UNIVERSITÀ CATTOLICA DEL SACRO CUORE

Sede di Piacenza

Dottorato di ricerca per il Sistema Agro-alimentare

Ph.D. in Agro-Food System

Cycle XXXV

S.S.D AGR/02 AGR/04

Studying the impact of agrivoltaic systems across the water-energy-food (WEF) nexus

Coordinator:

Ch.mo Prof. Paolo Ajmone Marsan

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1. Introduction

Humanity is currently facing multiple challenges due to the climate crisis, the increasing in food demand due to a global population growth and the consequently increasing demand for energy. The ongoing climate crisis is progressively impacting the agricultural sector through adverse events (e.g., extreme temperatures, floods, etc.), water scarcity and new measures must be applied to mitigate the effect of change to protect crops and soils from adverse conditions. The use of renewable energy sources provides multiple benefits to society, as they reduce CO_2 emissions, improve air quality, and economic growth, and can help to move forward to more efficient and cleaner power production. One way to tackle the climate crisis is to install more ground-mounted photovoltaic (GM-PV) systems (Ketzer et al., 2019) but this transition to renewable energy sources in particular GM-PV systems can generate competition for the land-use for food production or energy conversion.

While photovoltaic represent a viable opportunity, there is a conflict between using land for energy conversion and for food production to meet the goals set by Sustainable Development Goal (SDG), respectively the 7th SDG to attain only "Affordable and Clean Energy" and the 2nd "Zero Hanger" for food production. This energy-food debate has delayed the decarbonization and electrification processes worldwide, concurrently delaying the goals set to favour the renewable energy transitions. Agrivoltaic (AV) systems, the synergistic combination of photovoltaic systems and conventional agricultural practices, represent a solution to this debate. Agrivoltaic system includes installing large PV systems on agricultural land while preserving the soil for food production. Agrivoltaic systems represent a new technology that can mitigate climate change by reducing carbon emissions, but it can also be a climate adaptation technology thanks to the use of PV modules to reduce the impact of adverse conditions on crop production.

To date, data on the ability of crops to produce sustainable yield under the AV systems are scarce (Dupraz et al., 2011; Sekiyama and Nagashima, 2019, Amaducci et al., 2022) and future research and development are needed to identify the crops that can growth under AV system and that can contribute to the overall sustainability of the AV system by producing a marketable yield. Collection of field data on crop responses under AV systems is essential, but results are referred to the specific AV conditions in which crops were cultivated. It is therefore relevant to define eco-physiological parameters that can be used to classify crops for AV system and to better understand how crops respond to the dynamic conditions generated by the AV systems (e.g., shading). Despite this, experiments to validate crops under AV systems are expensive and time consuming therefore in the next years simulation studies will be used extensively.

The benefits of AV systems have been found across the water-energy-food (WEF) nexus, particularly where water is a limiting factor (Barron-Gafford et al., 2019). The cultivation under the shade of PV panels renders AV systems particularly suitable for hot and drought-prone environments because it increases water-use efficiency (Marrou et al., 2013a, 2013b; Hassanpour Adeh et al., 2018; Barron-Gafford et al., 2019) and it reduces the crop evapotranspiration rates that lead to a decrease in irrigation needs (Elamri et al., 2018a). Furthermore, a positive interaction of water management under an AV system is linked to the combination of gutters in the agrivoltaic infrastructure, with storage tanks (Hernandez et al., 2019). This would allow the rainwater storage for irrigation purposes (Weselek et al., 2019, Barron-Gafford et al., 2019) or for example for washing dust or inhibiting dust accumulation on the PV modules (Dinesh and Pearce, 2016). AV systems can increase the productivity of traditional crops grown in the region and/or allow the cultivation of other crops that typically could not tolerate the heat or lack of water (Weselek et al., 2019; Willockx et al., 2020).

In AV systems the crops benefit from the presence of the panels, but the PV system also benefits from the vegetative cover by creating a synergy. Crops can contribute to reduce soil particles blowing onto the PV modules (Ravi et al., 2016), furthermore, transpiration from plants cultivated under PV panels lowers the air temperature, thus significantly increasing the efficiency of the solar cells (Barron Gafford et al., 2019; Pastor et al., 2023) and, finally the crop albedo can increase the electricity yield of the PV panels, particularly for bifacial modules (Fraunhofer ISE, 2022, Schindele et al., 2020).

