from the baseline IFS model. These findings underline the significant long-term economic advantage of integrating solar energy into farming systems, especially when supported by financial incentives and policy frameworks. Beyond economic gains, the integration of solar panels into IFS enhances energy security and resource-use efficiency. The electricity generated can power essential farm operations such as irrigation pumps, cold storage, feed processing units, and value addition activities, thereby reducing operational costs and post-harvest losses. This aligns with India's broader objectives of improving farm incomes, promoting decentralized renewable energy adoption, and transitioning toward climate-resilient agriculture.

Nonetheless, several practical challenges remain. High upfront investment continues to be a barrier, particularly for small and marginal farmers. Additional considerations include land-use planning (to avoid shading of crops), access to affordable credit, system maintenance, and the need for farmer training. These factors emphasize the importance of institutional support, technical guidance, and scalable solar integration models tailored to regional agro-ecological conditions. The integration of solar energy into IFS thus emerges as a high-potential pathway for future-ready agriculture supporting productivity, economic stability, and environmental stewardship in a synergistic manner.

Table 3.14. Simulated Calculation (2nd Year) for IFS with Solar Panel Integration

Enterprise	Cost of Production (INR)	Net Expenses (₹)	Gross Income (₹)	Net Income (₹)
Cropping system	72,156	72,156	165,354	93,198
Dairy (3 cows)	330,482	330,482	492,120	161,638
Duckery (35 birds)	30,679	30,679	61,090	30,411
Fishery	53,792	53,792	91,080	37,288
Poultry (50 birds)	24,272	24,272	53,050	28,778
Fruit production	8,658	8,658	19,900	11,242
Biogas KVIC (2 m³)	4,000	4,000	9,000	5,000
Country bean (fencing area)	2,000	2,000	10,000	8,000
Solar panel	0	0	7,91,028	7,91,028
Total	**5,26,039**	**5,26,039**	**16,92,622**	**11,66,583**

IV.CONCLUSION

This review demonstrates that agrivoltaics systems provide substantial benefits for water conservation and agricultural sustainability by modifying the microclimate and improving soil moisture dynamics. Shading from PV panels reduces soil evaporation, moderates temperature extremes, and enhances late-season water availability, resulting in higher water use efficiency and, in many cases, increased crop biomass. The evidence shows that areas under solar panels can retain more soil moisture and require less irrigation, delivering both economic and environmental advantages to farmers. However, the spatial variability of shading and moisture distribution within agrivoltaics fields underscores the need for careful system design-particularly in panel layout and crop selection-to maximize these benefits. While agrivoltaics are especially effective for shade-tolerant crops and in water-limited regions, their broader adoption will depend on continued research into site-specific configurations and management practices. Ultimately, agrivoltaics represent a powerful land-sharing strategy that can simultaneously advance food production, renewable energy generation, and water resource sustainability for a changing climate.

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