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TITOLO TESI

Study and scientific validation of an integrated cropping model within the Solarfertigation agri-photovoltaic system

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Sommario

Abstract

Increased demand for food and energy at the global level implies problematic competition for agricultural land. Recently, the interest toward the integration of agricultural and energy production by photovoltaic (PV) systems known as agrivoltaics (AV) has been growing worldwide, in principle representing a promising approach to face the challenges of food security and energy supply from renewable sources. The present research deals with evaluating different agronomic and technological approaches for AV production in Mediterranean environment. We focused on vegetable species for the interest arised by AV cultivation in this sector, due to the importance of vegetable industry in the geographical areas where the research was conducted (Puglia region, South Eastern part of Italy; Murcia region, South Eastern part of Spain) and, in general, in the Mediterranean area.

The research can be schematically divided into three phases.

1) The performance of lettuce, pepper, and chili pepper, and the biological soil quality, in a ground-mounted PV system under cultivation conditions typical of the Mediterranean environment of the Puglia region were evaluated. Microclimatic parameters, plant growth and yield response, soil quality assessed using the QBS-ar index, and land equivalent ratio (LER) were determined in three different cultivation areas: a cultivation area outside the photovoltaic plant but immediately adjacent to it ('Control'); the inter-row area closest to the row of panels exposed to sunlight ('Area close PV structure'); the inter-row area distant from the row of panels ('Area distant PV structure'). Cumulated solar radiation, in particular during the summer growing cycles, was only slightly affected in the Area distant PV structure (1616 and 2130 MJ m^{-2} for pepper and chili pepper, respectively, in the control area, in comparison to 1630 and 2044 MJ m^{-2}, in the Area distant PV structure), while it was strongly reduced in the Area close PV structure (883 and 1091 MJ m^{-2} for pepper and chili pepper, respectively). In general, a reduction in air temperature and wind speed, as well as an increase in relative air humidity, was observed under PV conditions. On average, the evapotranspirative demand was reduced in the PV growing conditions compared to open field, with a more relevant effect in the sub-zone close to the photovoltaic structures, where cumulative ET0 was 28% and 34% lower than the Control in the pepper and chili pepper growing cycle, respectively. Lettuce growth was impaired by PV cultivation conditions, with an average reduction of 15% in plant height and 37% in marketable yield per plant, with no significant differences between the two sub-zones in the PV system. For pepper, the best growing conditions were observed in open field control compared to PV, but with differences related to the PV sub-zone. The plants grown in the Area distant PV structure were more negatively affected by the modified growing conditions, showing the lowest shoot and fruit fresh weight, the latter reduced by 51% compared to the Control; intermediate values were observed for these parameters in the Area close PV structure, with a less severe tendency to yield reduction. For

chili pepper, both shoot and fruit fresh weight were lower in PV conditions, regardless of the sub-zone, with a reduction of 82% in yield per plant compared to the Control. However, despite the yield reductions, the LER was improved (1.60 and 1.40 in case of a lettuce + pepper or lettuce + chili pepper annual cropping program, respectively), highlighting a more efficient use of land, without negative or even ameliorative impacts on biological soil quality and biodiversity in terms of QBS-ar and microarthropods taxa abundance. Knowledge of the response of different crops under cultivation conditions typical of specific environments is necessary to define optimal cropping programs aimed at maximizing resource-use efficiency and land use.

2) SolarFertigation is an intelligent fertigation system powered by solar energy, developed by the company co-financing the present PhD research project (SF System). An important phase of the research consisted in improving and testing the system in real AV conditions. It enables precise, adaptive management of fertigation processes based on real-time environmental, agronomic, and operational data. Developed to support sustainable and innovative agriculture, the system is also designed for effective integration within agrivoltaic contexts. Flexibility is ensured by the platform's capacity to seamlessly incorporate smart farming sensors and machines, both physically (hardware) and digitally, through a modular and scalable software architecture. The new cloud-based architecture introduces advanced automation models that adjust fertigation schedules dynamically according to crop phenology, weather conditions, soil characteristics, topography, and machine status. The system tracks detailed metrics such as nutrient composition and dosage (g), distributed water volumes (L), crop stages, and field operations across multiple levels (field, zone, crop). These data not only improve fertigation efficiency but also support compliance with the Italian Guidelines for Agrivoltaic Systems (MASE), including metrics such as LAOR – Land Area Occupation Ratio, limited to 40% photovoltaic coverage. These national directives could serve as a foundation for international standards, aligning with the recommendations of the International Energy Agency (IEA PVPS Task 13). In this framework, SolarFertigation acts as a strategic enabling technology, making these principles operational and scalable. Additionally, the cloud architecture supports future integration of photovoltaic production monitoring, including energy yield, inverter health, and solar panel orientation. Field validation of the system demonstrated its effectiveness in terms of LoRaWAN signal coverage and data transmission reliability, even in the presence of structural obstacles. Moreover, experimental field campaigns revealed a significant reduction in solar radiation and light intensity indices beneath the agrivoltaic modules, with implications on crop performance, including a general reduction in yield under photovoltaic panels, which in some cases exceeded 80% compared to open-field conditions.

3) Among economically significant greenhouse crops in arid and semi-arid regions, tomato is particularly relevant. This study systematically compared four greenhouses: control (C), shading net (SC), and two commercially available semi-transparent PV technologies, monocrystalline silicon (PV-Si) and cadmium telluride thin-film (PV-TF), under identical greenhouse conditions. The effects of each configuration on light availability, microclimate, and yield were evaluated across two growing seasons. During the winter–spring cycle, only the C and PV-Si greenhouses maintained daily light integral (DLI) values above the minimum threshold required for optimal crop development. Despite a similar number of fruits, the PV-Si greenhouse produced fruits with a mean weight 25% higher than the control, which was attributed to more favourable nighttime air temperatures and higher soil moisture. In the spring–summer cycle, although all the treatments exceeded the critical DLI threshold, photosynthetic activity in the SC and PV-TF greenhouses was restricted during key periods of the photoperiod, resulting in reduced yields. In contrast, the checkerboard configuration of the PV-Si panels allowed sufficient light transmission throughout both cycles, preventing shade-avoidance responses and maintaining yield levels comparable to or exceeding the control. The PV-Si system generated a total of 726.8 kWh over the study period, outperforming the PV-TF system. PV-induced shading moderated springtime temperature fluctuations but was insufficient to mitigate peak summer temperatures. Overall, the PV-Si system effectively balanced solar radiation management, thermal regulation, and energy production, demonstrating its potential as a suitable technology for agrivoltaic applications in regions with challenging climatic conditions.

Sintesi

L'aumento della domanda di cibo ed energia a livello globale implica una competizione problematica per i terreni agricoli. Recentemente, l'interesse verso l'integrazione della produzione agricola ed energetica mediante sistemi fotovoltaici (FV), noti come agrivoltaici (AV), è cresciuto in tutto il mondo, rappresentando in linea di principio un approccio promettente per affrontare le sfide della sicurezza alimentare e dell'approvvigionamento energetico da fonti rinnovabili. La presente ricerca si occupa di valutare diversi approcci agronomici e tecnologici per la produzione agrivoltaica in ambiente mediterraneo. Ci siamo concentrati sulle specie orticole per l'interesse suscitato dalla coltivazione di agrivoltaici in questo settore, data l'importanza dell'industria orticola nelle aree geografiche in cui è stata condotta la ricerca (Puglia, Italia sudorientale; Murcia, Spagna sudorientale) e, in generale, nell'area mediterranea.

La ricerca può essere schematicamente suddivisa in tre fasi.

1) Sono state valutate le prestazioni di lattuga, peperone e peperoncino, e la qualità biologica del suolo, in un sistema fotovoltaico installato a terra, in condizioni di coltivazione tipiche dell'ambiente mediterraneo della Puglia. I parametri microclimatici, la crescita delle piante e la risposta produttiva, la qualità del suolo valutata tramite l'indice QBS-ar e il Land Equivalent Ratio (LER) sono stati determinati in tre diverse aree di coltivazione: un'area di coltivazione esterna all'impianto fotovoltaico ma immediatamente adiacente ad esso ("Controllo"); l'area interfilare più vicina alla fila di pannelli esposta alla luce solare ("Area vicina alla struttura fotovoltaica"); l'area interfilare distante dalla fila di pannelli ("Area lontana dalla struttura fotovoltaica"). La radiazione solare cumulata, in particolare durante i cicli di crescita estivi, è stata solo leggermente influenzata nell'area lontana dalla struttura fotovoltaica (1616 e 2130 MJ m^{-2} rispettivamente per peperone e peperoncino nell'area di controllo, rispetto a 1630 e 2044 MJ m^{-2} nell'area lontana dalla struttura fotovoltaica), mentre è risultata fortemente ridotta nell'area vicina alla struttura fotovoltaica (883 e 1091 MJ m^{-2} rispettivamente per peperone e peperoncino). In generale, è stata osservata una riduzione della temperatura dell'aria e della velocità del vento, nonché un aumento dell'umidità relativa dell'aria, in condizioni di PV. In media, la domanda evapotraspirativa è stata ridotta nelle condizioni di coltivazione PV rispetto al pieno campo, con un effetto più rilevante nella sottozona vicina alle strutture fotovoltaiche, dove l'ET0 cumulativa è stata inferiore del 28% e del 34% rispetto al Controllo, rispettivamente nel ciclo di coltivazione del peperone e del peperoncino. La crescita della lattuga è stata compromessa dalle condizioni di coltivazione PV, con una riduzione media del 15% dell'altezza della pianta e del 37% della resa commercializzabile per pianta, senza differenze significative tra le due sottozone nel

sistema PV. Per il peperone, le migliori condizioni di crescita sono state osservate nel controllo in pieno campo rispetto al PV, ma con differenze legate alla sottozona PV. Le piante coltivate nell'area distante dalla struttura PV sono state influenzate più negativamente dalle condizioni di coltivazione modificate, mostrando il peso fresco più basso di germogli e frutti, quest'ultimo ridotto del 51% rispetto al Controllo; Sono stati osservati valori intermedi per questi parametri nell'Area vicino alla struttura PV, con una tendenza alla riduzione della resa meno marcata. Per il peperoncino, sia il peso fresco del germoglio che quello del frutto erano inferiori in condizioni PV, indipendentemente dalla sottozona, con una riduzione dell'82% della resa per pianta rispetto al Controllo. Tuttavia, nonostante le riduzioni di resa, il LER è migliorato (1,60 e 1,40 rispettivamente nel caso di un programma colturale annuale lattuga + peperone o lattuga + peperoncino), evidenziando un uso più efficiente del suolo, senza impatti negativi o addirittura migliorativi sulla qualità biologica del suolo e sulla biodiversità in termini di abbondanza di taxa di QBS-ar e microartropodi. La conoscenza della risposta di diverse colture in condizioni di coltivazione tipiche di specifici ambienti è necessaria per definire programmi colturali ottimali volti a massimizzare l'efficienza nell'uso delle risorse e l'uso del suolo.

2) SolarFertigation è un sistema di fertirrigazione intelligente alimentato da energia solare, sviluppato dall'azienda che cofinanzia il presente progetto di dottorato (Sistema SF). Una fase importante della ricerca è consistita nel migliorare e testare il sistema in condizioni di AV reali. Consente una gestione precisa e adattiva dei processi di fertirrigazione basata su dati ambientali, agronomici e operativi in tempo reale. Sviluppato per supportare un'agricoltura sostenibile e innovativa, il sistema è progettato anche per un'efficace integrazione in contesti agrivoltaici. La flessibilità è garantita dalla capacità della piattaforma di integrare perfettamente sensori e macchine per l'agricoltura intelligente, sia fisicamente (hardware) che digitalmente, attraverso un'architettura software modulare e scalabile. La nuova architettura basata su cloud introduce modelli di automazione avanzati che adattano dinamicamente i programmi di fertirrigazione in base alla fenologia delle colture, alle condizioni meteorologiche, alle caratteristiche del suolo, alla topografia e allo stato degli impianti. Il sistema traccia parametri dettagliati come la composizione e il dosaggio dei nutrienti (g), i volumi d'acqua distribuiti (L), le fasi della coltura e le operazioni sul campo su più livelli (campo, zona, coltura). Questi dati non solo migliorano l'efficienza della fertirrigazione, ma supportano anche la conformità alle Linee Guida Italiane per gli Impianti Agrivoltaici (MASE), inclusi parametri come il LAOR (Land Area Occupation Ratio), limitato al 40% della copertura fotovoltaica. Queste direttive nazionali potrebbero fungere da base per gli standard internazionali, allineandosi alle raccomandazioni dell'Agenzia Internazionale per l'Energia (IEA PVPS Task 13). In questo contesto, SolarFertigation

funge da tecnologia abilitante strategica, rendendo questi principi operativi e scalabili. Inoltre, l'architettura cloud supporta la futura integrazione del monitoraggio della produzione fotovoltaica, inclusi rendimento energetico, stato di salute degli inverter e orientamento dei pannelli solari. La validazione sul campo del sistema ha dimostrato la sua efficacia in termini di copertura del segnale LoRaWAN e affidabilità della trasmissione dati, anche in presenza di ostacoli strutturali. Inoltre, campagne sperimentali sul campo hanno rivelato una significativa riduzione della radiazione solare e degli indici di intensità luminosa al di sotto dei moduli agrivoltaici, con implicazioni sulle prestazioni delle colture, tra cui una generale riduzione della resa sotto i pannelli fotovoltaici, che in alcuni casi ha superato l'80% rispetto alle condizioni di campo aperto.

3) Tra le colture in serra economicamente significative nelle regioni aride e semi-aride, il pomodoro è particolarmente rilevante. Questo studio ha confrontato sistematicamente quattro serre: controllo (C), rete ombreggiante (SC) e due tecnologie fotovoltaiche semitrasparenti disponibili in commercio, silicio monocristallino (PV-Si) e film sottile di tellururo di cadmio (PV-TF), in identiche condizioni di serra. Gli effetti di ciascuna configurazione sulla disponibilità di luce, sul microclima e sulla resa sono stati valutati in due stagioni di crescita. Durante il ciclo invernale-primaverile, solo le serre C e PV-Si hanno mantenuto valori di integrale di luce giornaliera (DLI) superiori alla soglia minima richiesta per uno sviluppo ottimale della coltura. Nonostante un numero simile di frutti, la serra PV-Si ha prodotto frutti con un peso medio superiore del 25% rispetto al controllo, il che è stato attribuito a temperature notturne più favorevoli e a una maggiore umidità del suolo. Nel ciclo primaverile-estivo, sebbene tutti i trattamenti abbiano superato la soglia critica di DLI, l'attività fotosintetica nelle serre SC e PV-TF è stata limitata durante i periodi chiave del fotoperiodo, con conseguente riduzione delle rese. Al contrario, la configurazione a scacchiera dei pannelli PV-Si ha consentito una trasmissione luminosa sufficiente durante entrambi i cicli, mantenendo livelli di resa paragonabili o superiori al controllo. Il sistema PV-Si ha generato un totale di 726,8 kWh durante il periodo di studio, superando le prestazioni del sistema PV-TF. L'ombreggiamento indotto dal fotovoltaico ha moderato le fluttuazioni termiche primaverili, ma non è stato sufficiente a mitigare le temperature estive di punta. Nel complesso, il sistema PV-Si ha bilanciato efficacemente la gestione della radiazione solare, la regolazione termica e la produzione di energia, dimostrando il suo potenziale come tecnologia adatta per applicazioni agrivoltaiche in regioni con condizioni climatiche limitanti.

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Chapter 1

Introduction

1.1. Background

The escalating global requirements for both food and energy resources are creating a critical competition for agricultural land. In response, there is a burgeoning worldwide focus on Agrivoltaics (AV), which involves the co-location of agricultural production with photovoltaic (PV) energy generation. This integrated approach is emerging as a promising strategy to concurrently address the complex challenges of food security and the imperative for renewable energy supply [1].

The practical implementation of such a dual use of land for combined food and energy production, however, implies a series of issues of a not only technical nature, but also linked to the implications relating to the possible subtraction of land to be used primarily for agricultural production. Enhanced land use efficiency and contribution to reach renewable energy and decarbonization targets are generally reported as main benefits of AV. However, ensuring financial sustainability, setting up an effective regulation framework, and mitigating negative impacts on agricultural performances and soil quality conservation, are challenges that need to be addressed.

From an agronomic point of view, the primary consideration is the effect of modified microclimatic conditions—including shading, air dynamics, temperature, and relative humidity—on crop performance within the PV environment. Scientific findings on the impact of PV systems on crop yield are frequently contradictory. While some research suggests that AV systems can ameliorate the microclimate at the crop level, leading to enhanced yields [2,3], a significant body of literature documents a yield reduction, varying from 3% to 62% based on the specific crop and PV system configuration [4].

Despite extensive research on agronomic and energy outputs, the impacts of AV on soil ecosystems remain insufficiently documented. Soil invertebrates, particularly microarthropods, are recognized as crucial indicators and drivers of fundamental ecosystem processes, including organic matter decomposition, nutrient cycling, and maintenance of soil structure. Several indices, as QBS-ar Index and Eco-Morphological Index (EMI), are established diagnostic tools that can be utilized for assessing soil biological quality by quantifying the eco-morphological adaptations of microarthropods to the edaphic environment [5, 6].

Several recent scientific reports focused on Italy with the aim to assess the specific benefits and drawbacks of AV, as well as to assess under and agronomic point of view the effects of AV on agricultural system. In general, there is a general consensus on the fact that AV can significantly enhance land productivity with minimal land-use impact [7]. However, drawbacks are discussed, including high costs [8], complex procedures for approving projects aimed at protecting agricultural activity and landscapes [9], potential negative effects on traditional agro-ecosystems with agro-biodiversity loss [7]. The conceptualization of AV can be sensitive to varying regulatory jurisdictions. Italian official guidelines [10] delineate AV systems based on three operational requirements:

- Design and Configuration: Systems must be engineered with appropriate spatial configurations and technological selections to facilitate the integration and synergistic enhancement of both the agricultural and electrical sub-systems.

- Operational Management: They must guarantee the continuous, synergistic co-production of electricity and agricultural commodities over their technical lifespan, without compromising the ongoing farming or pastoral activities.

- Monitoring Protocol: Installations must incorporate monitoring systems to verify the continuity of farming operations, assess the impact on crop performance, and ensure the sustained viability of the agricultural enterprises involved.

Advanced AV systems are distinguished by meeting supplementary criteria, such as implementing innovative integrated solutions (e.g., elevated module structures) and deploying systems to monitor water conservation, soil fertility restoration, and resilience to climate change.

With specific reference to the above mentioned points, there is enormous interest from companies involved in the design and implementation of AV systems, in the development of advanced technological tools capable of integrated monitoring, control, and optimization of operations, aiming to support the management of AV systems.

It is important to note that while innovative structures are increasingly prioritized [11], the opportunity to explore the implications of co-production in existing standard ground-mounted PV arrays remains pertinent, considering that approximately 16,000 ha of these systems are currently operational in Italy [12].

However, the most recent trend consists of focusing the concept of AV to systems characterized by innovative layouts, i.e., PV structures lifted off the ground and further adapted to meet the requirements of sufficient crop production underneath [11].

Within this framework, AV greenhouses represent a specific category where PV modules are incorporated either into the primary structure or within the interior of the greenhouse itself [13]. The synergistic advantages of greenhouse cultivation, coupled with PV energy production, position these systems as an innovative and sustainable solution in agriculture. They offer significant potential for reducing greenhouse gas emissions through renewable energy generation while decreasing energy costs on farms via self-consumption. For highly technical greenhouses, the integration of PV energy is particularly impactful, as it provides power for essential agricultural operations, including ventilation, irrigation, temperature regulation (cooling and heating), and the operation of vehicles and machinery [14]. Additionally, when the PV infrastructure is designed to produce electricity exceeding farm consumption needs, these systems can generate supplementary income through the sale of surplus electricity. Various estimates of the maximum PV coverage ratio that can be installed in greenhouses without significantly reducing crop yields have been proposed [15]. Previous studies have shown that semi-transparent PV modules can enhance light homogeneity within greenhouses and improve crop yields [16, 17].

1.2. Research objectives and dissertation structure

Before outlining the specific research objectives of this doctoral project, and the methods used to achieve these objectives, it is appropriate to highlight a few considerations.

This doctoral research project was co-funded by the company SF System, based in the Puglia region (South eastern part of Italy), which is actively involved in the PV and AV sector for the design and implementation of AV systems and technological tools supporting the agronomic and operational management of these systems. For this reason, the objectives of this doctoral project were defined with due consideration to the specific needs of advancing the company's knowledge and technologies.

One of Italy's most important agricultural regions is Puglia, with about 80% of its total surface area used for agricultural purposes [18]. The region has a leading position for vegetable crops production at the national level [19].

Based on the above considerations, the objectives of this research project were:

- to evaluate the agronomic performance of different vegetable crops (lettuce, pepper, and chili pepper) and the biological soil quality, assessed using the QBS-ar index, in a ground-mounted PV system under cultivation conditions typical of the Mediterranean environment of the Puglia region. During the study, the microclimatic modifications of the growing environment were monitored with prototype and low-cost sensing and data transmission technologies specifically developed for agrivoltaic systems.

- To evaluate the "SolarFertigation" system, a smart fertigation system powered by solar energy, enabling precise, adaptive management of fertigation processes based on real-time environmental, agronomic, and operational data acquisition through an IoT sensor network deployment. The system was developed by SF System company for effective integration within agrivoltaic contexts, aiming to support in the agronomic management of crops under AV conditions, and in the compliance with the Italian Guidelines for Agrivoltaic Systems in terms of monitoring and reporting.

- To investigate the use of two semi-transparent PV technologies, monocrystalline silicon encapsulated in glass and thin-film PV, as greenhouse covering materials in AV systems for tomato production.