Agrivoltaic systems allow to meet not only the 2nd SDG and the 7th SDG but also other SDGs, such as the 6th SDG "Clean Water and Sanitation," by reducing crop water losses; the 8th SDG "Decent work and economic growth" by providing a dual income for farmers; the 13th SDG "Climate Action" helping for example in the decarbonisation process. In addition, the possibility of developing AV systems in urban and peri-urban areas (Majumdar and Pasqualetti, 2018) meet the 11th SDG 'Sustainable Cities and Communities' (SDG 11), while growing plants under the shade of the panels that attract pollinators or that increase biodiversity, making AV systems compatible to 'Life on Land' (SDG 15).

1.2 Objectives

The main objective of this thesis is to study the growth of crops under agrivoltaic system and their response in terms of productivity, morphology, physiology and on energy conversion throughout field activity and model simulations to support food security and sustainable agriculture worldwide across the water-energy-food nexus. In order to study how the crops growing under an agrivoltaic system are affected by the shading conditions generated by the PV modules, it is important to understand how crops are influenced by the microclimatic conditions under an AV system and how crops can contribute to the energy conversion, this can be studied by setting up field experiments and through modelling activities.

It is relevant to define a set of objective criteria that can be used for determining crop suitability to specific AV conditions, such as morphological and physiological traits (e.g. specific leaf area (SLA), which is the ratio between leaf area and leaf dry mass, Leaf Area Index (LAI), photosynthetic parameters, etc.) and field measurement (e.g., phenological measurement, quality of the fruits, incidence of disease, soil analysis etc.) to carry out in a field experiment to use it to enhance the model performance to forecast crop response in an AV system. To broaden the knowledge base on agrivoltaic the following questions should be addressed:

1. *What are the main aspects to be considered when developing an agrivoltaic system to enhance synergies between crop and energy production?*

Research and development on AV systems have increased steadily in the last decade and they are currently focusing on:

- materials to be used to increase the energy and crop performance and agrivoltaic design (Toledo and Scognamiglio, 2021; Johansson et al., 2022; Amaducci et al., 2022; Fraunhofer ISE, 2022; Gorijan et al. 2022; Stallknecht et al., 2023);
- understanding how the AV system affect the microclimate and crop production both through experimental activities and modelling studies (Dupraz et al., 2011; Marrou et al., 2013a,b,c; Amaducci et al., 2018; Weselek et al., 2021; Potenza et al., 2022).
- developing models and tools to simulate and optimize the agrivoltaic systems (Dupraz et al., 2011; Dinesh and Pearce, 2016, Amaducci et al., 2018; Campana et al., 2021; Lu et al., 2022; Katsikogiannis et al., 2022; Ko et al., 2021; Tahir and Butt, 2022; Casares De La Torre et al., 2022);
- assessing economic and environmental aspects of agrivoltaic systems (Pascaris et al., 2021; Agostini et al., 2021; Kumpanalaisatit et al., 2022; Giri and Mohanty 2022; Willockx et al., 2022; Casares De la Torre et al., 2022).

To explore the synergies between crop and PV production, through both field trials and modelling studies, the following research questions should be addressed:

2. *What are the main physiological and morphological crop parameters affected under agrivoltaic conditions?*
3. *How is crop production affected under PV panels?*
4. *What are the main morphological and physiological traits that affect crop albedo?*
5. *Can agricultural management influence the energy conversion of the bifacial PV modules?*
6. *How the crop albedo affects the energy conversion of the AV systems?*

Direct scientific data on the response of crops (crop physiological and morphological traits, crop yield and quality) when cultivated under agrivoltaic conditions is still scares, and this limits the expansion that this technology could experience under the ongoing, and future, climate and energy crisis. Although research in the agrivoltaic field has grown exponentially over the past years, more research is needed to confirm and strengthen the development of agrivoltaic technology as a sustainable system for both agricultural and energy production. The agrivoltaic environment due to its dynamism (due to the type of configuration, type of PV modules, infrastructure etc.) can influence the production response of crops by affecting their yield and quality and, to date, there are still limited results on crop production and how reduced light availability can affect crop response. Furthermore, in the coming years renewable energies will be of fundamental importance in meeting the goals proposed by the Paris agreement to mitigate climate change and, Agrivoltaic system can contribute to mitigate the climate change effects.

1.3 Thesis outline

The chapters of this thesis are based on 2 peer-reviewed publications and on 2 chapters not submitted to a journal, each addressing one or more research questions as provided in section 1.2. The Table 1 shows in which chapter each research question is addressed.

Table 1 *Research questions and chapters*

Research questions	Chapter
1	1,2,4
2	2,3
3	2,3
4	4
5	4
6	4

Chapter 1 outline the results obtained during the last decade on AV systems and on which aspect research has focused during the past years, what is the current state of art of the Agrivoltaic technology and what are the future trends in research. It highlights the how agrivoltaic system can optimise electricity and food production and it evaluate the effectiveness of AV systems to help meet global environmental goals.

Chapter 2 explores the productive, morphological, physiological response of soybean cultivated in Italy under a biaxial agrivoltaic system. It includes a simulation performed to understand how shading conditions vary in specific areas of the agrivoltaic and how much shading affect the plant's response. Furthermore, it examines the observed and simulated results to evaluate the modelling simulation performance to forecast soybean yield under shading conditions.

Chapter 3 examines the productive, morphological, physiological response of tomato cultivated in a simulated fixed agrivoltaic systems. It includes crop photosynthetic parameters and water use related traits (such as the intrinsic water use efficiency and the irrigation volume) to better understand the crop response under a shading environment.

Chapter 4 describes one of the main variables that can affect the energy conversion of the PV modules, the albedo, and it explores the impact of the measured crop albedo from different crops on the energy conversion of two AV systems with bifacial PV modules (vertical and 2-axis tracking). Furthermore, it includes the use of a simulation platform to evaluate the effect of crop albedo (field-derived and satellite-derived data) on the energy conversion compared to the albedo of the bare soil conditions.

Chapter 1: Developments in agrivoltaics: achieving synergies by combining plants with solar photovoltaic power systems

Stefano Amaducci, Eleonora Potenza and Michele Colauzzi, Università Cattolica del Sacro Cuore, Italy

Table of content

Abstract: Agrivoltaics are renewable energy systems that combine food production with electricity generation from solar photovoltaics (PV). Research and development on agrivoltaics has increased steadily in recent years to address the questions: "How is crop production affected under PV panels?" and "How can energy and food production be co-optimised on the same land?" Beneath solar PV panels, crop production can increase, decrease or remain unaltered depending on the crop species, the design of the PV system and the local environmental conditions. In dry weather and high radiation conditions, agrivoltaics can increase water use efficiency and therefore favour enhanced crop production levels. Simulation models, validated for specific conditions, would be useful to optimise agrivoltaic systems, to define optimal design solutions, to identify the most suitable crop species and to assess agronomic management strategies. Future research should develop modelling platforms that could aid agrivoltaic optimisation and expand the focus beyond energy and food production to include farm income, food quality, biodiversity and landscape value.

Citation: Amaducci, S., Potenza, E., & Colauzzi, M. Developments in agrivoltaics: achieving synergies by combining plants with solar photovoltaic power systems. Energy-Smart Farming: Efficiency, Renewable Energy and Sustainability. Editor Ralph E. H. Sims, 2022, pp. 231–262. https://doi.org/10.19103/as.2022.0100.22

1 Introduction

Agrivoltaic (AV) systems combine agricultural activities with the generation of electricity from solar photovoltaic (PV) panels constructed on the same area of land. To enable the access of tractors and machinery to carry out agricultural activities including crop cultivation and harvest, the PV panels should be mounted at a height above the soil to give adequate clearance. The alternative option – growing the crop in rows between the rows of PV panels – is less practical (Fig. 1).