The achievement of these objectives was pursued, schematically, through 3 phases of research, which are described in the following chapters 2, 3 and 4. Chapter 2 (*Microclimatic Parameters, Soil Quality, and Crop Performance of Lettuce, Pepper, and Chili Pepper as Affected by Modified Growing Conditions in a Photovoltaic Plant: A Case Study in the Puglia Region (Italy)*) focuses on a study that took place in Puglia, in a PV plant managed by the company that co-financed the doctoral project, in which several cultivation cycles of horticultural species of interest for regional agriculture were carried out. Chapter 3 (*SolarFertigation: A Unified Cloud Platform for Smart Fertigation and Agrivoltaic System Integration*) focuses on a series of activities aimed at evaluating and improving the Solar Fertigation system in the context of real cultivation conditions in an AV environment. Finally, chapter 4 (*Comparative Evaluation of Semi-Transparent Monocrystalline Silicon and Cadmium Telluride Photovoltaics for Tomato Cultivation in Mediterranean Agrivoltaic Greenhouses*) focuses on research highly innovative AV technologies carried out at IMIDA, Instituto Murciano de Investigaciòn y Desarollo Agrario (Murcia, Spain), with which a scientific collaboration was establishe.

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Chapter 2

Microclimatic Parameters, Soil Quality, and Crop Performance of Lettuce, Pepper, and Chili Pepper as Affected by Modified Growing Conditions in a Photovoltaic Plant: A Case Study in the Puglia Region (Italy)

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Abstract:

The performance of lettuce, pepper, and chili pepper, and the biological soil quality, in a ground-mounted PV system under cultivation conditions typical of the Mediterranean environment of the Puglia region were evaluated. Microclimatic parameters, plant growth and yield response, soil quality assessed using the QBS-ar index, and land equivalent ratio (LER) were determined in three different cultivation areas: a cultivation area outside the photovoltaic plant but immediately adjacent to it (‘Control’); the inter-row area closest to the row of panels exposed to sunlight (‘Area close PV structure’); the inter-row area distant from the row of panels (‘Area distant PV structure’). Cumulated solar radiation, in particular during the summer growing cycles, was only slightly affected in the Area distant PV structure (1616 and 2130 MJ m^{-2} for pepper and chili pepper, respectively, in the control area, in comparison to 1630 and 2044 MJ m^{-2}, in the Area distant PV structure), while it was strongly reduced in the Area close PV structure (883 and 1091 MJ m^{-2} for pepper and chili pepper, respectively). In general, a reduction in air temperature and wind speed, as well as an increase in relative air humidity, was observed under PV conditions. On average, the evapotranspirative demand was reduced in the PV growing conditions compared to open field, with a more relevant effect in the sub-zone close to the photovoltaic structures, where cumulative ET0 was 28% and 34% lower than the Control in the pepper and chili pepper growing cycle, respectively. Lettuce growth was impaired by PV cultivation conditions, with an average reduction of 15% in plant height and 37% in marketable yield per plant, with no significant differences between the two sub-zones in the PV system. For pepper, the best growing conditions were observed in open field control compared to PV, but with differences related to the PV sub-zone. The plants grown in the Area distant PV structure were more negatively affected by the modified growing conditions, showing the lowest shoot and fruit fresh weight, the latter reduced by 51% compared to the Control;

intermediate values were observed for these parameters in the Area close PV structure, with a less severe tendency to yield reduction. For chili pepper, both shoot and fruit fresh weight were lower in PV conditions, regardless of the sub-zone, with a reduction of 82% in yield per plant compared to the Control. However, despite the yield reductions, the LER was improved (1.60 and 1.40 in case of a lettuce + pepper or lettuce + chili pepper annual cropping program, respectively), highlighting a more efficient use of land, without negative or even ameliorative impacts on biological soil quality and biodiversity in terms of QBS-ar and microarthropods taxa abundance. Knowledge of the response of different crops under cultivation conditions typical of specific environments is necessary to define optimal cropping programs aimed at maximizing resource-use efficiency and land use.

Keywords: land equivalent ratio (LER); crop yield; QBS-ar index; environmental parameters monitoring

2.1 Introduction

Increased demand for food and energy at the global level implies problematic competition for agricultural land. Recently, the interest toward the integration of agricultural and energy production by photovoltaic (PV) systems known as agrivoltaics (AV) has been growing worldwide, in principle representing a promising approach to face the challenges of food security and energy supply from renewable sources [1].

In Italy, as well as in several other countries, the possibility of large-scale implementation of AV systems is sparking heated debate and discussions at various levels with focus on potential benefits and drawbacks that merit careful consideration. In general, on one hand, combining agricultural production with photovoltaic energy generation can enhance land use efficiency and contribute to reach renewable energy and decarbonization targets; however, high costs, regulatory challenges, and the impacts on agricultural performances, soil quality conservation, and land use need to be addressed.

Recent studies focused on Italy as a case study reported that by allowing simultaneous agricultural and energy production, AV can significantly enhance land productivity with minimal land-use impact [2]. According to a spatial multicriteria land eligibility analysis, based on factors that can affect both the photovoltaic potential and the agricultural use, it is estimated that an AV coverage of 1.24% of the eligible area would enable reaching the national 80 GW target of new renewable capacity to achieve the country's decarbonization and energy transition objectives by 2030 [3]. The potential of AV in stimulating local economies by reducing energy costs for farmers and creating new job opportunities in the renewable energy sector is also outlined [4]. However, drawbacks and critical issues are reported as well. The initial investment for AV systems is significantly higher than traditional photovoltaic setups, which may deter adoption without supportive policies [5]. The procedures for approving projects and granting permits to build new installations are still subject to regulations, which are often too complex and ambiguous, aimed at protecting agricultural activity and landscapes [4]. Further doubts have been raised on the potential negative effects resulting from the transformation of traditional agro-ecosystems into AV systems, with specific reference to agro-biodiversity loss [2].

Although the most recent trend consists of focusing the concept of AV to systems characterized by innovative layouts, i.e., PV structures lifted off the ground and further adapted to meet the requirements of sufficient crop production underneath [6], several scientific reports dealing with crop cultivation between ground-mounted PV rows designate such systems as agrivoltaic [7,8]. The definition of the AV concept may also be subjected to the specific regulatory framework of the different territories. Based on official guidelines at the Italian national level [9], under the definition of AV, the systems are described as follows: i) designed and built in such a way as to adopt a spatial configuration and appropriate technological choices, such as to allow the integration of agricultural activity and electricity production and enhance the production potential of both sub-systems; ii) operated, during their technical life, in such a way as to guarantee the synergistic production of electricity and agricultural products and not compromise the continuity of agricultural and/or pastoral activity; iii) provided with systems for monitoring the continuity of agricultural activity, namely the impact on crops and the continuity of the activities of the agricultural companies involved. The systems defined as "advanced AV systems" are those that meet additional requirements, such as the adoption of innovative integrated solutions with modules raised from the ground, and the implementation of systems aimed at monitoring the effects on water saving, soil fertility recovery, and climate change resilience.

Despite the increasing interest toward innovative structures and the perspective of new advanced installations, thousands of hectares of standard photovoltaic ground mounted and/or fixed configuration plants are still worldwide operative, with about 16,000 ha in Italy, suggesting the opportunity of exploring the implications of combining energy and agricultural production in such conditions [10].

From an agronomic point of view, in order to ensure the maintenance of profitable agricultural activity in PV plants, the main concern is related to the effects of modified microclimatic conditions (i.e., shading, air movement, temperature, and air relative humidity) on crop performance. Results on the effects of PV on crop yield are often contrasting. Although some studies indicate that agrivoltaic systems can ameliorate microclimate at the crop level resulting in improved yield [11,12], numerous studies report yield reduction, ranging from 3% to 62%, depending on the crop and panel configuration [13].

It has been proposed that the development of AV systems, combining agricultural production with solar energy generation, offers promising perspectives for sustainable land management. While agronomic implications and energy outputs of these systems have been the object of extensive research, their impacts on soil ecosystems remain poorly documented. Soil invertebrates, particularly microarthropods, play a key role in ecosystem processes such as organic matter decomposition, nutrient cycling, and soil structure maintenance. The QBS-ar index is an established tool for assessing soil biological quality, relying on the eco-morphological adaptations of microarthropods to edaphic environments. Each group is assigned a score (Eco-Morphological Index, EMI) ranging from 1 to 20, based on its degree of adaptation to soil life. The sum of the EMI scores of the taxonomic units present in a sample constitutes the final value of the QBS-ar index. QBS-ar provides an indication on soil biological quality related to land degradation, and is based on the morphological features mentioned above, assigning an Eco-Morphological Index (EMI), ranging between 1 and 20, in relation to the adaptation level to soil (1 = no adaptation; 20 = total adaptation) at each taxon. QBS-ar shows the results of the sum of each maximum EMI score assigned at each taxon identified in the soil sample (refer to Parisi et al., 2005 [14], and Menta et al., 2018 [15], for details of the method).

One of Italy's most important agricultural regions is Puglia in the south-eastern part of the country, with about 80% of its total surface area used for agricultural purposes [16]. Although there is considerable unused and unproductive land in rural areas [17], the region has a leading position for vegetable crops production, as it accounts for 22% (70,340 ha) and 18% (1,413,304 tons) of open-field cultivated area and production at the national level [18]. A recent study estimated that, based on an analysis aimed to assess land use and potential AV opportunities, a minimal (namely 0.25% corresponding to 3250 hectares) occupation of utilized agricultural land would allow a regional installed AV capacity of 1.3 GW, considered a reasonable range of AV development in the region, which can contribute both to the energy transition and the support of the agricultural sector, especially in marginal areas [19].

Based on the above-mentioned considerations, the aim of this study was to evaluate the agronomic performance of different vegetable crops (lettuce, pepper, and chili pepper) and the biological soil quality, assessed using the QBS-ar index, in a ground-mounted PV system under cultivation conditions typical of the Mediterranean environment of the Puglia region. During the study, the microclimatic modifications of the growing environment were monitored with prototype and low-cost sensing and data transmission technologies specifically developed for agrivoltaic systems.

2.2 Materials and Methods

2.2.1. Site Description, Experimental Layout, and Growing Conditions

The study was conducted in a photovoltaic plant located in the Puglia region, Italy, in the Montemesola countryside, Taranto province, 40°32′32″ N, 17°20′18″ E, at an altitude of 69 m a.s.l. The system is composed of ground-mounted fixed photovoltaic modules with an orientation of approximately 78.8° with respect to North, i.e., slightly inclined towards the South-East with an almost East–West orientation.

This configuration is optimized to ensure a more uniform distribution of solar radiation throughout the day, rather than maximizing production at midday, as occurs in South-oriented systems. The modules, 2.7 m high and inclined at 25°, are spaced 8 m apart.

The study area has a typical Mediterranean climate, with mild winters, and hot and dry summers. Minimum temperatures are usually recorded between January and February, but rarely fall below 5–7 °C. The warmest months are July and August, with average monthly temperatures ranging from 26 to 28 °C. The average annual rainfall is about 600 mm, concentrated in the autumn and winter. Relative humidity tends to be higher in the cold months (but rarely exceeds 80%), while in spring and summer it decreases, thanks to moderate winds from the northern quadrants, which favor ventilation and mitigate temperatures.

The soil has a loamy texture, good water retention and air capacity, normal salinity and medium alkaline reaction (EC 0.47 dS m^{-1} and pH 8.1 in 1:2.5 water extract), high active limestone content (13.2%), and low organic matter (1.9 g 100 g^{-1}). The macro- and meso-elements are in a satisfying range: total nitrogen 1.18 g kg^{-1}, available phosphorus 21 mg kg^{-1}, exchangeable potassium, calcium, and magnesium 480, 2760, and 294 mg kg^{-1}, respectively. The cation exchange capacity is 17.67 meq 100 g^{-1} and the base saturation percentage is 100%, indicating good potential soil fertility.

Three vegetable species were tested for their response to cultivation under PV conditions. The three growing cycles took place in 2024 in different seasons: lettuce (*Lactuca sativa* L. var. *longifolia*, cultivar F1 L7, Franchi Sementi, Milano, Italy; 16 February–7 May), pepper (*Capsicum annum* L., cultivar Corner F1, ISI Sementi, Fidenza, Italy; 5 June–27 August), and chili pepper (*Capsicum annum* L., cultivar Gorria F1, ESASEM, Casaleone, Italy; 5 June–10 October).

For the purposes of the study, three different cultivation areas were used and compared. In the photovoltaic field, the area between two rows of photovoltaic structures, excluding a 0.8 m strip immediately adjacent to the pillars of the structures on both sides, was virtually divided into two areas, the one closest to the row of panels exposed to sunlight, and therefore most affected by shading phenomena (‘Area close PV structure’), and the one further away, therefore less affected by shading (‘Area distant PV structure’). A cultivation area outside the photovoltaic plant but immediately adjacent to it was also included in the study (‘Control’).

For the three experiments, seedlings were obtained from a local nursery and transplanted (the lettuce on February 16th, and the pepper and chili pepper on June 5th) with a plant density of 6.2 plant·m^{-2} (distance of 0.4 × 0.4 m) for lettuce, and 3.1 plant·m^{-2} (distance of 0.4 between plants × 0.8 m between rows) for the pepper and chili pepper. In the summer experiments, a black 105 g·m^{-2} UV-stabilized, water- and air-permeable woven polypropylene mulch sheet was used to control weeds and reduce evaporation.

Seedlings were transplanted in the three different cultivation areas. Irrigation was provided with drip tubes (2.2 L h^{-1} drippers 0.5 m apart). Total irrigation volumes of 20, 90, and 109 mm were provided for lettuce, pepper, and chili pepper, respectively.

The AV plant was provided with an innovative system, SolarFerigation, designed and implemented using low-cost sensing and IoT technologies combined with advanced mechanical solutions for smart irrigation management and environmental parameter monitoring. The technical features of the innovative system implemented in a prototype version have been recently described in detail, and the results of tests for technological performances have been reported (20). Briefly, the system uses autonomous photovoltaic technologies to power its operations, reducing energy costs and making the system particularly suitable to be used in AV plants, and usable in contexts where it is not possible to connect to the traditional power grid. The system is composed of two main components: the central unit, enabling precise distribution of water and fertilizers in irrigation zones, and the sensor nodes, which allow the setup of sensor networks for collecting environmental and soil data.

Based on average nutrient uptake and common fertilization practice for the crops in the area, 110 kg·ha^{-1} N, 70 kg·ha^{-1} P-P2O_5, and 160 kg·ha^{-1} K-K2O for lettuce, and 200 kg·ha^{-1} N, 90 kg·ha^{-1} P-P2O_5, and 275 kg·ha^{-1} K-K2O for pepper and chili pepper were applied via fertigation, dividing the total dose during the crop cycle according to the crop needs in the different phenological phases.

2.2.2 Measurements

Environmental Data/Microclimatic Variables

For the purposes of microclimate monitoring in the different cultivation areas under comparison, the SolarFertigation system was used to collect meteorological data. As reported above, the system allows the deployment of an IoT sensor network, the acquisition and the processing of the related data through LoRaWan technology and cloud-computing logic [20]. Please refer to the aforementioned publication for a detailed description of technological aspects. For the lettuce experiment, two IoT weather station nodes were installed at 1.50 m above ground: one in the control area and one in the center of an inter-row lane between the PV sturctures, respectively. For the pepper and chili pepper cycles, weather stations were increased, and nodes were installed in the control area, in the area under PV structures, and in the area distant from PV structures. The sensor nodes were equipped with sensors for environmental parameters: solar irradiation (VEML7700-TT, Vishay Intertechnology, Shelton, CT, USA), air temperature and relative humidity (DHT20, AZ-Delivery Vertriebs GmbH, Deggendorf, Germany), and, only for the pepper and chili pepper growing cycles, wind speed (CALT 9–30 V DC Supply 0–5 V Output 0–45 m s^{-1} Range Air 3 Cup F1J, Shanghai QIYI Electrical & Mechanical Equipment Co., Ltd., Shanghai, China). Data were collected at a 15 min interval and then averaged or integrated at a daily scale.

For the pepper and chili pepper growing cycles, measured data have been used for calculating reference evapotranspiration (ET0) based on the Penman–Monteith equation according to the FAO procedure [21].

Plant Growth and Yield

On lettuce, when plants reached the commercial maturity stage (on 7 May 2024), non-destructive measurements of the SPAD index were performed (Spad 502, Minolta corporation, Ltd., Osaka, Japan) on 10 plants randomly selected for each experimental area. At harvest, plant height and marketable yield per plant were measured.

On pepper and chili pepper, two measurements were performed corresponding to two subsequent harvests (on 1 and 27 August 2024, and on 2 September and 11 October 2024, respectively). SPAD index, plant height, shoot fresh weight, and marketable yield per plant were measured.

QBS-ar Index and Soil Microarthropod Biodiversity

During the pepper and chili pepper growing cycles, soil samples were collected and categorized into three types of sampling points:

- Control: Open-field areas without any panel coverage.
- Area distant PV structure: Inter-row spaces that received partial shading.
- Area close PV structure: Areas directly beneath the photovoltaic panels.

A total of 18 samples (3 samples × 2 crops × 3 areas) were collected and processed according to the procedure described hereafter. For each area and crop combination, three replicated samples (R1, R2, R3) were collected to ensure consistency and statistical robustness. At each sampling site, soil microarthropods were collected by extracting three individual soil cores positioned at the vertices of an equilateral triangle with sides measuring 10 m. Each core measured 10 cm × 10 cm × 10 cm, resulting in a volume of approximately 1000 cm^3 per sample. The three cores, together amounting to a total volume of about 3000 cm^3, were combined into a single polyethene bag for subsequent laboratory processing. The samples were transported to the laboratory within 48 h under controlled conditions, ensuring they remained undisturbed and protected from thermal and mechanical shocks. This allowed for the prompt initiation of the extraction procedure, minimizing the risk of alteration or degradation. The sampling design and QBS-ar methodology were applied according to standard procedures, following approaches used in recent studies on soil quality in Mediterranean environments [22].

Microarthropods were extracted from the soil samples using Berlese–Tullgren funnels over seven days under controlled laboratory conditions. The extraction method uses a thermal and desiccation gradient to drive soil-dwelling fauna downward into collection vessels. The soil samples were subjected to continuous heat exposure from a 60-watt incandescent bulb positioned 20 cm above each sample. The bulb remained switched on 24 h a day throughout the entire seven-day extraction period. A mesh with 2 × 2 mm openings was used during the process. The extracted specimens were collected and preserved in a solution of ethyl alcohol and glycerol at a 3:1 ratio. All samples analyzed in this study are currently stored at the University of Bari. Specimens were identified and counted using a stereomicroscope with magnifications ranging from 8× to 50×. Following extraction, specimens were sorted and identified to major taxonomic groups under a stereomicroscope. Identification was carried out to the level required for application of the QBS-ar index [14]. Each taxon was assigned an Eco-Morphological Index (EMI) score ranging from 1 to 20, reflecting the degree of morphological adaptation to soil life. Euedaphic taxa highly adapted to soil habitats (e.g., Protura, Diplura, Pauropoda) receive an EMI of 20, while less adapted or epigeic taxa receive lower scores [14]. The QBS-ar value for each sample was calculated as the sum of the EMI scores of all taxa present. This methodology is widely recognized for its simplicity, ecological significance, and robustness across diverse environments, including agricultural land, forests, urban soils, and wetlands [15,22]. The QBS-ar index provides an integrative measure of soil biological quality by combining faunal diversity and functional traits linked to soil ecosystem services.

Land Equivalent Ratio (LER) Calculation

The performance of the agrivoltaic system in terms of land surface requirements was assessed using the Land Equivalent Ratio (LER), computed as:

LER = [Yield agri (dual)/Yield agri (mono)] + [Yield elec (dual)/Yield elec (mono)]

Yeld agri (dual) and (mono) are the economic values of the agricultural production in the mixed and single production system, respectively; Yield elec (dual) and (mono) are the economic values of the energy production in the mixed and single production system, respectively.

For agricultural production values in the LER calculation, the yield values measured in the experiments of this study were used. In particular, two different annual agricultural programs were hypothesized, based on (i) a lettuce cycle and a pepper cycle, and (ii) a lettuce cycle and a chili pepper cycle. For the Yield agri (mono) the yield values obtained in the control conditions, the lettuce + pepper and lettuce + chili pepper were used. For the Yield agri (dual), the yield values obtained in the PV conditions were used (yield per cultivated surface), considering a 49.3% of the total area usable for cultivation, half of which is characterized by ‘Area close PV structure’ conditions and half by ‘Area distant PV structure’ conditions. The plant densities reported in the 2.1 section were used for the calculations.

For the energy component, a 565,885 kWh ha^{-1} yield has been considered, according to the PVsyst model based on the characteristics of the system [23]. The same value was used both for dual and mono

Yield elec, since the system was designed as a pure photovoltaic system and only later converted to agrivoltaic use, without variation in electrical output.

All values used in the calculations were normalized for a 1 ha area.

2.2.3 Statistical Analysis

The crop measurements data were subjected to ANOVA, considering a completely randomized experimental design. Treatment means were separated by the Tukey HSD test when there was a significant effect at the $p = 0.05$ level. The statistical software STATISTICA 10.0 (StatSoft Inc., Tulsa, USA) was used for the analysis.

2.3 Results and Discussion

2.3.1. Environmental Data/Microclimatic Variables

Based on measurements provided by the sensors network implemented in the experimental field, rather evident differences were detected among the different growing conditions tested in the study, confirming the influence of the photovoltaic system on the observed microclimatic variables.