Goetzberger and Zastrow (1981) introduced the concept of AV systems but only more recently have the international economic and political frameworks and increased environmental concerns stimulated a growing interest in this technology. Articles published on agrivoltaics in scientific journals since 2011 were assessed (Fig. 2). Using Scopus, the titles, abstracts and keywords were searched for the terms ‘agrivoltaic’ (with 95 results), ‘agrivoltaic AND system’ (85) and ‘agrophotovoltaic’ (24), while using Google Scholar, articles with those same terms in just their titles were ‘agrivoltaic’ (113), ‘agrivoltaic system’ (27) and ’agrophotovoltaic’ (20), with citations not included.

- Increase water use efficiency (WUE)
- Decrease water inputs
- Reduce drought stress of crops
- Protect crops against adverse conditions
- Stabilise crop production
- Increase in specific leaf area (SLA)
- Improve land use efficiency
- Increase ecosystem services
- Minimise environmental impact
- Generate renewable electricity
- Mitigation of climate change
- Increase the economic value of crops
- Generate additional income for farmers
- Reduce dust and soil blown on to the panels (soiling)
- Increase PV cooling
- Crop albedo can increase electricity generation when using bi-facial panels

Figure 1 *Synergies between crop and photovoltaic panels in agrivoltaic (AV) system*

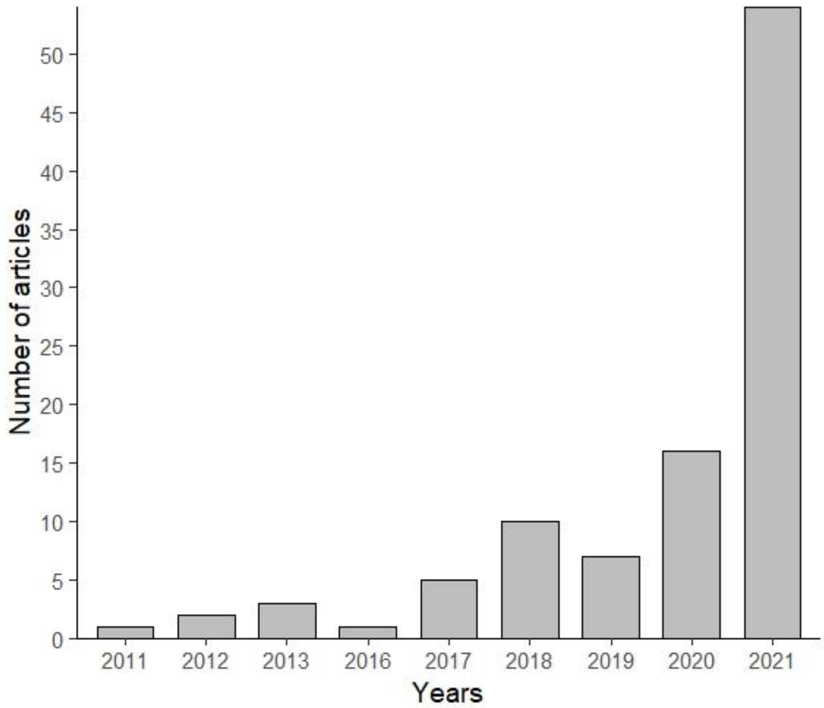

Figure 2 *Articles related to agrivoltaics, published in scientific journals from 2011 until end of 2021*

The main driver of the recent interest in AV systems is the transition towards renewable energies. To reach the goal set by the Paris Climate Agreement to limit the temperature increase to below 2°C and aim for 1.5°C, the global power sector has to be fully decarbonised by 2050 (Jäger-Waldau, 2019).

Renewable energy sources, which include biomass energy, wind energy, hydroelectric power, geothermal energy and solar energy, are low-carbon but not totally free from adverse environmental effects. Being characterised by a relatively low power density, the deployment of renewable energies on a large scale can have a significant impact on land use. Biomass produced from energy cropping, in particular, has been considered a major driver of direct or indirect land-use change (Dale et al., 2011). (This is not the case for biomass sources arising from crop or forest residues or animal wastes.)