In the lettuce growing cycle, cumulated radiation values of 365 MJ m^{-2} and 306 MJ m^{-2} were recorded in open field control and PV conditions, respectively (Figure 1A), with daily values remaining similar in the first half of the cycle up to the first decade of April, and then showing higher values in the Control, with an average difference of 25 MJ m^{-2} up to the beginning of May and a gradual increase up to 58 MJ m^{-2} at the end of the cycle in terms of cumulated radiation (Figure 1B). Much more evident differences were observed during the summer cycle. In this case, it was possible to monitor two sub-zones within the photovoltaic system, one closest to the row of panels exposed to sunlight, and therefore most affected by shading phenomena (‘Area close PV structure’), and one more distant, therefore less affected by shading (‘Area distant PV structure’) (see Sections 2.1 and 2.2.1). In particular, the highest cumulated radiation was observed in the Control area (1616 and 2130 MJ m^{-2} for pepper and chili pepper, respectively) and in the ‘Area distant PV structure’ treatment (1630 and 2044 MJ m^{-2} for pepper and chili pepper, respectively), showing very similar trends (Figure 2A). In contrast, a drastically lower cumulative radiation value, approximately half, was observed in the area inside the photovoltaic system closest to the structures (883 and 1091 MJ m^{-2} for pepper and chili pepper, respectively) (Figure 2A). Indeed, by observing the daily trend of solar radiation, it is possible to observe the substantially overlapping trends between the control and the cultivation area within the area more distant from the photovoltaic structures, while consistently lower values were observed in the area closest to the structures, with greater differences during the full summer period and gradually smaller as the autumn season approached (Figure 2B).

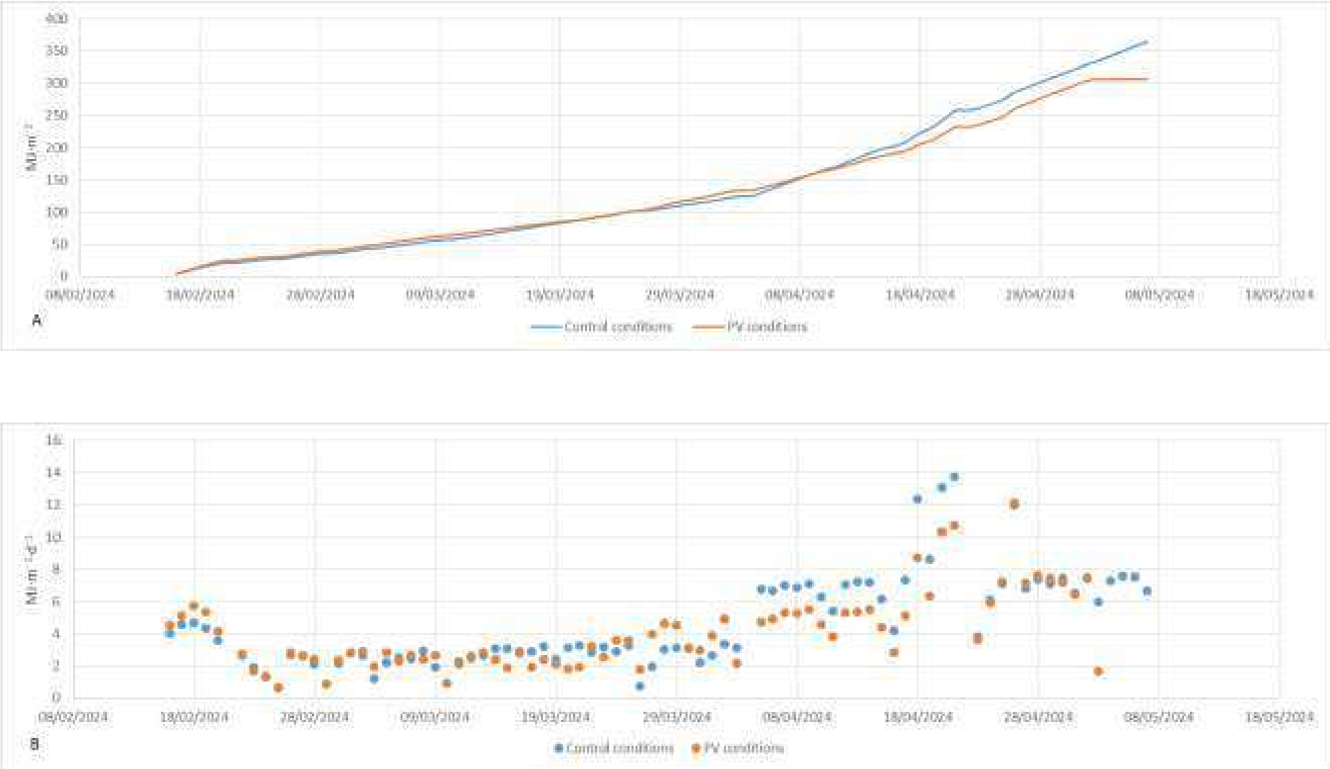

Figure 1. Solar irradiance (cumulated, (**A**); daily total, (**B**)) measured during the lettuce growing cycle in the control and in the photovoltaic (PV) cultivation conditions.

Figure 2. Solar irradiance (cumulated, (**A**); daily total, (**B**)) measured during the pepper and chili pepper growing cycles in the control and in two sub-zones of photovoltaic (PV) cultivation conditions (‘Area close PV structure’ and ‘Area distant PV structure’).

Our results are in agreement with numerous evidence that cultivation in photovoltaic environment involves a reduction in the availability of sunlight for the crop. This factor represents the main element of attention and concern regarding the effects of AV on crop performance [24]. However, our study clearly demonstrates that the shading effects can be highly variable depending on the position with respect to the photovoltaic structures. In the inter-row space, in fact, areas with a high level of shading and others with similar shade than open field conditions can be identified. Typically, the highest radiation reduction is recorded just below the panel’s array [25]; so, acting on the photovoltaic layout (density, inter-row spacing, etc.) has been identified as an optimization strategy to ameliorate crop growing conditions by limiting negative impact on energy production [26]. In this perspective, the use of models aimed at defining the effect of shading with spatial distribution analysis is deeply investigated. These models are considered an important tool for the identification of the most suitable agrivoltaic system layout for specific crops and geographical locations [27].

With regard to the other microclimatic variables monitored in the study, different trends were observed as affected both by the season and the position of the areas under comparison.

During the lettuce growing cycle, only data for daily mean air temperature and RH were available, showing no relevant differences for the two areas monitored (Control and PV, respectively) (Table 1). However, during the pepper and chili pepper growing cycles, the differences among the areas under comparison were more evident. In particular, during the pepper growing cycle daily mean temperature resulted 1.6 °C higher in open field control conditions compared to the PV system areas, with no differences between the two sub-zones (close and distant PV structures); RH was lower in control conditions compared the PV conditions (48.3 vs. 52.45%, on average), with slightly higher values in Area distant PV structure compared to the other sub-zone; the highest daily mean wind speed was observed in control conditions, while the lowest in the sub-zone distant from PV structure (Table 1). Similar trends were observed in the chili pepper growing cycle, with higher values of daily mean temperature and wind speed and lower RH in the control area (Table 1).

Table 1. Microclimatic variables during growing cycles of vegetable crops (lettuce, pepper, and chili pepper) cultivated in open field (Control) and under photovoltaic (PV) conditions. For pepper and chili pepper, two sub-zones within the PV system (‘Area close PV structure’ and ‘Area distant PV structure’) were monitored.

	Daily Mean T (°C)	Daily Mean RH (%)	Daily Mean Wind Speed ($m \cdot s^{-1}$)	Cumulated ET_0 (mm)
		Lettuce growing cycle		
Control	14.8	70.7		
PV conditions	15.1	70.9		
		Pepper growing cycle		
Control	32.0	48.3	2.4	480
Area close PV structure	30.4	52.3	2.2	345
Area distant PV structure	30.4	52.6	1.6	449
		Chili pepper growing cycle		
Control	29.6	56.7	2.3	597
Area close PV structure	27.4	64.9	1.8	397
Area distant PV structure	27.8	67.3	1.6	541

The evapotranspirative demand was reduced, on average, in the PV growing conditions compared to open field, as an effect of reduced solar radiation and wind speed and increased air relative humidity (Table 1). Among the sub-zones within the PV system, a more relevant effect was observed in the sub-zone close to the photovoltaic structures, where cumulative ET0 was 28% and 34% lower than the Control with reference to the pepper and chili pepper growing cycle, respectively. However, in the sub-zone distant to the photovoltaic structures, the ET0 was 6% and 9% lower than the Control (Table 1). In general, the effects observed on microclimatic conditions are consistent with previous studies. Fagnano et al. (2024) [10] observed a reduced evapotranspiration (29%) in a ground-mounted photovoltaic plant where aromatic crops have been cultivated; in that case, the plant layout presented a 3.5 m inter-row spacing (compared to 8 m in our study), so the conditions can be considered similar to those of the sub-zone close to PV structures in our study, in which it was indeed observed a very similar ET0 reduction. Mechanisms of reduced ET in agrivoltaic conditions have been well described by Marrou et al. (2013) [28], who concluded that evapotranspiration reduction was mainly driven by the modifications of the micrometeorological conditions below the solar panels. In the scenario of climate change, resulting in global warming and water resource shortage trends, identifying strategies for improved water use efficiency and/or water saving is a critical issue for agriculture [29]. In this perspective, reduced ET as a consequence of microclimatic variations has been often outlined as a benefit of agrivoltaics [30]. However, it has been pointed out that reduction in ET under agrivoltaic conditions may not systematically lead to increased water use efficiency, depending on the genotypic plant sensibility of dry matter accumulation to shade [28]. As an effect of the capacity of agrivoltaic systems to reduce evapotranspirative demand under shade and to slow down soil water depletion, Ramos-Fuente et al. (2023) [31] reported improved irrigation water productivity for maize in AV, but only in fully irrigated compared to deficit conditions. In rainfed conditions, average maize grain yield was higher and more stable under AV than under full sun, with a proportional relation between yield increase and drought stress, indicating that AV systems could increase crop resilience to climate change [32].

2.3.2. Plant Growth and Yield

Lettuce growth was impaired by PV cultivation conditions. Plant height was reduced by 15%, and marketable shoot fresh weight per plant by 37%, on average, with no significant differences between the two sub-zones in the PV system (Table 2). Conversely, SPAD index was not influenced by the growing environments under comparison.

Table 2. Growth and crop performance of lettuce, pepper, and chili pepper in open field (Control) and under photovoltaic (PV) conditions in two sub-zones within the PV system (‘Area close PV structure’ and ‘Area distant PV structure’).

	Plant Height (cm)	**Shoot Fresh Weight (g plant^{-1})**	**Fruit Fresh Weight (g plant^{-1})**	**SPAD**
		Lettuce		
Control	30.5 a	727.1 a		30.1
Area close PV structure	25.1 b	404.2 b		31.9
Area distant PV structure	26.6 b	518.6 b		30.3
Significance	***	***		ns
		Pepper		
Date				
1 August 2024	39.1	209.1	121.4	48
27 August 2024	61.2	372.7	242.2	49
Treatment				
Control	52.6 a	374 a	248.6 a	51 a
Area close PV structure	56.8 a	295 ab	174.2 ab	45 b
Area distant PV structure	41.1 b	204 b	122.7 b	50 a
Significance				
Date	***	***	***	ns
Treatment	***	***	***	**

Treatment × Date	***	ns	ns	ns
		Chili pepper		
Date				
2 September 2024	53.4	778.4	401.5	55
11 October 2024	55.4	862.6	409.0	53
Treatment				
Control	63.6 a	1514.8 a	913.8 a	49.9 b
Area close PV structure	54.7 b	510.7 b	195.7 b	50.6 b
Area distant PV structure	45.4 c	472.8 b	131.9 b	60.7 a
Significance				
Date	ns	ns	ns	ns
Treatment	***	***	***	***
Treatment × Date	ns	ns	ns	ns

Mean separation within columns by Tukey HSD test. Mean values followed by different letters within columns are significantly different ($p < 0.05$). Significance: ns = not significant, ** P ≤ 0.01, *** ≤ 0.001.

For pepper, highest values of plant height, shoot, and fruit fresh weight were observed at the second measurement date. In general, the best growing conditions were observed in open field control compared to PV, but with differences related to the PV sub-zone. In particular, the plant height was similar in the Control and in the Area close PV structure (54.7 cm, on average), while plants grown in the Area distant PV structure were more negatively affected by the modified growing conditions, showing the lowest shoot and fruit fresh weight, the latter reduced by 51% compared to the Control; intermediate values were observed for these parameters in the Area close PV structure, with a less severe tendency to yield (fruit fresh weight per plant) reduction. Conversely, SPAD resulted similar in Control and in Area distant PV structure, while values slightly lower were observed in the Area close PV structure.

For chili pepper, the highest plant height was observed in the Control, followed by plants grown in Area close PV structure, with lowest values in Area distant PV structure. Both shoot and fruit fresh weight were lower in PV conditions, regardless of the sub-zone, with yield reduction of 82% compared to the Control in terms of fruit fresh weight (Table 2).

Our results suggest that, in the conditions of our experiments, the microclimatic variations occurring under PV, compared to full-sun, open-field conditions, had relevant effects on plant growth. Although the reduction in solar radiation remains the key aspect, the interaction of other microclimatic conditions should be taken into account and further explored. Indeed, we observed reduced growth also on plants cultivated in the sub-zone less affected by shading, where solar irradiance values very similar to the full-sun control zone were recorded (Figure 2). We can hypothesize that reduced wind speed and increased RH under PV (Table 1) determined modified aerodynamic conditions, negatively affecting gas exchange and thermo-regulative mechanisms in plants. In addition, a different distribution of solar radiation during the day could have induced plant stress conditions in the cultivated area under PV and, in particular, in the area distant to structures. Further deepening should be implemented in order to explain the responses observed in the study, possibly including measurements related to gas exchange and photosynthetic activity parameters.

On the basis of the yield results reported in Table 1, taking into account the land available for cultivation in the PV system and in the Control, respectively, and the planting densities adopted for the different tested crops, the resulting yield per cultivated surface (on hectare basis) values are 14,230 and 45,444 kg ha^{-1} for lettuce, in PV and Control conditions, respectively; 2288 and 7769 kg ha^{-1} for pepper; 2525 and 28,556 kg ha^{-1} for chili pepper. As a result, yield reduction of 68.7%, 70.5%, and 91.2% were observed in this study under PV conditions for lettuce, pepper, and chili pepper, respectively.

It has been reported that there is still little and contrasting information on the effects of combined PV energy and agricultural production on crop performance, and often the available information arises from studies with simulated or AV comparable conditions, such as agroforestry experiments or studies with artificial shade, or by the application of simulation and modeling approaches [6]. The current study was implemented with the aim of gathering crop performance information in real PV cultivation conditions, with specific reference to the system configuration described. The current experiments carried out on three crops (lettuce, pepper, and chili pepper) revealed a general reduction in plant growth and production parameters, at a different extent depending on the species. This is in agreement with the assumption that agrivoltaics may lead to a certain loss of production, in terms of yield both per plant and per cultivated surface, depending on the crop species and the photovoltaic system configuration [13]. With specific reference to the species tested in the current study, the average production reduction in terms of marketable yield per plant (mean value of the crop performance in the two sub-zones), observed under PV conditions can be considered in line with other studies. Marrou et al. (2013b) [33] reported reduced fresh shoot weight per plant for lettuce under agrivoltaic cultivation up to 42% and 19% in conditions of full or half density of panels configuration. Zheng et al. (2021) [11] reported lettuce yield reduction of approximately 50% under conventional agrivoltaic conditions, while no differences compared to full-sun conditions were observed when an improved agrivoltaic system with a grooved glass plate was used. For chili pepper, Joukhadar et al. (2025) [34] reported a marketable yield reduction of approximately 50% under AV conditions, with similar findings reported by Asa'a et al. (2024) [35], while an increased yield (more than 60%) was reported by Hernández et al. (2022) [36].

Generalizing the impact of agrivoltaic installations on crops is difficult. Cultivation in an AV environment may result in a different impact on the agronomic performance of winter compared to summer crops, or on short compared to long cycle crops [37]. It has also been noted that often yield response for the same crop may show variable and even opposite trends, depending on the typology of the agrivoltaic systems, the cropping cycle season, the specific annual climatic conditions during the study, the agronomical management practices, and even the variety used [1].

However, it is generally acknowledged that conventional agrivoltaic configurations based on traditional PV systems (as the case of fixed ground-mounted PV systems) generally lead to significant reduction in crop yield and quality compared to the Control where the climatic conditions and agronomic inputs availability do not represent limiting factors to crop performance. However, there is evidence that even conventional PV systems may lead to beneficial effects on crop yield in areas characterized by unsuitable conditions for plant growth such as excessive solar radiation, high temperature, drought, and water shortage [38]. The current attention towards innovative AV configurations and layout brings about lively interest in the perspective to ameliorate the crop performance under these systems.

2.3.3. QBS-ar Index and Soil Microarthropod Bioiversity

The mean QBS-ar values obtained across treatments and crops are reported in Table 3. The highest mean QBS-ar values were observed in 'Area distant PV structure'—Pepper (QBS-ar = 70.7) and 'Area close PV structure'—Pepper (QBS-ar = 69.0). Conversely, the lowest QBS-ar values were observed in Control—Chili Pepper (QBS-ar = 45.3) and 'Area close PV structure'—Chili Pepper (QBS-ar = 52.0). These differences are clearly illustrated in Figure 3, where the bar chart shows QBS-ar trends across all treatments. Overall, both AV sub-zones exhibited higher QBS-ar values compared to Control for both crops under comparison. These findings suggest a positive influence of the PV system on soil biological quality. This trend is further supported by the maximum QBS-ar values (QBS-max) reported in Figure 3. The highest QBS-max values were recorded in "Area close to PV structure"—Chili Pepper (145), followed by "Area distant from PV structure"—Chili Pepper (126), and "Area close to PV structure"—Pepper (122). The lowest QBS-max value was found in Control—Chili Pepper (56). These results suggest that the microclimatic changes introduced by the PV structures—such as shading, reduced soil evaporation, and increased relative humidity—can create favorable conditions for soil fauna. Taxonomic richness (number of distinct taxa) across treatments and crops is summarized in Table 3. The highest richness was found in "Area close PV structure"—Pepper (48 taxa), while the lowest richness was observed in Control—Chili Pepper (25 taxa) followed by "Area distant PV structure"—Chili Pepper (26 taxa). These results further confirm a positive effect of photovoltaic installation combined with agricultural use of land on soil biodiversity, with marked differences between crops. The results demonstrate that agrivoltaic systems can positively influence soil biological quality. These findings align with previous research indicating that modified microclimatic conditions, such as shading and reduced soil evaporation, can create favorable environments for soil fauna. Dual use (agricultural and energy production) of land in PV installations, beyond its role in sustainable energy production, may also contribute positively to below-ground biodiversity. The QBS-ar index proved effective in capturing these effects, supporting its use as a monitoring tool in agroecological contexts.

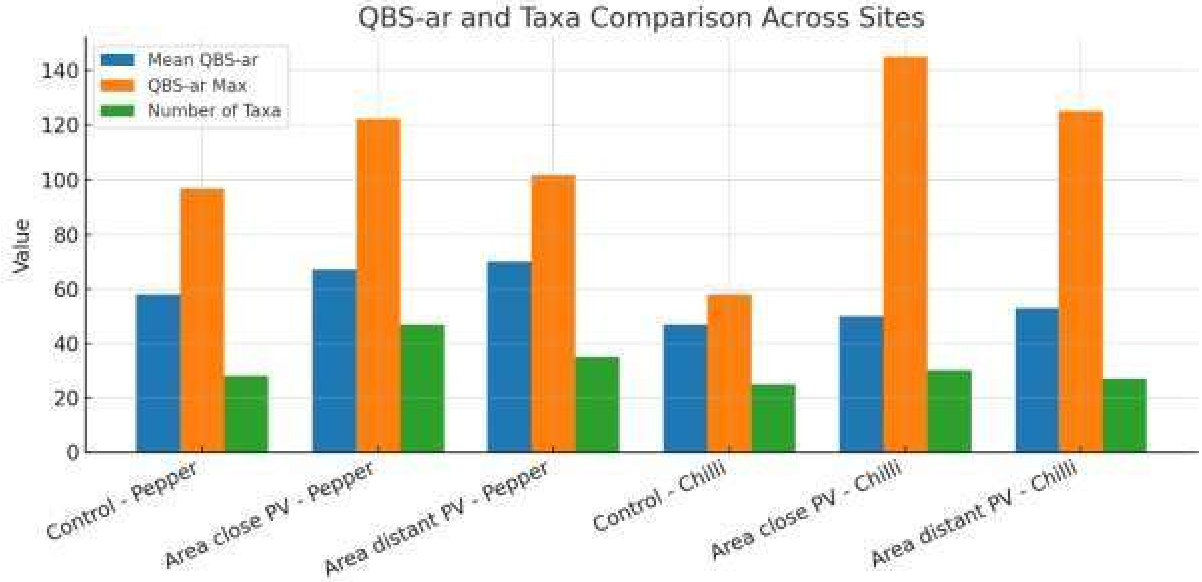

Figure 3. Comparison of mean QBS-ar values, maximum QBS-ar values (QBS-max), and taxonomic richness (number of taxa) across different treatments and crops. The analyzed areas include control zones and zones close to or distant from photovoltaic (PV) structures, for both pepper and chili pepper crops. Results indicate that agrivoltaics zones (both close and distant from PV structures) generally exhibit higher soil biological quality (QBS-ar) and greater biodiversity compared to Controls, suggesting a positive effect of PV installations on soil fauna communities.

Table 3. Summary of QBS-ar values and number of Taxa per crop and growing area per sample.

	QBS_R1	QBS_R2	QBS_R3	Mean QBS-ar	QBS-Max (R1 + R2 + R3)	Total Individuals
Pepper growing cycle						
Control	45	60	67	57.3	97	28
Area close PV structure	46	96	65	69	122	48
Area distant PV structure	60	70	82	70.7	102	34
Chili pepper growing cycle						
Control	46	45	45	45.3	56	25
Area close PV structure	51	75	30	52	145	30
Area distant PV structure	39	75	50	54.7	126	26

The relative abundance of taxonomic groups revealed marked differences among the six sampling sites (Figure 4). The most numerically dominant taxa were Acari and Collembola, with peak abundances recorded in areas located close to PV structures. Sites adjacent to photovoltaic installations exhibited a higher overall abundance compared to both control and distant sites, with a significantly greater number of individuals across several taxa. These results suggest that the microenvironmental conditions influenced by the presence of PV panels (e.g., reduced evapotranspirative demand, shading, reduced thermal stress) may favor the development and persistence of soil arthropod communities. The graphical analysis supports the hypothesis of a positive indirect effect of photovoltaic structures on soil biodiversity.

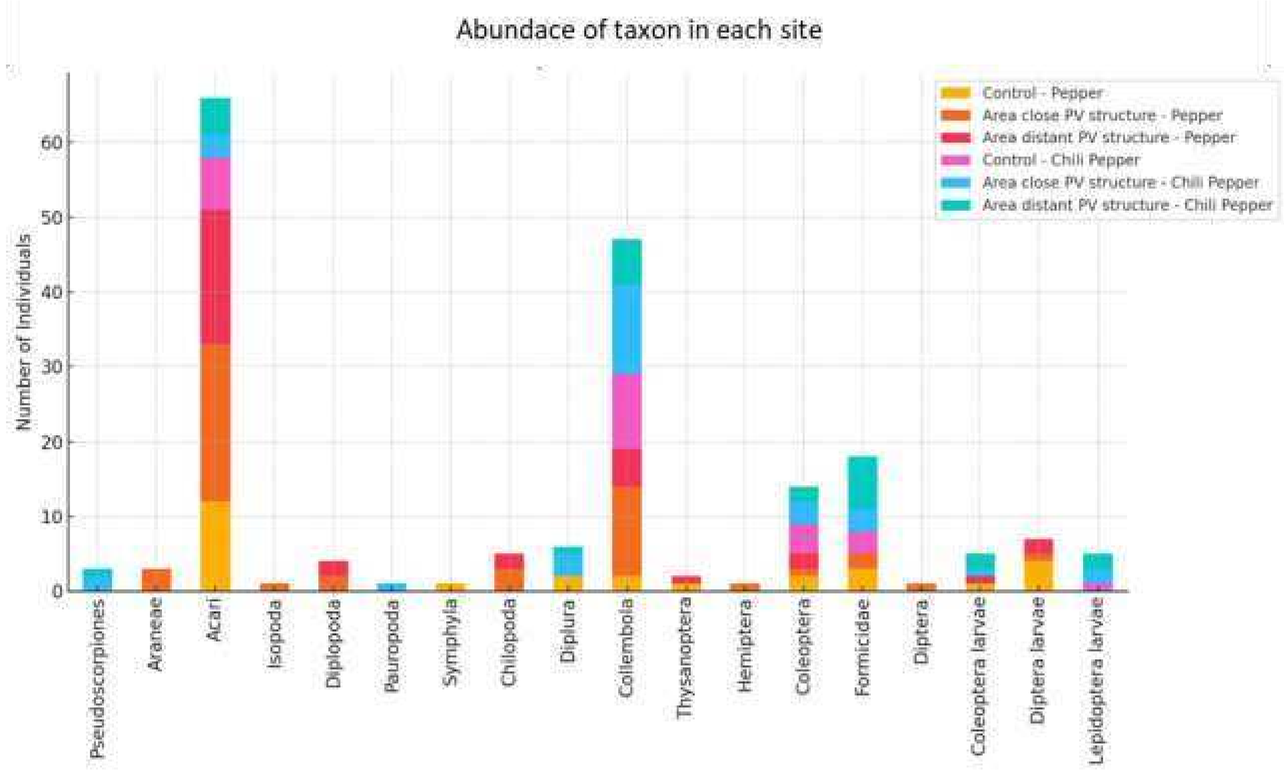

Figure 4. Total abundance of major taxonomic groups (scientific nomenclature) across six sampling sites.

Overall, the sites located near PV structures exhibited greater abundance and diversity compared to control or more distant sites. These results suggest that the microenvironmental conditions altered by the presence of the structures (e.g., shading, increased soil moisture, reduced thermal fluctuations) may favor the development and stability of soil communities.

2.3.4. LER

The LER, an index largely used to assess the effectiveness of any system that combines two (or more) production types on the same land unit (as the agrivoltaic case) [39], was used as an indicator of the productivity of the land used for the study. The LER indicator aims to compare the productivity of a mixed system versus a system based on a single production use.

When an annual cropping program consisting of a growing cycle of lettuce followed by pepper is hypothesized, the LER calculation results in the following:

$$\mathrm{LER} = \left[\frac{14{,}230\ \mathrm{kg\ ha^{-1}}}{45{,}444\ \mathrm{kg\ ha^{-1}}} + \frac{2288\ \mathrm{kg\ ha^{-1}}}{7769\ \mathrm{kg\ ha^{-1}}}\right] + \frac{565{,}885\ \mathrm{kWh\ ha^{-1}}}{565{,}885\ \mathrm{kWh\ ha^{-1}}} = 1.60$$

However, if the cropping program would consist of a lettuce followed by chili pepper growing cycle, the LER would result in the following:

$$\text{LER} = \left[\frac{14{,}230\ \text{kg ha}^{-1}}{45{,}444\ \text{kg ha}^{-1}} + \frac{2525\ \text{kg ha}^{-1}}{28{,}556\ \text{kg ha}^{-1}}\right] + \frac{565{,}885\ \text{kWh ha}^{-1}}{565{,}885\ \text{kWh ha}^{-1}} = 1.40$$

LER > 1 indicates that considered dual system results in more efficient use of land compared to separate agricultural or energy production use. Based on several studies dealing with the assessment of AV competitiveness, the LER values of systems combining agricultural and photovoltaic energy production are impressive. Values ranging from 1.35 to 1.73 have been predicted in half (optimized for agricultural production) or full (optimized for energy production) density systems, respectively [39]. Since the effects of AV on crop yield differ depending on the type of crop, specific evaluation should be performed through subsequent cultivation, with the aim to find optimal cropping systems to maximize LER [40]. In this perspective, our study demonstrates that the LER can be greatly influenced by the choice of the crop, as occurred in our case as an effect of including pepper or chili pepper in the cropping program.

2.4 Conclusions

Although the assessment of advanced agrivoltaic systems represents the main focus and interest of scientific and industrial activity, the exploitation of the existing traditional photovoltaic plants in terms of combined agricultural and energy production should be considered a relevant challenge and opportunity, due to the large area currently occupied by these systems. Our study confirmed that the crop performance was negatively affected by the presence of the PV plant, with a variable response according to the crop species considered. However, also in conditions of yield reductions, the LER was improved, underlying a more efficient use of land, without negative or even ameliorative impacts on biological soil quality. Since the effects on plants depend on the typology of the agrivoltaic systems, the cropping cycle season, the specific annual climatic conditions, the agronomical management practices, and even the variety used, improving the knowledge on the specific response of crops, determined under real cultivation conditions typical of different environments, is necessary to define optimal cropping programs aimed to maximize resources use efficiency and land use.

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Chapter 3

SolarFertigation: A Unified Cloud Platform for Smart Fertigation and Agrivoltaic System Integration

Abstract:

SolarFertigation is an intelligent fertigation system powered by solar energy. It enables precise, adaptive management of fertigation processes based on real-time environmental, agronomic, and operational data [1,2]. Developed to support sustainable and innovative agriculture, the system is also designed for effective integration within agrivoltaic contexts. Flexibility is ensured by the platform's capacity to seamlessly incorporate smart farming sensors and machines, both physically (hardware) and digitally, through a modular and scalable software architecture. The new cloud-based architecture introduces advanced automation models that adjust fertigation schedules dynamically according to crop phenology, weather conditions, soil characteristics, topography, and machine status [3]. The system tracks detailed metrics such as nutrient composition and dosage (g), distributed water volumes (L), crop stages, and field operations across multiple levels (field, zone, crop). These data not only improve fertigation efficiency but also support compliance with the Italian Guidelines for Agrivoltaic Systems (MASE), including metrics such as LAOR – Land Area Occupation Ratio, limited to 40% photovoltaic coverage [4]. These national directives could serve as a foundation for international standards, aligning with the recommendations of the International Energy Agency (IEA PVPS Task 13) [5]. In this framework, SolarFertigation acts as a strategic enabling technology, making these principles operational and scalable. Additionally, the cloud architecture supports future integration of photovoltaic production monitoring, including energy yield, inverter health, and solar panel orientation [6]. Field validation of the system demonstrated its effectiveness in terms of LoRaWAN signal coverage and data transmission reliability, even in the presence of structural obstacles. Moreover, experimental field campaigns revealed a significant reduction in solar radiation and light intensity indices beneath the agrivoltaic modules, with implications on crop performance that will be discussed in the following sections, including a general reduction in yield under photovoltaic panels, which in some cases exceeded 80% compared to open-field conditions. This paper presents the system's architecture and outlines future scenarios for intelligent and scalable farm management aligned with ecological transition objectives.

3.1 Introduction

In recent years, there has been a growing convergence between technological innovation, precision agriculture, and renewable energy. This trend is driven by the urgent need to adopt sustainable agricultural practices and to implement an energy transition that aligns with environmental protection. Within this framework, agrivoltaic systems have emerged as a promising solution for the synergistic valorization of agricultural land and energy production, promoting a multifunctional and resilient use of the territory.

However, the integrated management of agricultural activities and photovoltaic energy generation introduces complex challenges, both agronomic and technical. To ensure that these systems deliver real benefits, it is essential to guarantee the continuity of cultivation, maintain optimal environmental conditions for crops, and promote the efficient use of water and fertilizers [7], while also monitoring and mitigating the impact of solar panels on microclimate and productivity. It is therefore crucial to have technological tools capable of integrated monitoring, control, and optimization of operations.

A concrete response to these challenges is provided by SolarFertigation, a smart fertigation system powered by solar energy. It is designed to integrate agricultural equipment, sensor networks, and a centralized, scalable software platform. SolarFertigation enables the automated planning and monitoring of irrigation and nutrient delivery, dynamically adapting to environmental and agronomic conditions [1]. This contribution presents the system architecture, with a focus on its data collection capabilities, intelligent automation, and interoperability with regulatory requirements specific to advanced agrivoltaic systems. The potential of the cloud-based platform will also be explored, along with its configurable automation models and adaptability to various regulatory scenarios, with particular attention to the Italian Guidelines and the broader goal of establishing an international standard.

3.2 System Architecture of SolarFertigation

SolarFertigation is designed as a modular and scalable system, capable of integrating distributed field devices with a centralized Amazon Web Services [8] cloud-based management platform. The SolarFertigation system employs LoRaWAN communication [9] between distributed sensor nodes and the central unit, which is responsible for the automated management of fertigation. Both devices are based on microcontrollers with integrated sub-GHz LoRa transceivers. The sensor nodes are deployed in open-field conditions, while the central unit and the gateway are housed inside a wooden shelter, as illustrated in the system's architectural diagram (Figure 1). Two gateway configurations were tested for the LoRaWAN connection:

- a low-power indoor unit with integrated antenna, suitable for cost-effective scenarios;

- a high-performance unit with external antenna and enhanced receiver sensitivity, intended for large-scale deployments.

Based on standard LoRaWAN parameters (868 MHz frequency, 14 dBm transmission power, spreading factor SF7–SF12), field tests demonstrated reliable coverage ranging from 600 to 1500 meters, depending on environmental conditions and gateway configuration. Under optimal line-of-sight conditions, the system achieved a 98% transmission success rate over distances exceeding 1 km.

The results were obtained through dedicated field measurement campaigns, by analyzing the packets received by the gateway and monitoring the radio link quality between the sensor nodes and the central unit in various operational scenarios.

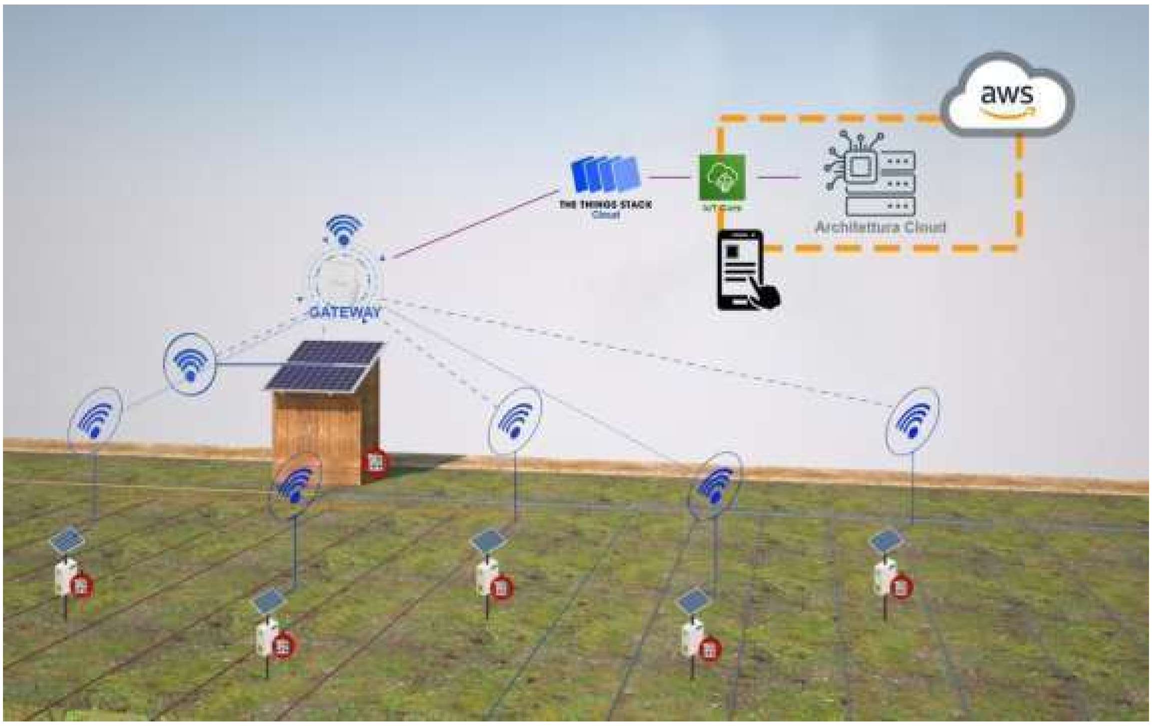

Fig. 1. SolarFertigation general hardware and cloud architecture.

3.2.1. Sensor Nodes: Distributed and Unified Network

The sensor nodes monitor agro-environmental conditions in real time. Installed in various zones of the field, they form a mesh network adaptable to the farm layout or application type. Each node [1] can be equipped with sensors for:

- soil moisture and temperature,
- air temperature and humidity,
- electrical conductivity (EC),
- pH,
- solar radiation,

- wind,
- precipitation,
- nutrient levels in soil and solution.

Each node uses the same microcontroller as the central units, ensuring maintenance simplicity, expandability, and uniformity across the network. The data transmission interval is customizable via web app. The data are sent to the gateway, which routes them to the cloud platform for storage, visualization, and analysis.

3.2.2. Control Unit: Dosing, Mixing, and Monitoring

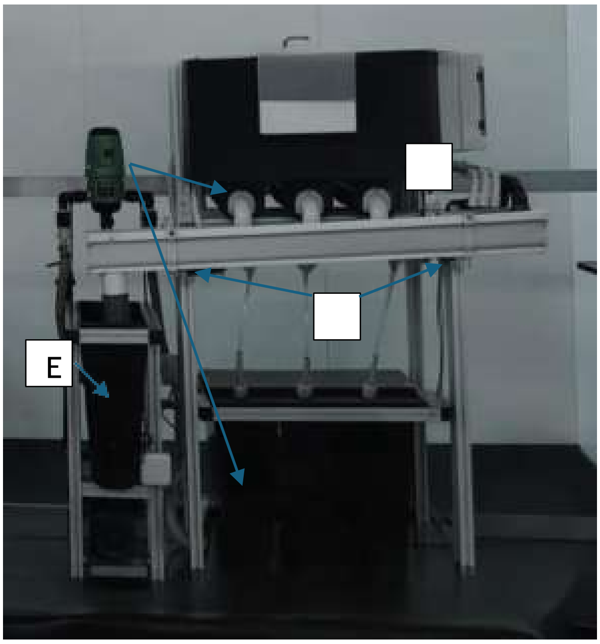

Fig. 2. Front view of the SolarFertigation dosing system unit in a modular configuration, with an aluminum profile structure. Top: drawers for solid (granular or powdered) fertilizers; bottom: liquid fertilizer modules with electronic control. Left: suction module, mixing tank, and mixing pump. The modularity allows management of up to 6 different fertilizers per event, ensuring flexibility and precision in nutrient delivery.

The control unit is the operational core of the system [1], responsible for preparing and distributing fertigation solutions. Each unit is equipped with a dosing and mixing system as illustrated in Figure 1, including:

- drawers for solid (granular/powdered) and liquid fertilizers [Fig.2 A],
- independent motors and peristaltic pumps for dosing,
- load cells (±50g precision) for direct weight measurement [Fig.2 B],

- controlled release vessel for liquid fertilizers (2L capacity) [Fig.2 C],
- collection gutter [Fig.2 D],
- washing and mixing system [Fig.2 E].

The dosing process unfolds in two stages:

1. Controlled dosage of fertilizer, measured via load cells;
2. Transfer to the mixing tank using dedicated water jets, ensuring complete gutter flushing and homogeneous mixing.

This setup enables not only accurate monitoring of the applied quantities but also automatic diagnosis of errors (e.g., empty containers or failed release), through integrated alarm logic.

Traditional fertigation systems rely primarily on low-cost volumetric dosing, often using Venturi injectors or manual control, as outlined in FAO guidelines for small-scale farmers [10]. Most automated fertigation systems rely on volumetric dosing using Venturi injectors or proportional pumps, with preset configurations and limited monitoring [11,12]. In contrast, SolarFertigation introduces a weight-based dosing system driven by cloud logic, overcoming the limitations of manual or semi-automated setups.

3.2.3 Cloud-Based Automatic Nutrient Optimization

A distinctive feature of the SolarFertigation system is the ability for users to configure fertigation events directly through a web app by defining the target nutritional composition (e.g., N, P_2O_5, K_2O, CaO, MgO), independently of the type or brand of fertilizers loaded into the control unit drawers.

The generation of the optimal mixture is performed by a mixed-integer linear programming (MILP) algorithm running in the cloud, which calculates the quantities of each available fertilizer based on:

- the declared chemical composition of each product,
- the remaining availability in each drawer,
- solubility and chemical compatibility,
- and the maximum dosage allowed per fertigation event.

Users can replace the fertilizers in the drawers without needing to recalculate doses: the system automatically recalculates the new optimal combination while maintaining the desired nutritional profile. This approach standardizes nutrient management logic independently of commercial products, simplifying operations and improving interoperability.

An additional advantage is the system's ability to store the actual distribution data in terms of active nutrients (e.g., grams of N, P_2O_5, K_2O per zone and event). This allows for direct correlation with agronomic and environmental variables such as crop type, phenological stage, location, and season building a structured data foundation that supports historical analysis and agronomic calibration, reporting and traceability and the development of predictive, data-driven models.

From a system perspective, this abstraction process feeds into an agricultural data lake, aggregating environmental, operational, and decision-making data. This enables the use of data analytics and machine learning techniques to optimize fertigation plans over time and generate increasingly accurate and context- aware automated events.

In existing systems, fertigation strategies are often limited to threshold-based adjustments of EC or pH [13], without dynamic optimization logic. SolarFertigation stands out for its ability to enable cognitive automation
[14] through the native integration of hardware, data, and intelligent algorithms.

3.2.3. Hydraulic and Energy Configurations of the Central Units

Fig. 3. Front view of the central unit in standalone configuration with integrated pump. Top: logic panel with microcontroller, power supply, and relay system. Bottom: hydraulic manifold with zone solenoid valves, pressure gauges, and impulse water meter.

The SolarFertigation central unit is engineered to adapt to different operational configurations based on field size, water availability, and energy supply strategy. Structurally, each central unit can be customized with:

- up to 10 fertilizer drawers (solid or liquid),
- up to 10 irrigation zones managed through independent solenoid valves.

A real-world implementation of the logic and hydraulic section of a central unit with an integrated pump and a 4-zone manifold is shown in Figure 3.

Two main hydraulic-energy architectures are currently supported, enabling scalable deployment of the platform across agricultural A and B scenarios.

A. Standalone Configuration with Integrated Pump

In this configuration, the central unit includes an internal distribution pump powered directly by its own photovoltaic system. The locally stored solar energy can support:

- 4–5 hours of daily autonomous operation,
- coverage of plots up to approximately 2000 m²,
- fully off-grid use, ideal for remote locations or fields without pre-existing infrastructure.

This setup maximizes the system's "smart & solar" concept, offering an autonomous and ecologically sustainable fertigation model, particularly suited for small to medium-sized farms.

B. Configuration on Pressurized External Line

In this scenario, the central unit is installed on a pre-pressurized irrigation line maintained by an external system (well, tank, or public network). Locally generated solar energy is then used exclusively for powering solenoid valves and control logic, significantly reducing the unit's energy requirements.

This configuration allows:

- greater energy availability (up to continuous operation),
- parallel deployment of multiple central units along the same mainline,
- effective adaptation to large-scale installations or farms with existing water infrastructure.

Although the pressure system's power supply is not inherently renewable, this limitation can be overcome in agrivoltaic contexts through on-farm photovoltaic integration.

3.3 Automation Models for Fertigation

The **SolarFertigation** system is designed to offer users a wide range of automation strategies, scalable according to the technological level of the farm and the degree of digitalization of the field. All automation logic is managed through the cloud platform and is powered by the data collected from sensor nodes and central units.

3.3.1. Guided Manual Programming

In the basic mode, users can configure fertigation events by specifying:

- the target crop,

- desired nutritional composition (e.g., N-P-K),
- irrigation zone,
- schedule and duration,
- maximum volume or concentration thresholds.