Solar photovoltaic (PV) systems will play a key role in achieving the Paris Climate Agreement goals and providing a sustainable electricity supply (Jäger-Waldau, 2019; IRENA, 2019). The installed global solar PV capacity was over 600 GW in 2019, after high growth rates, and is expected to reach 2840 GW by 2030 and 8519 GW by 2050 (IRENA, 2019). Integrated PV technologies on buildings are preferred as they would minimise land use impact, but to achieve these ambitious PV targets, the implementation of land-based PV systems also seems necessary (IEA, 2020). This could exacerbate the problem of land-use change, particularly when PV solar farms, with either fixed or tracking panels, occupy agricultural land currently dedicated to crop production (Van de Ven et al., 2021). To avoid land-use competition, floating PV systems on ponds, lakes and estuaries are also being constructed up to a capacity of over 40 MW (Vella, 2021).

In this chapter, the conditions under which AV systems could offer a sustainable solution to land-based PV deployments are discussed.

A fundamental issue related to the sustainable implementation of AV systems is the impact of PV panels on crop productivity. Photovoltaic support structures can affect micro-meteorological conditions in the field; the panels also cause shading, which reduces the solar radiation level available to the growing crops (Dupraz et al., 2011; Weselek et al., 2019). The radiation intercepted by plant canopies is the main driver of crop growth and development (Campillo et al., 2012). However, considering that only a fraction of the incoming radiation is actually absorbed by plants during photosynthesis, AV systems can be designed and managed as 'solar sharing' systems, where the surplus solar radiation, which is not contributing to crop production, is used for power generation (Sekiyama and Nagashima, 2019). In this way, AV systems can increase the overall productivity of the land.

Multiple studies have quantified the impact of AV systems in terms of land equivalent ratio (LER), an ecological index usually employed to evaluate the efficiency of intercropping and agro-forestry systems (see Section 2 for details) (Dupraz et al., 2011; Valle et al., 2018; Amaducci et al., 2018; Elamri et al., 2018a; Fraunhofer ISE, 2020; Trommsdorff et al., 2021). It is important to note that the positive impact of AV systems on land-use efficiency largely depend on the specific environmental conditions, the crop in question and the design features of the AV system.

On the other hand, the success and expansion of AV systems strongly depend on social acceptability and policy support. Emerging policies regulating the construction and management of AV systems support implementation where they preserve agricultural productivity but aim to prevent the speculative expansion of poorly designed ground-mounted PV structures that claim to be AV systems.

Preserving agricultural productivity in an AV system implies that conventional agricultural machinery is still able to operate in the field (e.g. when the PV panels are mounted at least 3 m above ground level) and that yield reductions do not exceed a specific threshold (Irie et al., 2019, Schindele et al., 2020). The design and implementation of sustainable AV systems should also be evaluated around the water–food–energy nexus (Barron-Gafford et al., 2019).

There is a broad consensus that cultivation under the shade of PV panels increases water-use efficiency (Marrou et al., 2013a,b; Hassanpour Adeh et al., 2018; Barron-Gafford et al., 2019). Reduction of crop evapo-transpiration rates can decrease irrigation needs, for example in lettuce by about 20% (Elamri et al., 2018a). An additional positive interaction of water management under an AV system is related to the possible integration of gutters in the infrastructure, with storage tanks (Hernandez et al., 2019). This would enable the collection of rainwater to be used for irrigation of cultivated crops (Weselek et al., 2019) or for washing any dust generated, inhibiting dust accumulation on the PV modules (Dinesh and Pearce, 2016).

The positive effect on crop evapo-transpiration rates, combined with the possibility of implementing rainwater harvesting systems, renders AV systems particularly suitable for hot and drought-prone environments (Barron-Gafford et al., 2019). They could increase the productivity of conventional crops grown in the region and/or enable the cultivation of other crops that normally could not withstand the heat or lack of water (Weselek et al., 2019; Willockx et al., 2020).

In AV systems, the interaction between electricity generation and crop production is synergistic: not only do crops benefit from the presence of the panels, but the PV system also benefits from the vegetative cover. In particular, transpiration from crops cultivated under PV panels lowers the air temperature, thereby significantly increasing the performance of the solar cells (Barron Gafford et al., 2019). Crops can also contribute towards reducing soil particles blowing onto the panels (Ravi et al., 2016) and the crop albedo can increase the electricity yield of the PV panels, particularly for bifacial modules (Fraunhofer ISE, 2020).