This approach, widely used in **precision irrigation systems** [15], enables gradual digital adoption even in low-tech contexts, while maintaining full user control over the fertigation plan.

3.3.2. Conditional Automation: Environmental Thresholds and Logical Rules

The second level of automation is based on customizable *if–then* rules, which can trigger, modify, or cancel fertigation events based on environmental thresholds or operational conditions. Example rules include:

- "Irrigate only if soil moisture < 20%" (to avoid overwatering),
- "Suspend irrigation if rainfall forecast > 5 mm in the next 12 hours",
- "Block fertigation if EC > 3.5 mS/cm or pH < 5.8",
- "Irrigate only between 07:00 and 11:00 if wind speed < 3 m/s",
- "Cancel pre-irrigation if soil moisture > 15%".

These logic-driven strategies, widely applied in smart farming contexts [14], are executed in real-time via the cloud, using live data from the field.

3.3.3. Agronomic Automation: Phenological Logic and Crop Calendar

A more advanced level of automation leverages **agronomic logic**, enabling fertigation plans based on:

- the phenological stage (e.g., germination, growth, flowering, fruiting),
- the season (e.g., reduced irrigation at the end of the cycle),
- the crop × zone combination stored in the cloud.

For instance, a lettuce crop in zone 3 can follow a predefined plan of 7 fertigation events during vegetative growth and reduced dosages during flowering. This strategy is inspired by Variable Rate Irrigation (VRI) techniques and enhances agronomic efficiency [16].

3.3.4. Predictive Automation and Artificial Intelligence

Thanks to its modular structure and continuous data collection, SolarFertigation is prepared for the integration of advanced predictive models, including:

- regression models to estimate water and nutrient demand,
- recurrent neural networks (RNNs) to forecast future events based on historical data (e.g., daily zone consumption),

- expert systems combining fuzzy logic and conditional rules to emulate agronomist decision-making.

Recent studies show that AI-based fertigation can increase crop yields and reduce fertilizer use [15,18]. The platform is designed to leverage such models using its internal data lake, which aggregates structured information by crop, zone, season, and environmental conditions.

This evolution toward a cognitive platform enables a shift from a prescriptive to a predictive approach, where fertigation events are automatically generated and dynamically adapted to real field conditions.

4 Integration with Agrivoltaic Systems

The SolarFertigation system is designed for synergistic use with agrivoltaic systems, which combine agricultural production with photovoltaic energy generation on the same cultivated land. The aim is to support the ecological transition through a multifunctional and optimized use of available agricultural surfaces.

Fig. 4 Rendering of the integrated APV with SolarFertigation system

Fig. 5 Experimental campaign in an agrivoltaic field (Province of Taranto, Italy)

Figure 4 presents a 3D rendering of the integration between the agrivoltaic installation and the SolarFertigation system. This integration was validated through an experimental field campaign conducted at a commercial photovoltaic plant adapted to an agrivoltaic configuration in the Province of Taranto (Italy) (Fig.5), where the complete system architecture was implemented, including a central fertigation unit and a network of four sensor nodes.

4.1 Experimental Method and Field Layout

The field trials included two crop cycles—winter (lettuce) and summer-autumn (pepper and chili pepper)— under three cultivation conditions:

1. Open-field cultivation (control);
2. Cultivation in the area directly beneath the photovoltaic panels (proximal zone);
3. Cultivation in the inter-row zone, partially shaded between PV strings (distal zone).

Data were collected using the SolarFertigation sensor network and in-field agronomic measurements. The system managed in real time the recording, transmission, and cloud storage of the following parameters:

- solar radiation,
- air temperature and relative humidity,
- wind conditions,
- volume of distributed water (in liters),
- quantity and type of fertilizers applied (in grams),
- fertigation events (geo-referenced per crop and zone).

4.2 Collected Data and Results

During the summer and autumn cycles, the system recorded:

- a 45–50% reduction in solar radiation under the photovoltaic modules compared to the open field (e.g., from 20 to 10 n for pepper);
- over 60 automatic fertigation events monitored and recorded, with adaptive adjustment of water volumes based on real-time temperature and humidity;
- application of simple liquid fertilizers (e.g., calcium nitrate, monopotassium phosphate), dosed precisely through proportional pumps, and managed by the system based on crop calendars and phenology;
- an average distribution of 900 liters of water per fertigation or irrigation cycle, with adaptive variations in response to local microclimate.

Preliminary agronomic results show a general reduction in crop yield in plots cultivated under photovoltaic panels. The extent of reduction varied from 30% to 87% according to the position within the system (proximal or distal zone) and the type of crop.

It is important to note that the field test was not designed to manage different zones independently. Water and fertilizers were applied uniformly across all plots, regardless of local microclimate. This methodological choice allowed for the isolation and quantification of the direct effect of shading from photovoltaic structures on crop yield, without introducing management-related variables.

The environmental and agronomic data collected via SolarFertigation proved essential to identifying critical areas and sensitive environmental parameters (e.g., radiation, humidity, temperature thresholds) most affecting productivity. These insights now form the basis for developing targeted strategies to:

- adapt irrigation and fertilization management by crop zone,
- optimize the interaction between shading and plant development,
- improve overall productivity in agrivoltaic systems.

4.3 Compliance and Interoperability

SolarFertigation is compliant by design with the Italian Guidelines for Agrivoltaic Systems issued by the Ministry for the Environment and Energy Security (MASE) [4,10], which require:

- traceability of agricultural operations and water/fertilizer volumes,
- adaptability of systems to coverage constraints (e.g., LAOR ≤ 40%),
- and continuous monitoring of agronomic parameters.

Thanks to its modular, cloud-based architecture, SolarFertigation enables:

- detailed recording of activities per crop and zone,
- extraction of standardized reports for regulatory audits,
- direct integration with photovoltaic systems, thanks to off-grid operation capabilities and optimized self-consumption.

Recent developments in agrivoltaic technology focus on dynamic panel orientation systems ("dynamic agrivoltaics"), which adjust the tilt angle of the solar panels based on crop and weather conditions to optimize both agricultural and energy productivity. These solutions, already tested at industrial scale [19], can: reduce water and thermal stress on crops, increase sunlight use efficiency (Light Productivity Factor) [20,21] and enhance energy-agriculture balance during critical periods.

SolarFertigation is ready to interface with such dynamic systems, offering: real-time cloud-based access to environmental and agronomic models, synchronization of fertigation events with shading strategies, and potential integration with inverter and solar tracker controllers.

This unified architecture enables synergistic agro-energy management, where agricultural and energy data can be co-optimized within a single digital platform.

5 Conclusions

SolarFertigation was not developed as a closed system, but as an open and adaptive platform that integrates agricultural hardware, distributed sensors, cloud architectures, and decision-making logic aimed at sustainability. Throughout its development, the project has followed a clear direction: transforming fertigation from a technical process into a strategic tool—not only to improve the nutritional efficiency of crops, but also to make every cultivated hectare a digital, sensitive, and responsive space.

The adopted approach (from nutrient mix optimization to integrated energy management) demonstrates that it is possible to design systems that are compliance-ready, modular, scalable, and above all agronomically focused. Systems that communicate with the field, with water resources, with the sun, and with data.

Looking ahead, the real challenge is no longer just to monitor, but to anticipate. Not merely to irrigate, but to know when not to. Not only to adapt the system to the field, but to let the field express itself through data. In this context, SolarFertigation positions itself as an enabling technology for agriculture that is not only more precise, but also more intelligent, more ecological, and more autonomous. Not just a system, but a bridge between land and cloud, between energy and cultivation, between knowledge and automation.

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Chapter 4

Comparative Evaluation of Semi-Transparent Monocrystalline Silicon and Cadmium Telluride Photovoltaics for Tomato Cultivation in Mediterranean Agrivoltaic Greenhouses

This chapter has been adapted from a manuscript under revision on the journal Scientia Horticulturae at the moment of the dissertation writing:

*Virginia Hernández, Fulgencio Contreras López, Carlos Toledo, **Vincenzo Tucci**, Ricardo Abadía, Alicia Sánchez, Pilar Hellín, Elia Molina, José Fenoll, Pilar Flores. Assessment of Semi-Transparent Photovoltaic Technology for Tomato Cultivation in Agrivoltaic Greenhouses. Submitted to Scientia Horticulturae, under review.*

Abstract:

Among economically significant greenhouse crops in arid and semi-arid regions, tomato is particularly relevant. This study systematically compares four greenhouses: control (C), shading net (SC), and two commercially available semi-transparent PV technologies, monocrystalline silicon (PV-Si) and cadmium telluride thin-film (PV-TF), under identical greenhouse conditions. The effects of each configuration on light availability, microclimate, and yield were evaluated across two growing seasons. During the winter–spring cycle, only the C and PV-Si greenhouses maintained daily light integral (DLI) values above the minimum threshold required for optimal crop development. Despite a similar number of fruits, the PV-Si greenhouse produced fruits with a mean weight 25% higher than the control, which was attributed to more favourable nighttime air temperatures and higher soil moisture. In the spring–summer cycle, although all the treatments exceeded the critical DLI threshold, photosynthetic activity in the SC and PV-TF greenhouses was restricted during key periods of the photoperiod, resulting in reduced yields. In contrast, the checkerboard configuration of the PV-Si panels allowed sufficient light transmission throughout both cycles, preventing shade-avoidance responses and maintaining yield levels comparable to or exceeding the control. The PV-Si system generated a total of 726.8 kWh over the study period, outperforming the PV-TF system. PV-induced shading moderated springtime temperature fluctuations but was insufficient to mitigate peak summer temperatures. Overall, the PV-Si system effectively balanced solar radiation management, thermal regulation, and energy production, demonstrating its potential as a suitable technology for agrivoltaic applications in regions with challenging climatic conditions.

Keywords: PV panels, Agrivoltaics, Agrophotovoltaics, AV, Crop Yield, Plant growth, Photosynthesis, Sustainability, Solar energy.

4.1 Introduction

The growing global demand for food and energy has intensified the need for sustainable solutions that optimise land use. International organisations such as the Intergovernmental Panel on Climate Change (IPCC) or the International Renewable Energy Agency (IRENA) recognise the role of renewable energy, particularly solar power, in strengthening food security and climate resilience, in line with the United Nations' Sustainable Development Goals (SDG) and the Paris Agreement at the UN Climate Change Conference (COP21) [1,2]. Agrivoltaic (AV) systems, which integrate photovoltaic (PV) technologies into agricultural production, enable the dual use of land for both crop cultivation and solar energy generation [3,4]. This approach enhances resource efficiency, improving agricultural productivity and economic performance while supporting energy diversification, rural development, and the mitigation of land-use conflicts [5,6]. Within this framework, AV greenhouses represent a specific category where PV modules are incorporated either into the primary structure or within the interior of the greenhouse itself [7]. The synergistic advantages of greenhouse cultivation, coupled with PV energy production, position these systems as an innovative and sustain able solution in agriculture. For highly technological greenhouses, the integration of PV energy is particularly impactful, as it provides power for essential agricultural operations, including ventilation, irrigation, temperature regulation (cooling and heating), and the operation of vehicles and machinery [8]. Additionally, when the PV infrastructure is designed to produce electricity exceeding farm consumption needs, these systems can generate supplementary income through the sale of surplus electricity. Among the economically significant crops grown in greenhouses in arid and semi-arid climates, tomato is particularly relevant. Approximately 500,000 hectares worldwide are dedicated to greenhouse tomato production, highlighting the importance of assessing its integration into AV greenhouses.

For these AV systems, radiation is a crucial factor, as shading caused by opaque or semi-transparent photovoltaic modules can influence crop performance in either beneficial or detrimental ways [9]. Fundamentally, PV energy generation inherently competes with crops, as both rely on sunlight; plants for photosynthesis and PV systems for electricity production. Besides reducing the amount of solar radiation reaching the plants, photovoltaic modules can also influence the greenhouse microclimate by altering temperature and relative humidity levels. These microclimatic changes depend on factors such as location and season, as well as the presence of ventilation systems [10]. As a result of these environmental modifications, alterations in plant morphology and physiology, as well as changes in the incidence of pests and diseases, may occur [11], potentially influencing crop yield positively or negatively [12,13].

The economic viability of the PV infrastructure without compromising agricultural productivity primarily depends on the solar radiation at the greenhouse site and the light requirements of the cultivated crop. A particularly relevant variable is the daily light integral (DLI), which quantifies the number of photosynthetically active photons (400–700 nm, PAR) received by a specific area over 24 hours [14]. Based on these DLI requirements, horticultural crops are classified as high light-demanding (DLI > 30 mol m^{-2} day^{-1}), medium light-demanding (10–20 mol m^{-2} day^{-1}), or low light-demanding (5–10 mol m^{-2} day^{-1}) [15]. As a crop with high light requirements, tomato needs determining the optimal PV coverage ratio and shading distribution to maximise energy generation without compromising yield [16]. However, these calculations are often complex, as plant light requirements are also influenced by factors such as spectral alterations, spatial light distribution, internal microclimatic conditions, and the crop phenological stage [17–19]. In fact, beyond the global coverage index, the configuration of PV panel systems and their shading distribution are critical factors influencing both electricity production and crop development in AV systems. Previous studies have shown that semi-transparent PV modules can enhance light homogeneity within greenhouses and improve crop yields [20,21]. Semi-transparent PV modules can be designed using transparent encapsulations and (i) spacing opaque silicon solar cells, or (ii) employing second- or third-generation thin-film PV technologies (PV-TF) such as cadmium telluride (CdTe), organic photovoltaics (OPV), or dye-sensitised solar cells (DSSC). Among these options, crystalline silicon modules, and to a lesser extent, second-generation technologies (particularly thin-film PV-TF), are currently the most commercially established due to their efficiency and durability. Although OPV and DSSC modules hold promise for AV systems by enabling selective transparency to optimise photosynthetically active radiation (PAR) transmission, their adoption remains limited due to lower efficiency and durability compared to established technologies [22,23].

Despite growing interest in semi-transparent PV integration, information remains scarce. Previous studies have either developed modelling frameworks linking spectral performance with crop photosynthesis [24] or conducted greenhouse experiments involving multiple PV technologies within a shared structure [21]. However, there is still a need for empirical data, particularly for thin-film technologies, and for detailed crop-response analyses under controlled conditions [25,26]. In this context, the present study provides a novel experimental contribution by directly comparing two established semi-transparent PV technologies under greenhouse conditions. The use of four independent, identical greenhouses enables a robust assessment of their respective impacts on microclimate, crop performance, and energy generation. Specifically, the study aimed to evaluate the agronomic and energy performance of two commercially available semi-transparent PV technologies (PV-Si and PV-TF), with distinct light transmission patterns, in comparison with control and shading-net treatments.

4.2 Material and methods

Pilot greenhouses

The study was conducted at the Instituto Murciano de Investigación y Desarrollo Agrario y Medioambiental (IMIDA) in La Alberca, Murcia, Spain. This region has a semi-arid Mediterranean climate, with mean summer and winter temperatures of 30 °C and 12 °C, respectively, and 300 mm annual rainfall, supporting agriculture and solar energy. Four experimental greenhouses constructed from polyethylene (Celloflex 4D 5000) were built with dimensions of 3.90 m length × 2.00 m width × 3.10 m height. The materials under evaluation were installed on the roof and south façade of each greenhouse. In the control greenhouse (C), the same polyethylene film used for the rest of the structure was applied. For the shading control greenhouse (SC), the same polyethylene film was used, but an additional shading net was applied to the designated zones. The two PV pilot greenhouses utilised first- and second-generation PV technologies. One greenhouse incorporated monofacial silicon PV modules with 50% transparency (Brite®), achieved by spacing the solar cells within a glass-glass encapsulation (PV-Si). The other greenhouse employed thin-film cadmium telluride (CdTe) PV technology, also with 50% transparency (Polysolar®), achieved by reducing the thickness of the absorbing layer (PV-TF). The PV coverage ratio, calculated as the sum of the roof and façade PV surface areas divided by the total greenhouse envelope area, was approximately 40%, with 20% corresponding to the roof and 20% to the south façade. All four greenhouses were equipped with a roof and front ventilation to ensure an adequate air exchange rate and to regulate the greenhouse's temperature and humidity (Figure 1).

Environmental Monitoring

The microclimatic conditions inside each pilot greenhouse were monitored at 2-minute intervals. The measurements include air temperature and relative humidity (Inta Crop Technology), solar irradiance (Hukseflux SR05-D2A2), and photosynthetically active radiation (400-700 nm, PAR) (Apogee SQ-521) (Supplementary Table S1). Additionally, soil temperature and humidity were measured at 5-minute intervals and depths ranging from 10 to 60 cm in 10-cm increments (Sentek Drill & Drop 60). The accumulated daily availability of PAR, expressed as the daily light integral (DLI, mol m^{-2} day^{-1}), was used as an indicator of the irradiance received by the crop. DLI was calculated using the trapezoidal rule from the daily values of photosynthetic photon flux density (PPFD, µmol m^{-2} s^{1}). Similarly, air temperature and humidity were analysed by calculating daily accumulated values, expressed as daily temperature integral (DTI) and daily humidity integral (DHI). PAR data collected at the canopy level from 11:30 a.m. to 1:30 p.m. on a sunny day were used to calculate the coefficient of variation (CV) of

PPFD, quantifying the temporal variation in light caused by solar movement and shading from the PV panels. In addition, PPFD was measured at multiple canopy points (15 points within a 1 m² area) at 12:00 p.m. to evaluate spatial variation across the canopy, enabling an objective comparison of the light environments among all greenhouses.

A further analysis was conducted by categorising temperature and humidity into optimal, low, and high levels and assessing the duration of each level throughout the day. This approach allowed for the calculation of daily optimal temperature and humidity integrals (DOTI and DOHI), daily lower limit integrals for temperature and humidity (DLTI and DLHI), daily higher limit integrals for temperature and humidity (DHTI and DHHI) and daily duration at each level (in hours): optimal ranges (tOT and tOH), lower limits (tLT and tLH), and higher limits (tHT and tHH). For tomato cultivation, the optimal air temperature was defined to be between 15 and 25 °C, and optimal relative humidity between 60% and 80%. High limits were set at temperatures above 30 °C and relative humidity above 90%, while low limits were defined as temperatures below 5 °C and relative humidity below 50% [27,28].

Photovoltaic Design and Monitoring

In the PV greenhouses, each system was equipped with 18 monofacial PV modules, comprising 9 units installed on the roof and 9 units on the façade. The PV modules had a glass-glass encapsulation and the same dimensions. The PV-Si modules had a nominal power of 59 W under standard test conditions (STC), while the PV-TF modules provided 40 W. Therefore, the total capacity for each system was 1.06 kWp and 0.72 kWp (DC), respectively. Both experimental greenhouses were grid-connected PV systems; therefore, they were equipped with single-phase 2 kW PV inverters that had multiple maximum power point tracking (MPPT) capabilities. In the PV-Si greenhouse, the inverter was configured with 2 input strings: one for the PV modules located on the façade and another for those on the roof. In the PV-TF greenhouse, the inverter had 4 input strings, arranged with 2 strings for the roof PV modules and 2 strings for the façade PV modules. The energy data used in our analysis were collected directly from the PV inverter (technical specifications are provided in Table S2) and therefore correspond to AC output measurements. Data were recorded at 15-minute intervals for PV-Si and at 5-minute intervals for PV-TF. The energy output from both PV greenhouses was assessed for 91 days in each cycle, differentiating between cycles and the contribution from the façade and roof. The energy production results were obtained from January 19^{h} to April 18th, 2024 (cycle 1) and from April 30th to July 31th, 2024 (cycle 2). The latter excluded data on May 13 and 14, 2024, due to maintenance work.

Experimental Design and Tomato Crop Evaluation

Two tomato cultivation seasons were measured: a winter-spring season (cycle 1; December 19th, 2023, to April 18th, 2024; 120 days) and a spring-summer season (cycle 2; April 30th, 2024, to July 31st, 2024; 98 days). In each greenhouse, tomato plants (Solanum lycopersicum cv Optima) were arranged in three rows with a planting spacing of 0.35 m between plants and 0.7 m between rows. Irrigation was applied according to the crop's needs, as determined by data from the soil probes, and was uniformly distributed across all four greenhouses. Fertigation was carried out using a nutrient solution which concentration and volume were adjusted according to climatic conditions and the phenological stage of the crop. In the first cycle, the total dose of essential macronutrients: 136 N, 43.2 P, 165 K, 112 Ca, 17 Mg and 24 S (kg ha^{-1}) were incorporated. In the second cycle, the total doses were 208 N, 92.5 P, 472 K, 246 Ca, 37 Mg and 49 S (kg ha^{-1}). Regarding water management, an irrigation dose of 35 L $plant^{-1}$ and 77 L $plant^{-1}$ was established in the first and second cycle, respectively.

Tomato plant growth was evaluated over two growing seasons by measuring biomass production, including shoot weight and height, leaf number and area, as well as fruit number and mean fruit weight. Seven plants per greenhouse were sampled independently, with those in the central row selected to minimise edge effects, and each plant was considered a replicate. Fully developed fruits were harvested throughout the growing season, and any remaining fruits were collected at the end of the cycle. The mean fruit weight was calculated from fully developed fruits. Additionally, during the second growing season, coinciding with the typical tomato growing period at the study site, cumulative yield was evaluated by sampling fruits at 64, 66, 71, 74, 77, 78, 81, 91 and 93 days after transplanting (DAT). Plant gas exchange parameters, including the net CO_2 assimilation rate (net photosynthesis, A_N) and stomatal conductance (g_s), were measured at 37 DAT using a LI-6800 portable photosynthesis system equipped with a broadleaf chamber (6 cm^2). Measurements were taken on two young, fully expanded leaves from each of the seven plants selected per greenhouse, resulting in a total of 14 measurements per treatment. All measurements were conducted at a reference CO_2 concentration of 420 µmol mol^{-1} and under a saturating photosynthetic photon flux of 1200 µmol m^{-2} s^{-1}.

All data were analysed using IBM SPSS Advanced Statistics (version 25.0). Before analysis, the data were checked for normality and homogeneity of variance using the Shapiro-Wilk and Levene's tests, respectively. Differences between treatments were assessed using one-way analysis of variance (ANOVA). When significant differences were detected ($p<0.05$), means were compared using the Duncan's post hoc test.

4.3 Results

Energy performance

The PV-Si system outperformed the PV-TF system in terms of total energy generation across both cycles, yielding higher average daily and cumulative energy outputs. Specifically, the PV-Si technology generated an average daily energy production of 3.92 kWh day^{-1} in cycle 1 and 4.07 kWh day^{-1} in cycle 2 (Figure 2). For the PV-TF technology, these values were 2.58 kWh day^{-1} and 2.79 kWh day^{-1}, respectively. Over the 182 days, the total energy production from both cycles amounted to 726.8 kWh for PV-Si and 488.4 kWh for PV-TF. From the total generation in each case, the façade-integrated PV-Si system contributed 44% (320.8 kWh), while PV-TF accounted for 33% (164.2 kWh). Despite this difference in total production, the specific yields of both systems were very similar, with values of 685.7 kWh kWp^{-1} for PV-Si and 678.3 kWh kWp^{-1} for PV-TF. This similarity is expected, as both PV greenhouses operate under the same conditions: they are located in the same location with identical incident radiation and have the same design and orientation. Therefore, when assessing energy performance, it is more appropriate to consider total energy production (kWh/m^2). In this case, since both systems cover the same PV area (almost 13 m^2 per greenhouse, consisting of 18 modules of 1200 × 600 mm each; details in Table S2), the previously described kWh values can be used as a reference.

Environmental Parameters

The evaluated PV technologies showed significant differences in the distribution and intensity of radiation within the greenhouses. The PAR radiation profile corresponding to a sunny day (July 5th, 2024) shows the differences in the distribution and intensity of the radiation received by plants grown under the control greenhouses with and without shading, and the different PV technologies (Figure 3). Under the PV-Si system, the checkerboard arrangement of opaque and transparent panels generated a distinctive, discontinuous PAR profile characterised by intermittent, abrupt increases at specific points. Instead of producing a homogeneous shade, this configuration created alternating zones of light and shadow within the same plant, so that some leaves remained exposed to direct sunlight while others experienced reduced irradiance. In contrast, the PV-TF system produced a more uniform shading effect, resulting in lower and more evenly distributed PAR. This pattern was reflected in the markedly higher variability observed under PV-Si, with spatial heterogeneity and temporal fluctuation of 41.6% and 62.3% respectively. These values far exceed those recorded under PV-TF (13.8% and 14.3%), shading (10.9% and 9.9%) and control (5.8% and 11.5%) conditions.

Although PV-Si technology rendered 50% of the PV panel surface opaque, the specific panel arrangement and the higher transmittance of the encapsulating glass compared to the control covering material (polyethylene) resulted in a reduction of the average daily light integral (DLI) by 26% and 28% relative to the control in cycles 1 and 2, respectively (Table 1). In contrast, the reductions in DLI observed in semi-transparent crystalline silicon (SC) greenhouses were 54% and 50%, while those in cadmium telluride (PV-TF) greenhouses were 56% and 52% for cycles 1 and 2, respectively. During the first cycle, only the C and PV-Si greenhouses achieved an average DLI value within the range considered adequate for crop development (15-30 $mol \cdot m^{-2} \cdot day^{-1}$). In contrast, during the second cycle, all greenhouses exhibited average DLI values exceeding 15 $mol \cdot m^{-2} \cdot day^{-1}$. During the first cycle, the maximum DLI in the C and PV-Si greenhouses was approximately 2.3 times higher than in the SC and

PV-TF greenhouses. Although the minimum DLI fell below the adequate threshold in all cases, this occurred on only 9 days in the C greenhouse, compared to 35 days in the PV-Si and 66 days in both the SC and PV-TF greenhouses (Supplementary Figure S1). During the second cycle, DLI_{max} values exceeded 20 mol·m⁻²·day⁻¹ in all greenhouses. DLI_{min} in the C greenhouse fell within the adequate range, it was near the lower limit in the SC and PV-Si greenhouses, and was slightly below the threshold in the PV-TF greenhouse. Moreover, the DLI in the C greenhouse never dropped below 15 mol m^{-2} day^{-1}, whereas in the SC, PV-Si, and PV-TF greenhouses, it fell below this threshold on 5, 1, and 18 days, respectively (Supplementary Figure S2).

Regarding air temperature, during the first cycle, greenhouse C had the lowest average duration within the optimal range (15-25 °C) and showed a longer duration of both high temperature (above 30 °C) and low temperature (below 5 °C) compared to the other greenhouses (Table 2). The higher maximum air temperature observed in greenhouse C relative to the other greenhouses was especially evident during the initial period of cycle 1 (Supplementary Figure S3). In addition, the lower minimum temperature during the night observed in this greenhouse was consistently observed throughout the first cycle (Supplementary Figure S4). The increase in the maximum air temperature observed in greenhouse C, compared to the others, was also reflected in the average soil temperature, which was 9-15 % higher than that recorded in the other greenhouses (Table 3). The increase in temperature observed in the control was significantly evident during the daytime, whereas at night it was only noticeable during the final stage of the growing cycle (Supplementary Figures S5 and S6). Along with this temperature increase, the average, maximum, and minimum soil humidity levels in greenhouse C were lower than those in the other greenhouses, despite identical irrigation management (dose and frequency) across all of them (Table 3). In contrast to the first cycle, greenhouse C exhibited the longest average daily duration within the optimal temperature range during the second cycle (Table 2 and Supplementary Figure S7). Furthermore, during this cycle, the temperature did not fall below the optimal lower limit (15 °C) in any of the greenhouses, although PV-Si and PV-TF were on average 0.7 and 0.5 h higher than the control at temperatures above the optimal temperature per day (Table 2 and Supplementary Figure S8). As observed in the first cycle, during the second cycle the maximum and minimum soil temperatures in the control greenhouse exceeded those recorded in the other greenhouses, particularly during the daytime phase of the photoperiod Supplementary Figures S9 and S10). The air relative humidity remained below the optimal range (60–80%) for an average duration of approximately 10 h during the winter–spring cycle and 12 h during the spring–summer cycle across all four greenhouse types (Table 4). However, the average duration within the optimal range was slightly higher in greenhouses equipped with PV technologies (PV-Si and PV-TF) compared with C and SC greenhouses in both cultivation cycles.

Humidity values exceeding the optimal range were observed only in the control (C) greenhouse during the first cycle.

Plant development

The vegetative biomass production, measured as shoot fresh weight, was not significantly affected by the type of greenhouse in any of the crop cycles (Table 5). However, differences in plant morphology between technologies were observed, with control plants and those grown in the PV-Si greenhouse being significantly taller than those grown in the other two technologies during cycle 2. Additionally, a higher number of leaves was observed in greenhouse C (cycle 1) and PV-Si (cycle 2), and, compared to the control, higher values of leaf area were found in greenhouse PV-TF (cycles 1 and 2) and SC (cycle 1). Regarding fruit production, no significant differences were observed in the number of fruits among the shaded greenhouses (SC, PV-Si, and PV-TF) during the first cycle, although a limitation in fruit set was observed in the PV-TF greenhouse compared to the control. On the other hand, fruits grown under the PV-Si technology achieved higher mean weights than those from the other greenhouses at the first cycle. Under the less light-limiting conditions during the second cycle, no differences were observed in the mean fruit weight between technologies; however, differences were noted in fruit set, with higher fruit numbers recorded for plants grown in greenhouse C and PV-Si.

Plant gas exchange parameters

The influence of photovoltaic (PV) technologies on plant photosynthetic capacity and fruit production profile throughout the growth cycle was evaluated during cycle 2 (Table 6). Gas exchange measurements revealed a limitation in photosynthetic activity (A_N) in plants grown in SC and PV-TF greenhouses compared to the control during the early hours of the photoperiod (09:00 am). This reduced A_N was accompanied by a significantly reduced stomatal conductance (g_s) in plants grown under the PV-TF greenhouse. Plants cultivated in the PV-Si greenhouse demonstrated the highest g_s, indicating a greater potential for gas exchange compared to those grown in SC and PV-TF greenhouses. At 12:00 PM, all treatments showed an increase in A_N and g_s relative to the measurements taken at 9:00 AM. No significant differences in any gas exchange parameters were observed among the greenhouse treatments at this time point.

Yield dynamics

Greenhouses C and PV-Si exhibited very similar yield dynamics throughout the growth cycle, while SC followed a comparable pattern up until the end of July (Figure 4). In contrast, PV-TF consistently recorded the lowest accumulated yield values throughout the entire period, with increasingly significant differences compared to the other treatments by late July. During the second half of July, all treatments experienced a decrease in yield accumulation, followed by a marked increase in C and PV-Si, both exceeding 2000 g plant^{-1}. Although PV-TF also showed an increase during this period, its yield remained below that of the other technologies. Notably, the increase observed in the SC greenhouse was less pronounced than those recorded in the other greenhouses. Consequently, PV-Si attained a final yield similar to that of the control treatment, with both significantly surpassing SC and PV-TF in total yield.

4.4 Discussion

AV systems have occasionally been shown to reduce tomato yield but also improve some fruit quality attributes, while reducing irrigation demand [29,30]. However, in specific scenarios involving abiotic stress, particularly under warm and water-limited conditions typical of arid and semi-arid regions, the shade provided by the photovoltaic panels helped to maintain or even improve tomato yields as compared to those achieved in full sunlight conditions [31,32]. Overall, reduced light availability was identified as the main limiting factor affecting plant growth in AV systems [12,33]. Tomato crops require a high radiation [15]. Reduced light availability due to shading has been associated with a decline in leaf initiation, particularly during the early stages of plant development, while concurrently promoting an increase in individual leaf area as an adaptive strategy to enhance light interception [34]. As a final consequence, light limitation may lead to yield reduction, resulting from a decreased number of fruits and/or the development of smaller-sized fruits [35,36].

Therefore, it is crucial to understand how PV panels affect light availability inside the greenhouse, especially for species with high light requirements, such as tomato plants. Under the cultivation conditions of the winter-spring cycle, the SC and PV-TF greenhouses showed average DLIs ($\overline{DLI}$) below the minimum value considered sufficient to meet crop light requirements. However, in the PV-Si greenhouse, $\overline{DLI}$ exceeded the threshold value and was reduced by only 26% as compared to the control. During this period, the PV infrastructure impacted not only light availability during the winter months, but also altered air temperature and soil moisture, both of which are recognised as critical factors influencing plant growth [37]. Notably, the C greenhouse exhibited less favourable thermal conditions, with nighttime air temperatures up to 1 °C lower and consistently reduced soil moisture compared with the other systems throughout the growing cycle. A decline in nighttime temperature has been associated with restricted vegetative growth, delayed phenological development, and ultimately, reduced yield in horticultural crops, including tomatoes [28]. In addition, stable and adequate soil moisture promotes plant growth, fruit size, and yield, as compared to conditions with fluctuating or more limiting soil moisture [38–40]. Thus, both the morphological and yield differences observed between the greenhouses during this first cycle could be attributed to a combination of environmental factors (light, temperature and soil moisture) specific to each system. The increased leaf area and/or reduced number of leaves observed in the shaded greenhouses (SC, PV-Si and PV-TF) are likely to be a consequence of a shade-avoidance response, resulting from the lower light availability when compared to the control [41,42]. In the SC and PV-TF greenhouses, the more pronounced reduction in light availability resulted in a lower number and smaller size of fruits compared to the control and PV-Si greenhouses. Lastly, the reduced fruit production observed in the C greenhouse compared to the PV-Si was likely due to the combined effects of the observed decreased nighttime temperatures and lower soil moisture.

During the spring-summer cycle, the longer duration of the light phase within the photoperiod, in addition to higher radiation intensity, implies that light conditions in the greenhouses that were partially shaded by photovoltaic (PV) panels were less limiting than those of the first cycle. Although $\overline{DLI}$ values indicate that there was no light limitation for crop development in any of the greenhouses, clear differences in light intensity were observed. In the SC and PV-TF greenhouses, the photosynthetic saturation point for tomatoes, estimated at 400–600 $\mu mol \cdot m^{-2} \cdot s^{-1}$ [43], was reached and declined more quickly than in the C and PV-Si treatments. Despite gas exchange measurements being taken only twice, which provides a limited view of plant responses, the lower PAR availability in the SC and PV-TF greenhouses could be linked to reduced photosynthetic capacity compared with the control at specific times of the photoperiod, potentially contributing to the observed reduction in fruit production. In agreement with these results, previous studies under open-field conditions reported yield reductions of 28–30% beneath semi-transparent PV panels due to significant PAR losses [30,32]. In contrast, in the PV-Si greenhouse, PAR values comparable to those of the control were intermittently achieved throughout the photoperiod, and no detrimental effect of PV-Si panels on fruit production was observed in either cycle. Moreover, from an energy standpoint, PV-Si appears to be the preferred option, highlighting the potential of this technology for application in AV greenhouses, where it can safeguard crop yield while maximizing energy production.

Understanding the results requires evaluating how the light heterogeneity produced by this system may impact crop performance. Previous studies have examined how plants acclimate to the temporal and spatial distribution of shading and the subsequent effects on fruit yield. Savalle-Gloire et al. [11] found that the alternating light and shade conditions generated by mobile PV panels in AV systems induced a shade-avoidance response. This was evidenced by increased stem elongation and leaf expansion, without altering developmental timing, but ultimately reduced fruit dry mass due to constrained carbon assimilation during critical growth phases. At the leaf level, exposure to fluctuating light (lightflecks) enhanced photosynthetic capacity in partially shaded leaves, but this acclimation diminishes as leaves become more deeply shaded by the canopy [44]. Overall, while intermittent shade can help manage heat and the microclimate, excessive or poorly timed shading generally reduces the yield and quality of tomatoes, so careful management is needed to balance plant growth, fruit production and environmental control.

In the present study, the spatial heterogeneity of PAR observed under PV-Si had important physiological implications for the crop. The checkerboard shading pattern created by the PV-Si panels prevented the complete shading of individual plants, generating intermittent high-light flecks across the canopy as evidenced by our PAR data. The coexistence of illuminated and shaded leaves likely minimized shade avoidance responses, as parts of the canopy consistently received sufficient light for photosynthetic activity. These brief exposures likely maintained photosynthetic electron transport activity in shaded leaves, preventing the down-regulation commonly observed under continuous shade [45]. This micro-scale light variability favoured the maintenance of photosynthetic efficiency and gas exchange, as indicated by the higher net CO_2 assimilation and stomatal conductance measured under PV-Si compared with PV-TF. Consequently, photosynthetic activity was sustained, leaf area remained unaffected. The improved photosynthetic performance contributed to the higher yield observed under PV-Si, linking the spatial distribution of light within the canopy to the overall agronomic advantage of this configuration. In line with the findings from our study, a previous study on strawberries found that the 40% red thin-film PV module achieved 87% of the average fresh weight relative to the control, while the 44% transparent c-Si module reached 104%. Notably, the 69% transparent c-Si module increased fresh weight by 18%, highlighting the potential of non-uniform, semitransparent c-Si modules to outperform both uniform thin-film systems and control conditions [46].

The differences observed between the first cycle, in which fruit production in the PV-Si greenhouse exceeded that of the control, and the second cycle, where yields were similar in both greenhouses, can be explained by environmental conditions. In the second cycle, the absence of photosynthetic limitations in PV-Si, together with the lack of low nighttime temperatures constraining control plants, resulted in comparable fruit yields between the two greenhouses. Lastly, regarding the role of the photovoltaic structure as a means of mitigating high temperatures inside the greenhouse through shading, it was effective in reducing daytime temperatures only during the spring–summer cycle, allowing optimal thermal conditions to be maintained for a longer period. However, during the summer, an opposite trend was observed, indicating that photovoltaic materials were not suitable for lowering greenhouse temperatures during the hottest months in warm climates.

Balancing crop yield and energy production is a key challenge in AV systems, particularly for high-light-demand crops such as tomato. The experimental design of this study allowed a controlled comparison between PV-Si and PV-TF technologies under similar environmental conditions, ensuring that differences in microclimate and crop performance were primarily due to the PV systems. Although the small scale of our greenhouses limits extrapolation to commercial facilities and economic analyses, the results provide valuable guidance for the design of commercial AV systems. Future research should validate these findings on a larger scale and explore dynamic PV systems, such as movable panels that adjust light according to crop stage and daily light requirements, as well as new PV materials. Optimising irrigation, resource use, and fruit quality under PV-induced shading will also be important. Finally, long-term stability and scalability should be prioritised to allow reliable implementation across different climates and agricultural systems, supporting sustainable rural development.

4.4 Conclusions

Although the system did not effectively reduce air temperature inside the greenhouse during the summer period, the use of photovoltaic panels and shading nets during winter contributed to maintaining more favourable nighttime air temperatures and soil moisture levels as compared to the control greenhouse. Furthermore, the semi-transparent silicon-based photovoltaic technology used in the PV-Si greenhouse ensured sufficient light availability to sustain photosynthetic activity comparable to that of control plants. As a consequence, during the winter–spring cycle, crop yields in the PV-Si greenhouse were higher, and during the spring–summer cycle, similar to those of the control. These outcomes, together with the improved energy performance relative to the PV-TF greenhouse, highlight the potential of this technology as a strong candidate for the development of agrivoltaic greenhouse systems.

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4.8 Figure Legend

Figure 1. Images of the experimental greenhouses: control (C), shading control (SC), monofacial silicon photovoltaic (PV-Si), and thin-film cadmium telluride (CdTe) photovoltaic (PV-TF) greenhouses.

Figure 2. Daily energy production (kWh day^{-1}) for PV-Si and PV-TF across two cycles, indicating contributions from roof-integrated (18° tilt) and facade-integrated (90° tilt) PV modules.

Figure 3. PAR profiles measured on a sunny day inside the control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies.

Figure 4. Accumulated fruit production (g $plant^{-1}$) during the spring-summer cycle for tomato plants grown in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies. Data are means ±SE (n=7).

Table 1. Average ($\overline{DLI}$), maximum (DLI_{max}), and minimum (DLI_{min}) daily light integral, expressed as mol m^{-2} day^{-1}, during the winter-spring and spring-summer cycles in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).

Cycle	**Tech.**	$\overline{DLI}$	DLI_{max}	DLI_{min}
Winter-spring	**C**	24.4	35.9	5.6
	SC	11.2	15.9	3.0
	PV-Si	18.1	36.1	3.3
	PV-TF	10.8	16.4	2.1
Spring-summer	**C**	35.4	45.8	15.8
	SC	17.7	19.9	10.7
	PV-Si	25.4	37.2	14.2
	PV-TF	17.0	21.4	9.3

Table 2. Average daily time at optimal ($\overline{tOT}$, h), high ($\overline{tHT}$, h), and low ($\overline{tLT}$, h) temperature, during the winter-spring and spring-summer cycles in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).

Cycle	Tech.	$\overline{tOT}$	$\overline{tHT}$	$\overline{tLT}$
Winter-spring	**C**	6.5	2.2	0.7
	SC	7.4	1.2	0.6
	PV-Si	7.2	1.6	0.6
	PV-TF	7.3	2.0	0.5
Spring-summer	**C**	9.9	8.2	0
	SC	9.7	8.1	0
	PV-Si	9.4	8.9	0
	PV-TF	9.3	8.7	0

Table 3. Average ($\overline{T}$), maximum (*Tmax*) and minimum (*Tmin*) soil temperature (˚C) and average ($\overline{H}$), maximum (*Hmax*) and minimum (*Hmin*) soil humidity (%) at 10 cm depth, during the winter-spring and spring-summer cycles in control (C), shaded control (SC), crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).

Cycle	Tech.	$\overline{T}$	*Tmax*	*Tmin*	$\overline{H}$	*Hmax*	*Hmin*
Winter-spring	**C**	18.2	31.4	8.5	23.9	35.7	14.7
	SC	15.9	28.2	9.0	32.1	44.0	23.8
	PV-Si	16.7	28.1	9.6	35.4	46.5	25.6
	PV-TF	16.4	30.4	8.3	27.2	44.1	17.4
Spring-summer	**C**	26.4	40.1	14.1	12.2	49.1	6.8
	SC	24.3	39.0	12.3	19.7	52.1	10.8
	PV-Si	25.2	36.7	13.4	33.0	47.8	23.8
	PV-TF	24.8	39.0	12.4	32.7	46.4	24.7

Table 4. Average time (h) at optimal ($\overline{tOH}$), high ($\overline{tHH}$) and low ($\overline{tLH}$) air humidity, during the winter-spring and spring-summer cycles in control (C), shaded control (SC), crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).

Cycle	Tech.	$\overline{tOH}$	$\overline{tHH}$	$\overline{tLH}$
Winter-spring	**C**	7.0	0.13	10.3
	SC	7.3	0	10.4
	PV-Si	7.9	0	10.4
	PV-TF	7.9	0	10.3
Spring-summer	**C**	7.6	0	11.8
	SC	7.6	0	12.5
	PV-Si	7.9	0	12.3
	PV-TF	7.8	0	12.3

Table 5. Shoot weight (g), plant height (cm), leaf number, leaf area (cm^2), fruit number and mean fruit weight –considering fully developed fruits– (g) of plants grown in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).

Cycle	Tech.	Shoot weight	Plant height	Leaves number	Foliar area	Fruit number	Mean fruit weight
Winter-spring	**C**	578	141	32^b	20^a	22^b	59^a
	SC	650	143	28^a	25^b	19^{ab}	49^a
	PV-Si	636	150	29^a	23^{ab}	21^{ab}	74^b
	PV-TF	607	145	28^a	27^b	18^a	50^a
		n.s.	n.s.	*	*	*	**
Spring-summer	**C**	1044	193^b	35^a	23^a	30^b	94
	SC	1009	171^a	32^a	37^b	24^a	91
	PV-Si	1032	195^b	41^b	21^a	30^b	93
	PV-TF	1000	178^a	33^a	34^b	23^a	79
		n.s.	**	***	**	*	n.s.