Agrivoltaic systems bring about most of the benefits of the so-called photovoltaic agriculture, which combines PV power generation with agricultural activities (Xue, 2017). On-farm production of solar electricity can boost the overall sustainability of farm activities by providing low-carbon energy used for wastewater purification, water pumping, controlled-environment buildings, and the cooling, drying and storage of agricultural products (Mekhilef et al., 2013; Xue, 2017; Weselek et al., 2019). In remote rural areas and in developing countries, AV systems can provide electricity to remote communities that have limited or no access to the electricity grid (Meah et al., 2008; Xue, 2017).

Before designing and developing an AV system, its integration into the landscape should be carefully considered. The design of a ground-mounted PV system is generally well-defined and solar farm installations are usually optimised for electricity production and land occupation following an energy– cost-oriented design approach. Consequently, in large ground-mounted PV arrays, the panels are arranged in rows, facing the optimal azimuth angle and have an optimal tilt angle based on the latitude of the site (Scognamiglio, 2016). This rigid structural design renders traditional PV plants aesthetically unattractive and poorly integrated into the landscape, and in general, they reduce the provision of ecosystem services from the land they occupy (Scognamiglio, 2016).

If properly designed and harmonised into the landscape, AV systems can respond better to the 'sustainable energy landscape approach' (Scognamiglio, 2016). This links energy and society in a design vision that aims to maximise food production, foster biodiversity, maintain landscape quality and favour ecosystem services. When considered from this point of view, AV systems can offer a more sustainable renewable energy solution than ground-mounted PV alternatives.

Having introduced AV systems and clarifying that 'photovoltaic agriculture' has many positive aspects, the following sections will focus on how system design, modelling and management activities can exploit the reciprocal benefits that can be reaped by combining agricultural activities with the production of solar electricity on the same land area.

2 Design of agrivoltaic systems to maximise the synergy between energy and agricultural production

The most crucial aspect in the development and expansion of sustainable AV systems is the optimisation of their design. Optimising PV systems has been dealt with extensively (Alsadi and Khatib, 2018), and their economic, energetic and environmental sustainability have also been well addressed (Tawalbeh et al., 2021).

The levelised cost of electricity (LCOE) is one of the most commonly used metrics when comparing different solutions for electricity generation (Branker et al., 2011). For PV systems, it is affected by various factors relative to their design and management. For ground-mounted PV systems, the optimisation process is mainly affected by economic evaluations that have supported the development of many PV plants with common design solutions (Scognamiglio, 2016).

A major factor in determining the construction costs of PV infrastructures and their environmental impact relative to resource depletion (Agostini et al., 2021) is the steel used for the supporting structure (IRENA, 2019). In a conventional ground-mounted PV system, the height of the panels from the ground is minimised to reduce the use of materials (Santra et al., 2017; Fraunhofer ISE, 2020). This renders the use of the land under the panels very difficult for most agricultural applications.

Moreover, the design of ground-mounted PV systems makes their integration into the landscape very difficult and significantly limits the provision of ecosystem services from the land they occupy (Scognamiglio, 2016). Recently, the possibility of growing plants that attract pollinators between the arrays of PV panels has been proposed as a measure to increase their environmental sustainability. A methodology to assess the impact of this management strategy in terms of increased yield of the crops cultivated in the land around the PV plants was proposed (Macknick et al., 2013; Ravi et al., 2016; Walston et al., 2018; Hernandez et al.; 2019; Graham et al., 2021).

Agrivoltaic systems which facilitate the cultivation of agricultural crops underneath the PV panels, constitute a paradigm shift in the integration of PV infrastructures at a landscape level. Their design includes a set of parameters that go beyond those taken into account for ground-mounted PV systems. For example, the height at which the panels are mounted, the number of panels per array, the distance between arrays and the possibility of modulating these parameters are essential features for the growth and management of crops under the PV panels.

A minimum height from the ground is necessary to enable the access of machinery for agricultural operations (Dinesh and Pearce, 2016; Fraunhofer ISE, 2020). By ensuring freedom of movement for agricultural machinery, the choice of suitable crops is wider and crop rotation is similar to what is applicable in open-field conditions in the same region. Large cereal-harvesting machines require a height clearance of at least 5 m; therefore, a minimum height from the ground of 5–6 m is a requisite feature of an AV system that can then be integrated into conventional crop production systems.