*, **, *** Significant differences between means at 5, 1 or 0.1% level of probability, respectively; n.s., non-significant at P = 5%. For each compartment, different letters in the same column indicate

significant differences between means according to Duncan's test at the 5% level. For each cycle, means within the same column followed by the same letter are not significantly different according to Duncan's test at the 5% level.

Table 6. Net photosynthesis (A_N, μmol CO_2 m^{-2} s^{-1}) and stomatal conductance (g_s, mol m^{-2} s^{-1}) measured at 9:00 AM and 12:00 PM during the spring–summer growing cycle in plants grown under control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).

	9:00 AM		**12:00 PM**	
Tech.	**A**	**g_s**	**A**	**g_s**
C	13.4^{b}	0.10^{bc}	13.8	0.13
SC	10.0^{a}	0.08^{ab}	14.5	0.18
PV-Si	13.2^{b}	0.12^{c}	14.4	0.15
PV-TF	8.3^{a}	0.06^{a}	13.5	0.16
	*	*	n.s.	n.s.

*Significant differences between means at 5% level of probability, respectively; n.s., non-significant at P = 5%. For each compartment, different letters in the same column indicate significant differences between means according to Duncan's test at the 5% level. Means within the same column followed by the same letter are not significantly different according to Duncan's test at the 5% level.

Figure 1

Figure 2

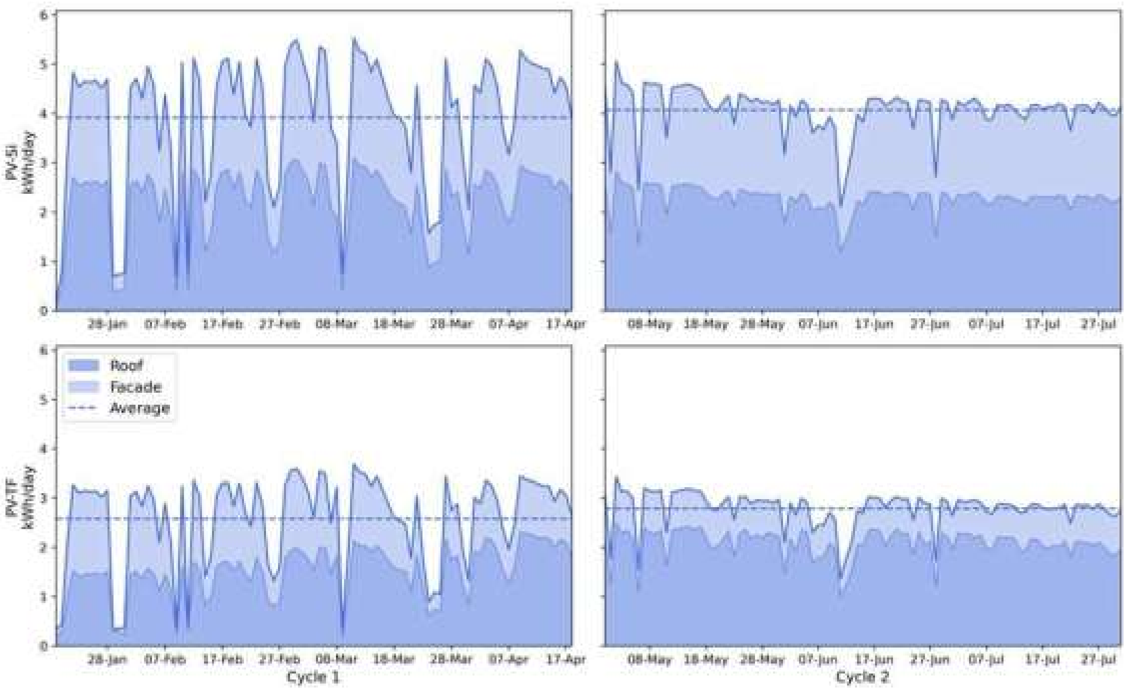


Figure 3

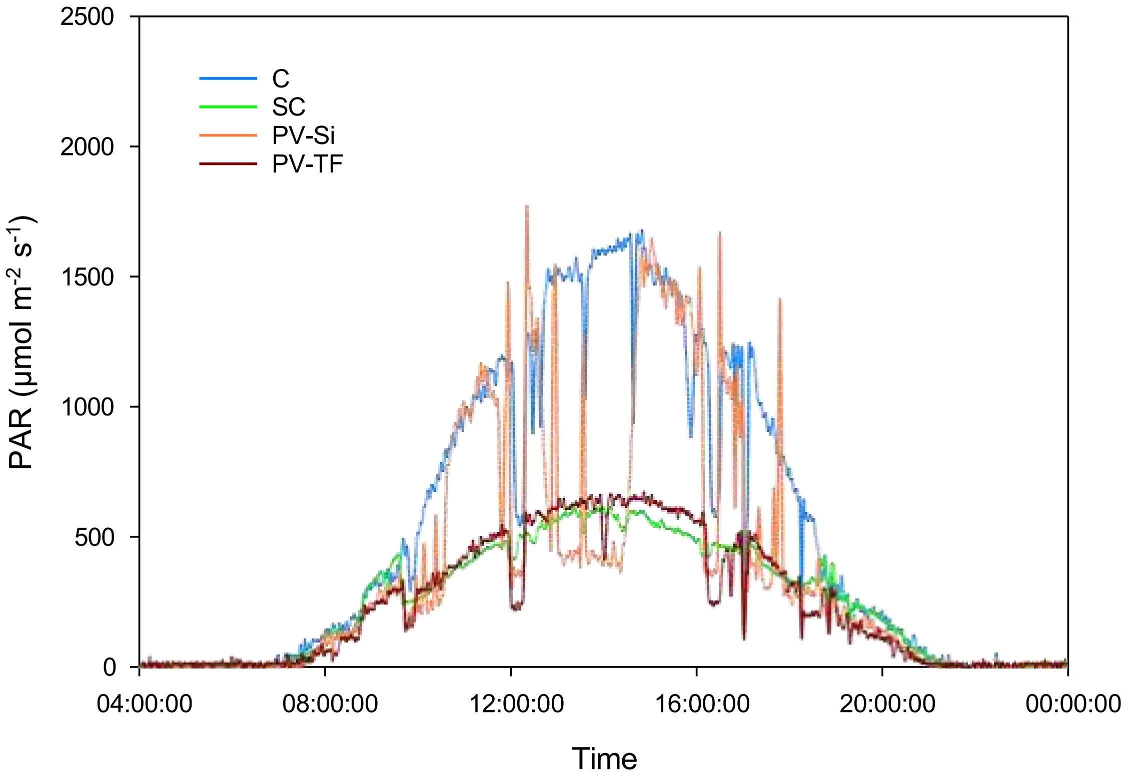
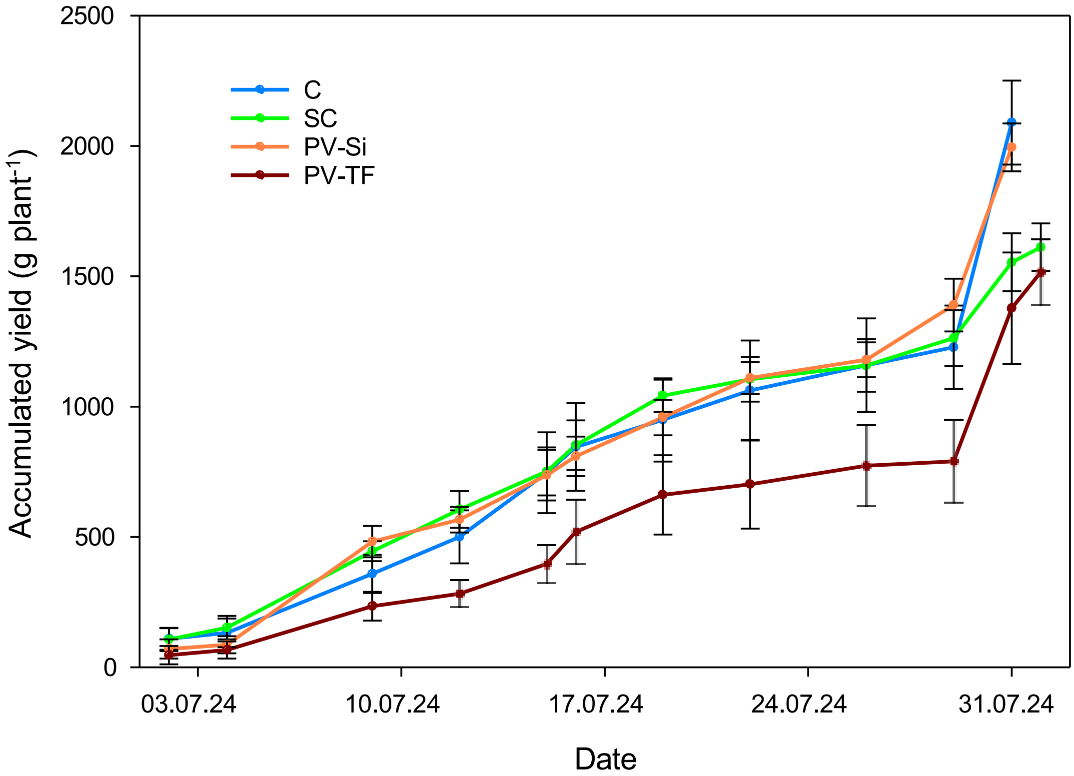
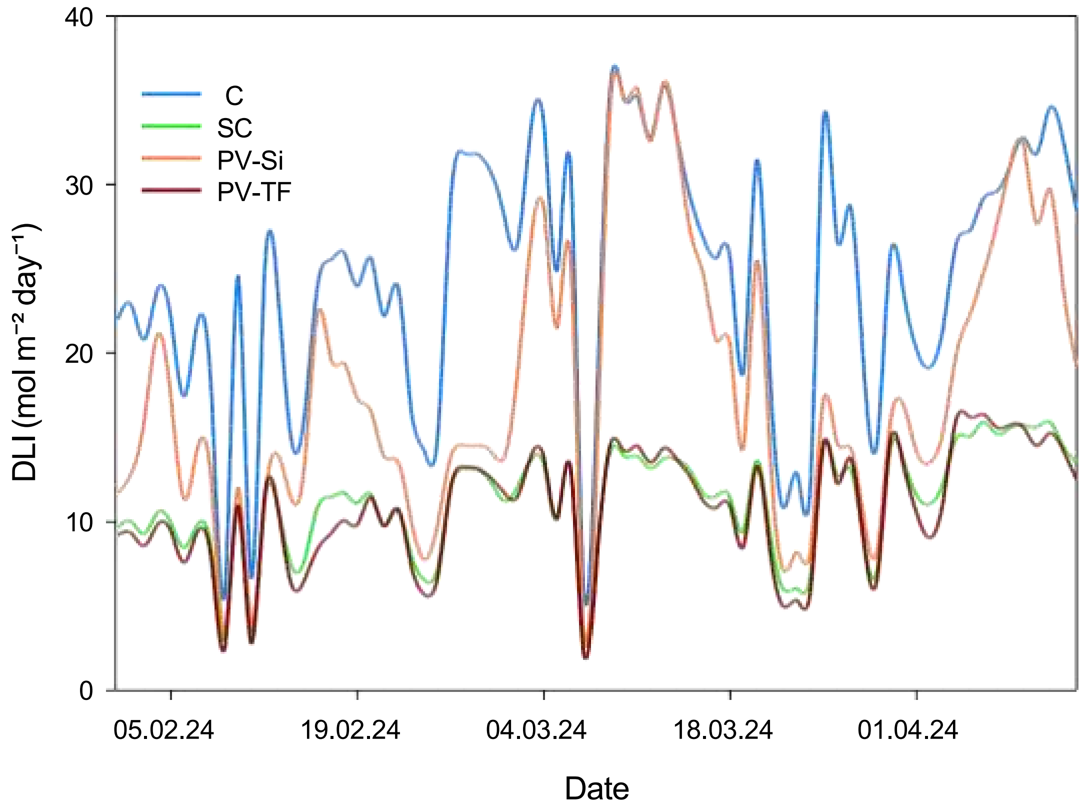


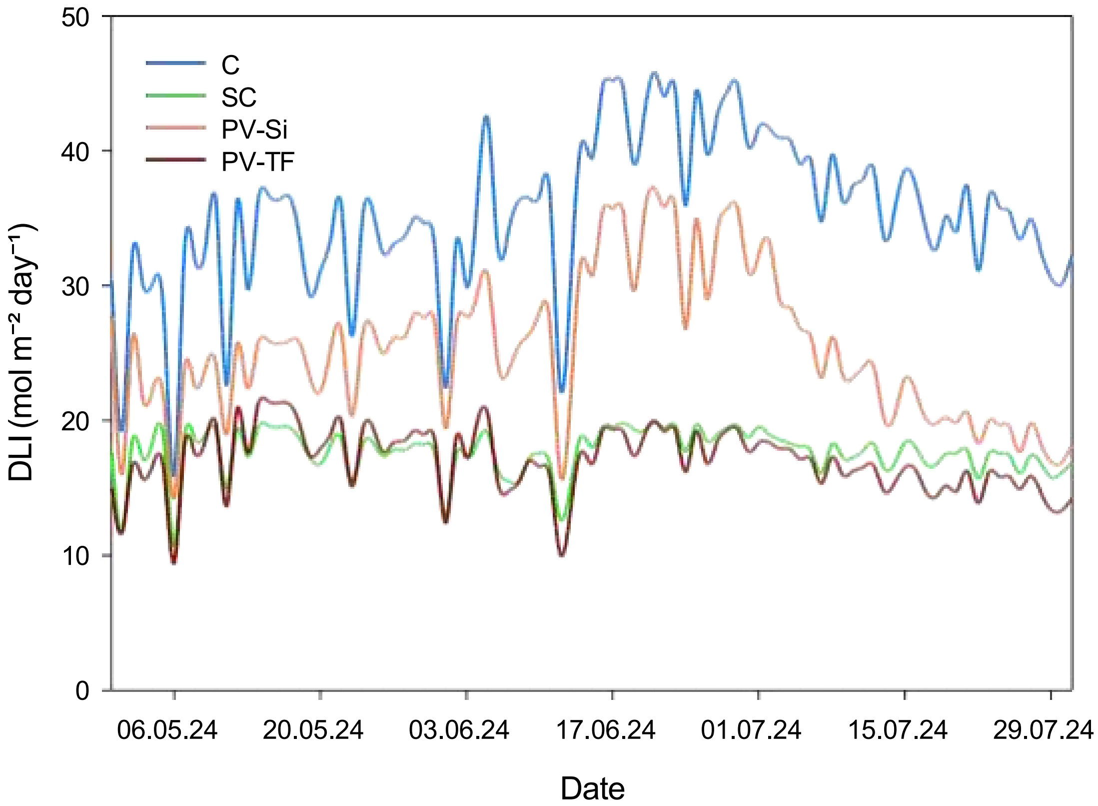
Figure 4



C
SC
PV-Si
PV-TF
Accumulated yield (g plant^{-1})
2500
2000
1500
1000
500
0
03.07.24
10.07.24
17.07.24
24.07.24
31.07.24
Date



Supplementary Figure S1. Daily light integral (DLI, expressed as mol m^{-2} day^{-1}) during the winter-spring cycle, in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).



Supplementary Figure S2. Daily light integral (DLI, expressed as mol m^{-2} day^{-1}) during the spring-summer cycle, in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).

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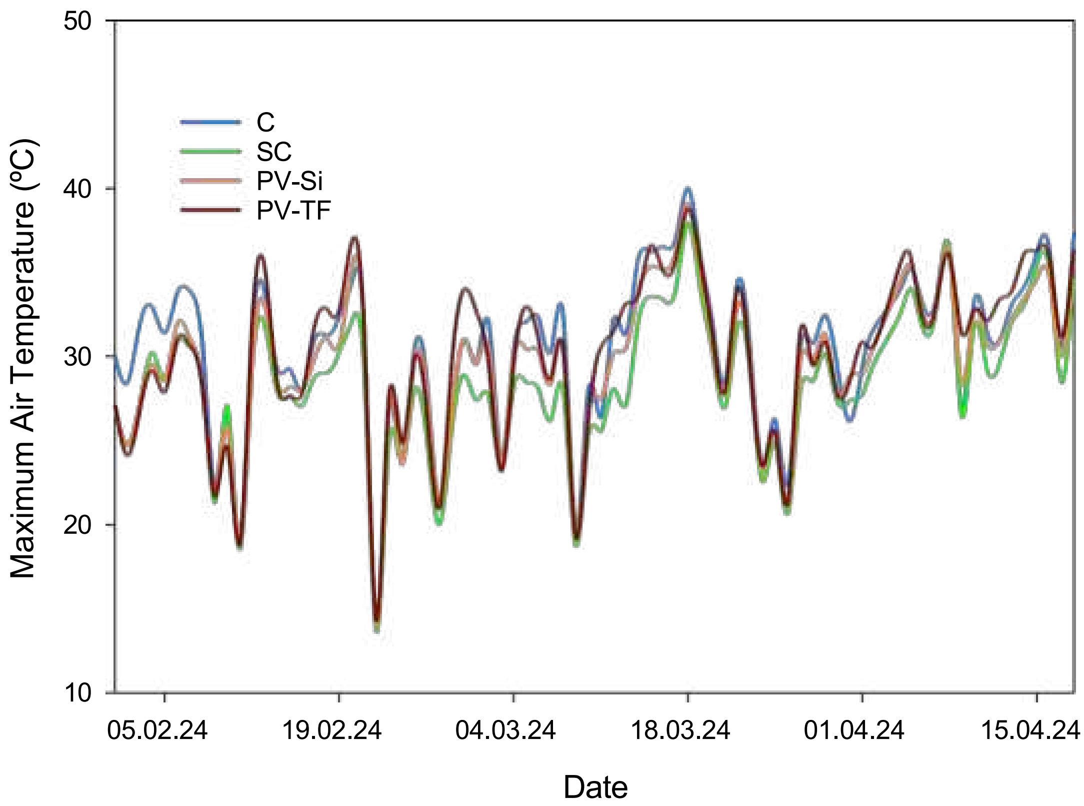
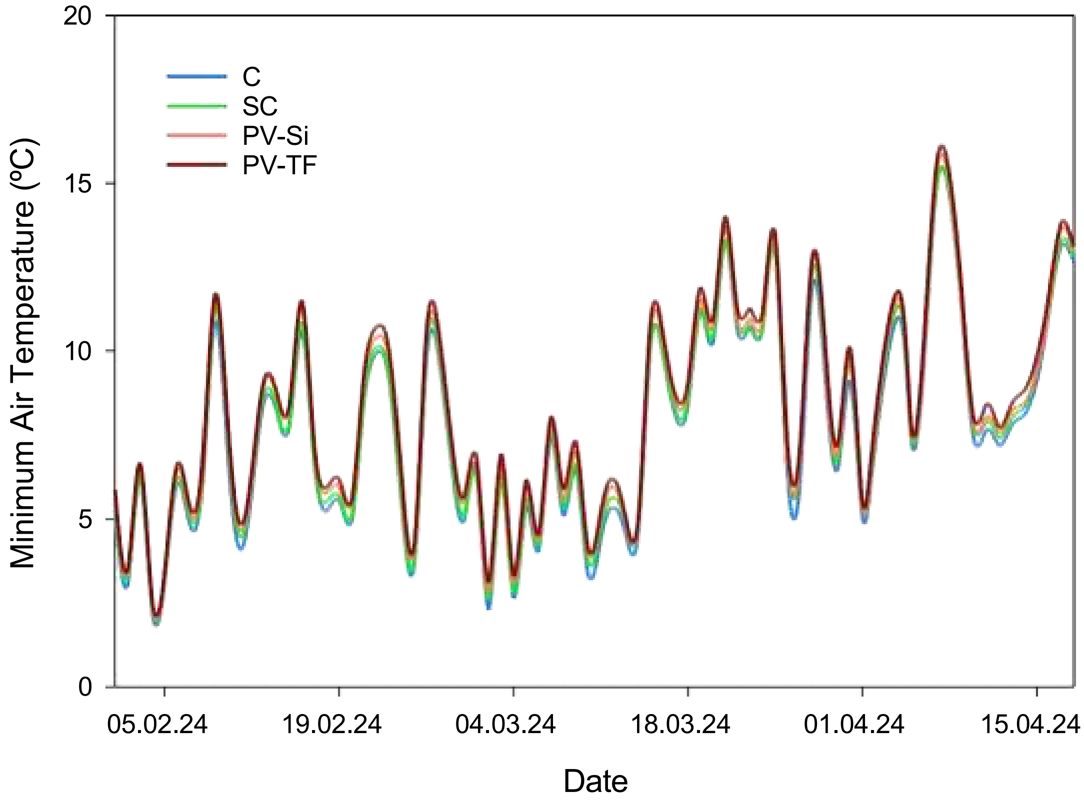
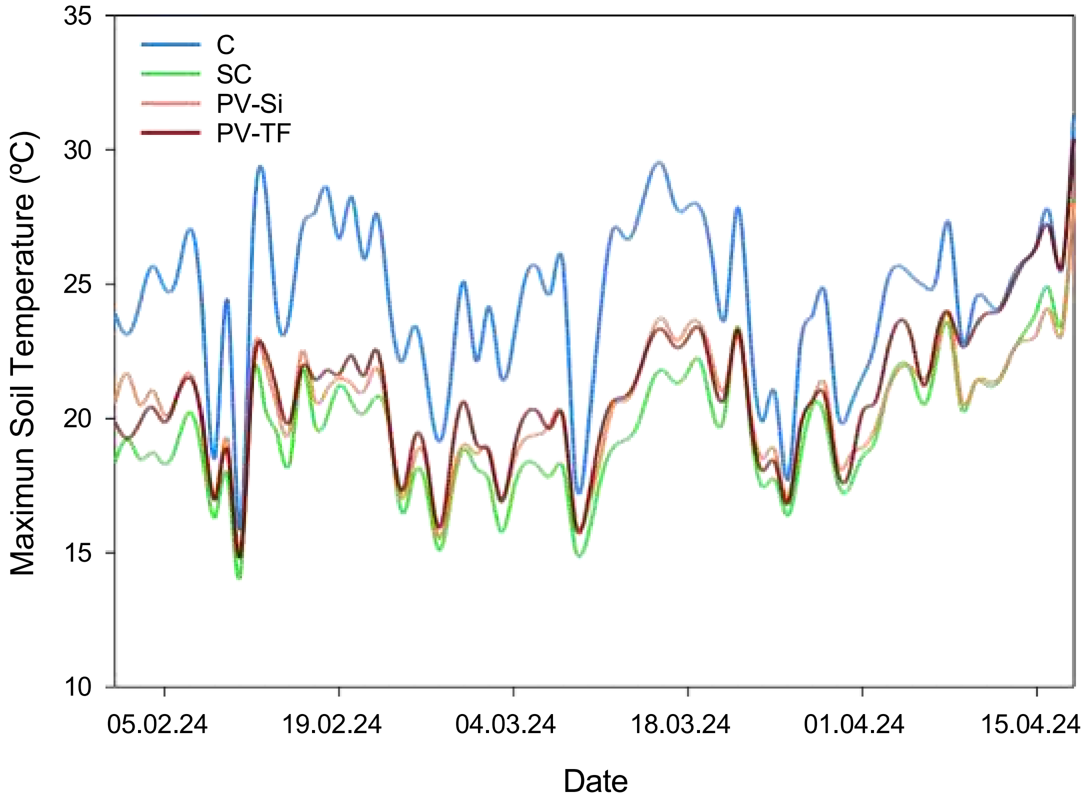