The height of solar panels from the ground should also take into consideration the mature height of the crops that will be cultivated. A crop such as maize or sorghum should not exceed the height of the panels above the ground. Sekiyama and Nagashima (2019) showed that stilt-mounted AV systems (with panels placed well above the maximum height of traditional maize crops) can enable a wide range of commercial crops for which standard agricultural machinery is used. Perennial crops, grape vines and fruit trees can also be cultivated under AV systems, provided that their height can be easily managed, through pruning for example (Santra et al., 2017). In some circumstances, AV systems can be designed with PV panels installed at a relatively low height, for example when growing aloe vera (Ravi et al., 2016). Aloe vera has a crop cycle of around 5 years, short crop height, and a thick shallow root system that can maximise water-use efficiency when grown on drylands.

Existing AV prototypes and commercially available systems illustrate how crop choice and relative management practices can have an impact on design. The panel height above the ground can vary between 2.7 m (Sekiyama and Nagashima, 2019), 4 m (Dupraz et al., 2011; Marrou et al., 2013a), 5 m (Amaducci et al., 2018, Elamri et al., 2018a; Valle et al., 2018) and up to 8 m at the highest side of an inclined panel (Schindele et al., 2020; Fraunhofer ISE, 2020). Photovoltaic panels used may be monocrystalline, bifacial or thinfilm (Dupraz et al., 2011; Valle et al., 2018, Cho et al., 2020, Fraunhofer ISE, 2020, Schindele et al., 2020; Trommsdorff et al., 2021). The panels can be fixed (Dupraz et al., 2011; Marrou et al., 2013a) or installed on single- or dual-axis sun-tracking systems (Elamri et al.; 2018a, Valle et al., 2018; Amaducci et al; 2018). The distance between the lower sides of two consecutive panels can vary between 0.7 m (Sekiyama and Nagashima, 2019) and 1.6 m (Dupraz et al., 2011; Valle et al., 2018; Sekiyama and Nagashima, 2019) and up to 3.2 m (Valle et al., 2018; Elamri et al., 2018a).

The optimisation of AV systems must consider a set of design solutions that affect the 'sustainability' of electricity production from PV panels in its broadest sense. At the same time, all the factors relevant to crop production should be considered. To date, very few studies have addressed the problem or proposed a methodology for the optimisation of AV systems. In a recent simulation study, Trommsdorff et al. (2021) analysed the effect of an AV system´s design on the availability of solar radiation to crops grown underneath, by calculating the land equivalent ratio (LER) as used by Dupraz et al. (2011) to calculate land productivity under an AV system.

$$LER = \frac{crop\ yield\ in\ AV\ system}{crop\ yield\ in\ a\ monocrop\ system} + \frac{electricity\ output\ in\ AV\ system}{electricity\ outpuy\ in\ PV\ system}$$

LER values higher than 1 indicate a positive synergy between energy and food production on the same area for an AV system, as reported in several studies (Dupraz et al., 2011; Valle et al., 2018; Amaducci et al., 2018, Elamri et al., 2018a; Trommsdorff et al., 2021). This indicates that AV systems can significantly improve overall land use. The LER of an AV system further increases when solar-tracking PV systems are used instead of fixed panels (Valle et al., 2018; Amaducci et al., 2018; Elamri et al., 2018a).

Campana et al. (2021), in their seminal work, conducted a multi-object optimisation in order to explore the trade-off between competing AV key performance indicators. The design of vertically mounted AV systems with bifacial PV modules was optimised according to three objectives – electricity generation output, power fluctuations and LER – by varying the distance between PV arrays and their orientation.

This work highlighted the complexity of optimising AV systems. Besides electricity and land productivity, multi-objective optimisation should also include economic indicators. Studies have been conducted on a simple solar farm design with fixed, tilted bifacial PV panels (Trommsdorff et al., 2021) and on AV systems with vertically mounted bifacial modules (Campana et al., 2021). The design of appropriate AV systems should also include other relevant features that can affect crop yield and/or electricity generation including the PV panel area; the solar PV technology; transparency of the solar cells; the tilt angle; the type of system (whether fixed or tracking); the height of the PV panels above the ground; the pillars and the foundations.