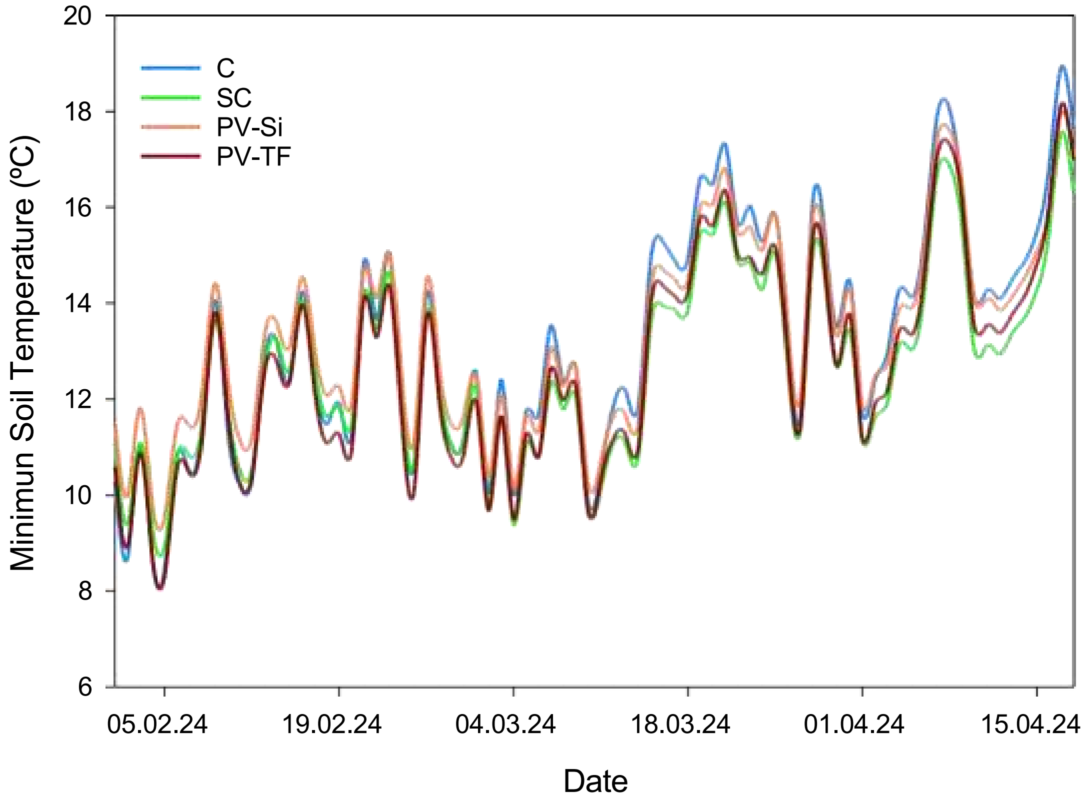
Supplementary Figure S3. Daily maximum air temperature (˚C) during the winter-spring cycle, in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).



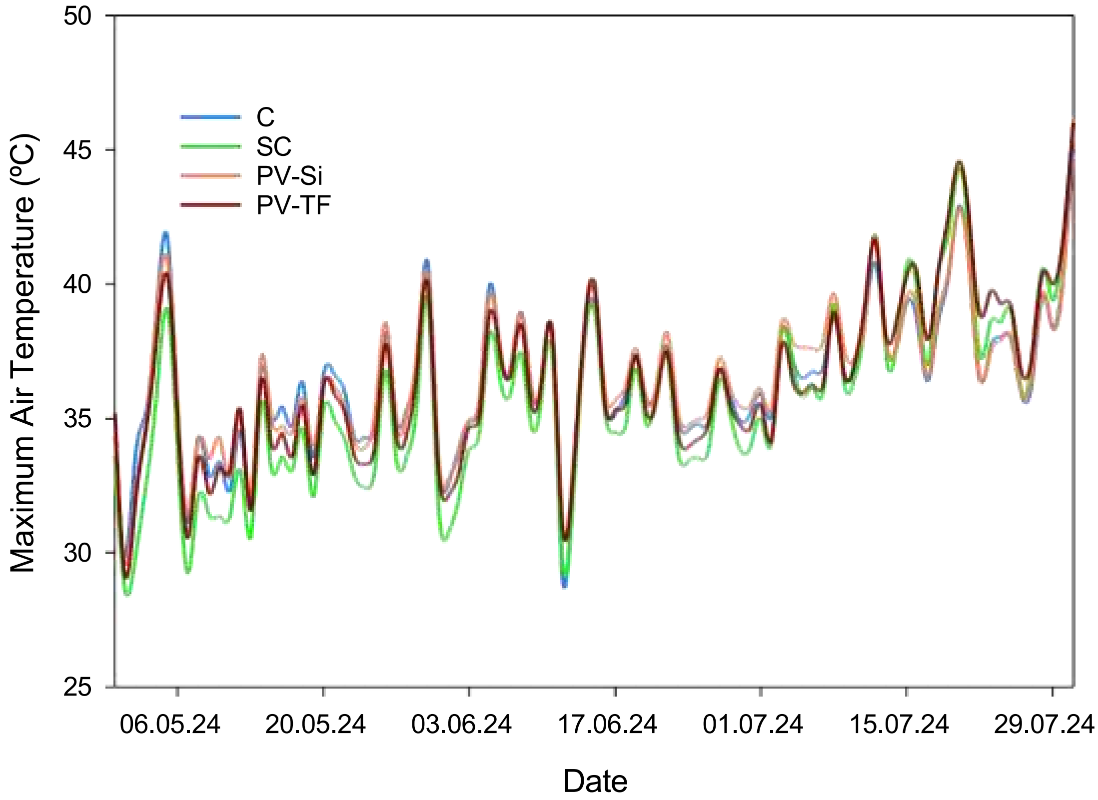
Supplementary Figure S4. Daily minimum air temperature (˚C) during the winter-spring cycle, in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).



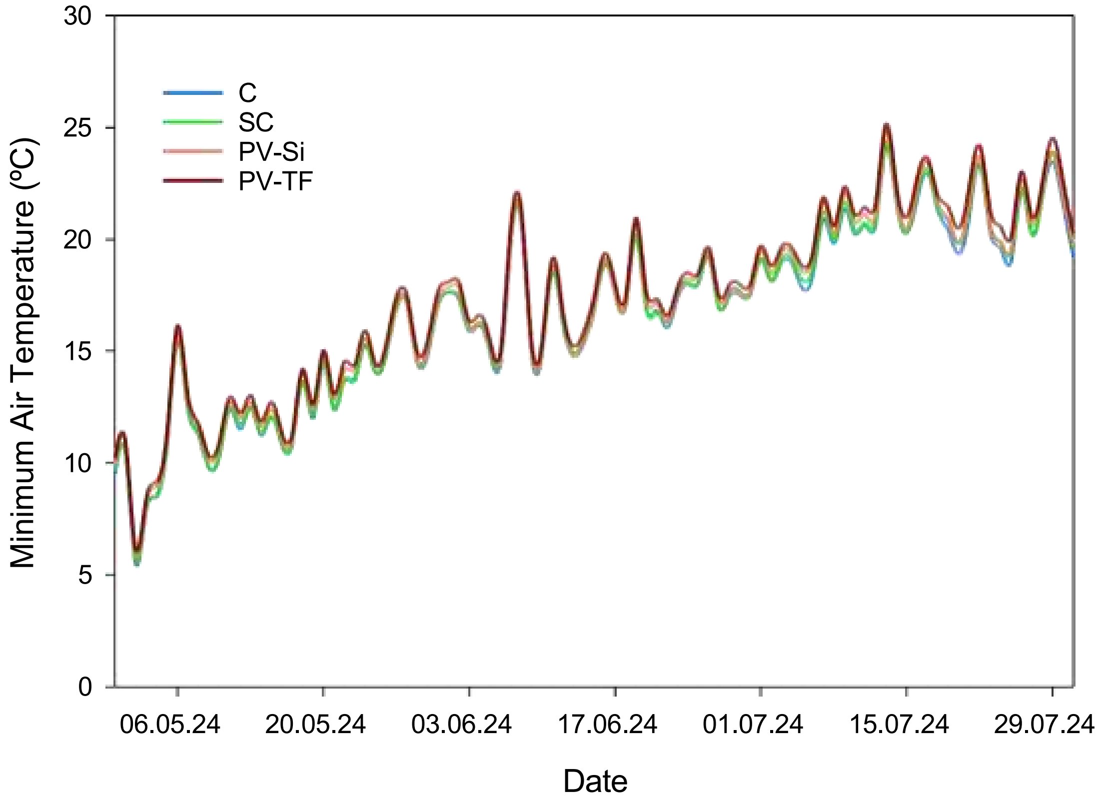
Supplementary Figure S5. Daily maximum soil temperature (°C) at 10 cm depth during the winter-spring cycle in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).



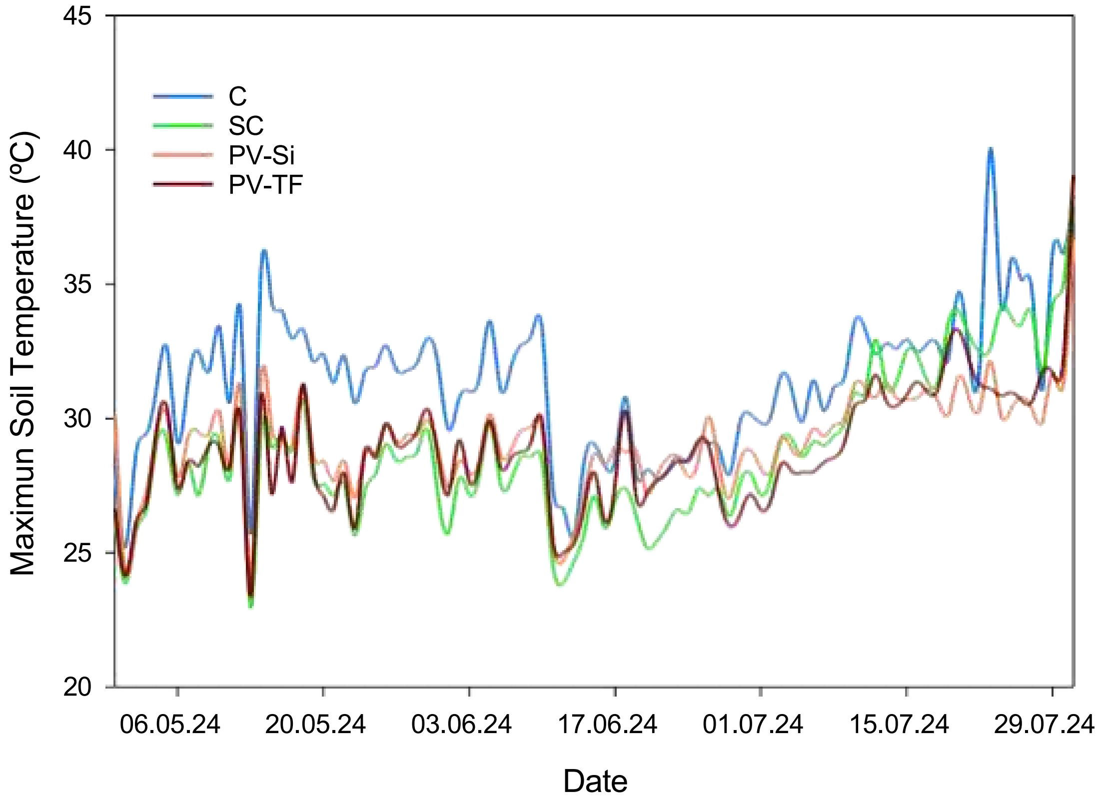
Supplementary Figure S6. Daily minimum soil temperature (°C) at 10 cm depth during the winter-spring cycle in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).



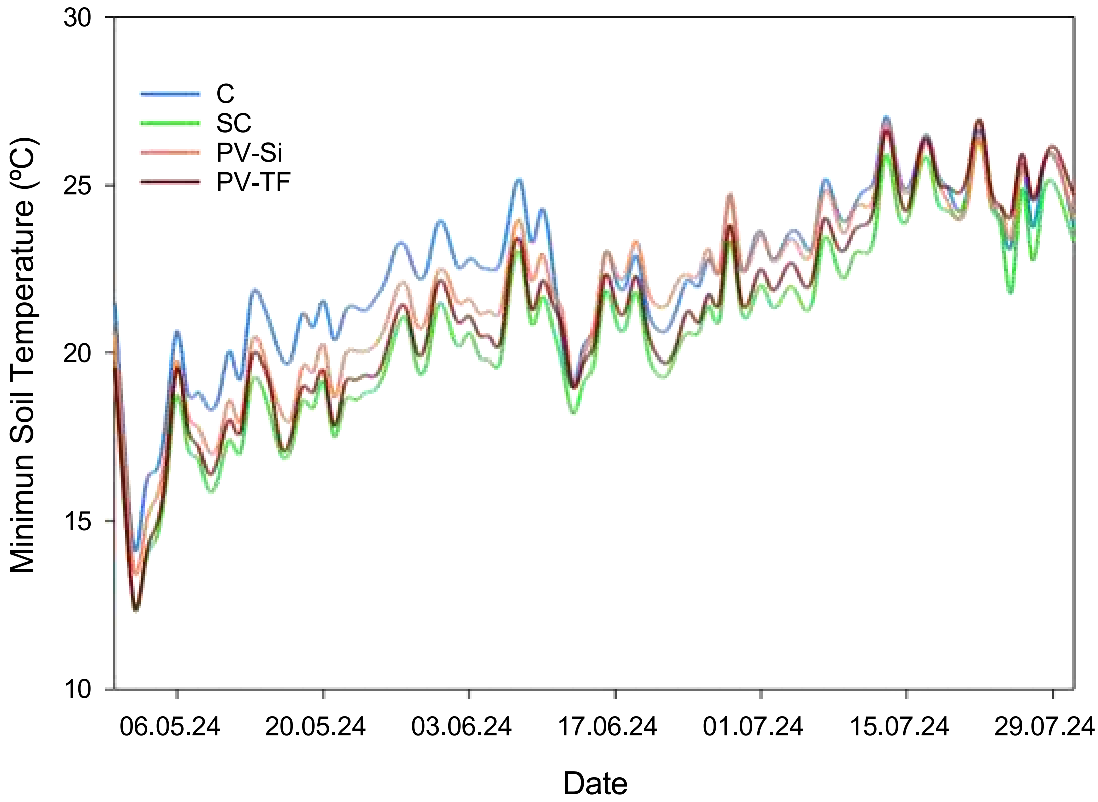
Supplementary Figure S7. Daily maximum air temperature (˚C) during the spring-summer, in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).



Supplementary Figure S8. Daily minimum air temperature (˚C) during the spring-summer cycle, in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).



Supplementary Figure S9. Daily maximum soil temperature (°C) at 10 cm depth during the spring-summer cycle in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).



Supplementary Figure S10. Daily minimum soil temperature (°C) at 10 cm depth during the spring-summer cycle in control (C), shaded control (SC), and photovoltaic greenhouses with crystalline silicon (PV-Si) and thin-film cadmium telluride (PV-TF) technologies (Tech).

Supplementary Table S1. Technical specifications of the monitoring system.

Sensor model	Variable	Measurement range	Resolution
Apogee SQ-521	PAR	0 – 4000 µmol m^{-2} s^{-1}	0.01 µmol m^{-2} s^{-1}
Hukseflux SR05-D2A2	Solar irradiance	0 – 1600 W m^{-2}	0.1 W m^{-2}
INTA crop technology	Air temperature	-30 – 80 °C	0.3 °C
	Relative humidity	0 – 100%	1%
Sentek Drill & Drop 60	Soil temperature	-20 – 60 °C	0.3 °C
	Soil humidity	0 – 100%	0.03%

Supplementary Table S2. Technical specifications of the PV systems.

PV module	**PV-Si**	**PV-TF**
Model	ML-S6MF/G0-59	Polysolar PS-CT-40
Active cell material	Mono-crystalline	Cadmium Telluride (CdTe)
Nominal power	59 W	40 W
Power conversion efficiency (PCE)	20%	6%
Power temperature coefficient	-0.42 %/°C	-0.21 %/°C
Transparency	50%	50%
Encapsulation	glass-glass (1mm + 4mm)	glass-glass (3.2mm + 3.2mm)
Dimensions	600mm x 1200mm	600mm x 1200mm
PV Inverter		
Model	HMS-2000-4T	SUN2000-2KTL-L1
Rated output power	2000 W	2000 W
Efficiency	99.8%	98.2 %
Grid connection	1AC 230V; 50Hz	1AC 230V; 50Hz
PV system		
Facade capacity (tilt 90°)	531 W	360 W
Roof capacity (tilt 18°)	531 W	360 W
Total system capacity	1.06 kW	0.72 kW

Chapter 5

Conclusions

In general, research has demonstrated the concrete possibility of integrating agricultural and photovoltaic production, while highlighting the need to carefully consider the effects of agrivoltaic cultivation on crop performance. Crop performance is strongly influenced by the crop species, environmental conditions, and the type of agrivoltaic system employed. Agrivoltaic cultivation is undoubtedly a winning strategy for efficient land use, although in some cases this may not necessarily translate into equally positive effects on agricultural yields. The use of innovative agrivoltaic systems can certainly help mitigate these negative effects, as can the use of advanced monitoring and decision support systems for the overall management of the agrivoltaic system.

Although the assessment of advanced agrivoltaic systems represents the main focus and interest of scientific and industrial activity, the exploitation of the existing traditional photovoltaic plants in terms of combined agricultural and energy production should be considered a relevant challenge and opportunity, due to the large area currently occupied by these systems. Our first study confirmed that the crop performance was negatively affected by the presence of the PV plant, with a variable response according to the crop species considered. However, also in conditions of yield reductions, the LER was improved, underlying a more efficient use of land, without negative or even ameliorative impacts on biological soil quality. Since the effects on plants depend on the typology of the agrivoltaic systems, the cropping cycle season, the specific annual climatic conditions, the agronomical management practices, and even the variety used, improving the knowledge on the specific response of crops, determined under real cultivation conditions typical of different environments, is necessary to define optimal cropping programs aimed to maximize resources use efficiency and land use.

With specific reference to the part of the research focused on the implementation of a system aimed to support in the management of the AV process, SolarFertigation was not developed as a closed system, but as an open and adaptive platform that integrates agricultural hardware, distributed sensors, cloud architectures, and decision-making logic aimed at sustainability. Throughout its development, the project has followed a clear direction: transforming fertigation from a technical process into a strategic tool—not only to improve the nutritional efficiency of crops, but also to make every cultivated hectare a digital, sensitive, and responsive space.

The adopted approach (from nutrient mix optimization to integrated energy management) demonstrates that it is possible to design systems that are compliance-ready, modular, scalable, and above all agronomically focused. Systems that communicate with the field, with water resources, with the sun, and with data.

Looking ahead, the real challenge is no longer just to monitor, but to anticipate. Not merely to irrigate, but to know when not to. Not only to adapt the system to the field, but to let the field express itself through data. In this context, SolarFertigation positions itself as an enabling technology for agriculture that is not only more precise, but also more intelligent, more ecological, and more autonomous. Not just a system, but a bridge between land and cloud, between energy and cultivation, between knowledge and automation.

Finally, our research covered tests on advanced AV technogies for greenhouse cultivation. Although the system did not effectively reduce air temperature inside the greenhouse during the summer period, the use of photovoltaic panels and shading nets during winter contributed to maintaining more favourable nighttime air temperatures and soil moisture levels as compared to the control greenhouse. Furthermore, the semi-transparent silicon-based photovoltaic technology used in the PV-Si greenhouse ensured sufficient light availability to sustain photosynthetic activity comparable to that of control plants. As a consequence, during the winter–spring cycle, crop yields in the PV-Si greenhouse were higher, and during the spring–summer cycle, similar to those of the control. These outcomes, together with the improved energy performance relative to the PV-TF greenhouse, highlight the potential of this technology as a strong candidate for the development of agrivoltaic greenhouse systems.