In recent years, a reduction in the cost of solar PV panels has led to the construction of PV systems with larger area panels, reduced inter-row spacing, and consequently, increased ground coverage ratio (GCR, the ratio of total PV panel surface area to the ground area) (Sánchez-Carbajal et al., 2019; Fretzen et al., 2021). The GCR, indicated here as 'panel density,' is one of the most relevant parameters to be considered in the design of AV systems. It influences the level of shading and consequently the solar radiation levels available for crops to carry out photosynthesis. It is also the greatest determinant of annual electricity production per unit of land (Willockx et al., 2020).

The panel tilt angle also affects both electricity output and crop productivity, as does changing it dynamically with a solar tracking system. A single-axis tracker moves the solar modules horizontally, according to the elevation of the sun, or vertically, according to the azimuth, most commonly from east to west. A double-axis tracker orientates the modules both horizontally and vertically from both north to south and east to west, thus maximising generation (Valle et al., 2018), especially when compared with a fixed ground-mounted PV system (Seme et al., 2020).

The position of the panels in a tracking system can also be adjusted to enable easier access to large agricultural machinery (Fig. 3). Tracking systems can also enhance crop productivity by managing shading during specific growing stages when crop growth is favoured by either high or low levels of radiation.

Panel density alone is not sufficient to predict shading and crop productivity. Under the same panel density, crop and electricity production is significantly affected by PV technologies with contrasting transparency or energy conversion efficiency.

Transparency is a physical property that enables light to pass through the panels without interrupting the light transmission (Husain et al., 2018).

Figure 3 *Panels mounted on double-axis trackers are kept horizontal to enable cereal harvesting with a conventional combine harvester (Courtesy RemTec https://remtec.energy/en/agrivoltaico/)*

Semi-transparent panels have a transmission rate of 50% or more due to the distance between the silicon cells (if opaque cells are arranged widely apart, the panels become more transparent because of a larger surface of the glass) (Wong et al., 2008; Dinesh and Pearce, 2016). Semi-transparent panels reduce the shading of the plants beneath the panels, which can help to mitigate the negative effect of shading from AV systems (Dinesh and Pearce, 2016). Thin-film technology is among the most frequently employed for transparent PV panels (Husain et al., 2018). Light transmittance can be adjusted by the thickness of the film (Husain et al., 2018; Lee et al., 2020). In addition, the cost per unit area of thin-film modules is lower than monocrystalline and polycrystalline PV cells, which could help reduce the overall cost of an AV system (Fraunhofer ISE, 2020).

For a given panel density, the use of bifacial PV panels significantly affects the production of electricity per square metre and potentially that of crops too, compared to monofacial ones (Cho et al., 2020; Schindele et al., 2020). Bifacial panels increase the level of diffuse radiation available to the crops due to small gaps between single solar cells, which increases the transparency

(Trommsdorff et al., 2021). In addition, the electricity output of bifacial panels is higher than in monofacial designs because the radiation reflected from the ground is intercepted by the rear side of the panel. As a result, bifacial panels enable AV system designs to have larger inter-row distances, which increases the levels of solar radiation available to crops while maintaining the same level of electricity generation per unit of land area (Schindele et al., 2020). Bifacial panels can be mounted either horizontally (facing the north/south direction or vertically (facing the east/west direction), without affecting electricity production (Riaz et al., 2020). When installed vertically and spaced more than 6 m apart, regular agricultural practices can result in standard crop growth and development. Vertical mounting can also reduce dust and soil particles covering the surface of the panels (the tilt angle greatly affects this), which occurs as a result of tillage operations and machinery activity and reduces PV efficiency (Fraunhofer ISE, 2020; Riaz et al., 2020).

Tubular PV modules and organic photovoltaics (OPV) are promising innovative technologies for AV system applications (Meitzner et al., 2020). Tubular modules (©TubeSolar AG1) are flexible PV strips in a glass tube, which can be installed horizontally on supports and suspended over the cultivation area. This configuration renders the modules permeable to light and water which can then reach the crops, favouring uniform growth. Organic photovoltaics are still in the market launch phase and have low efficiency and durability (Fraunhofer ISE, 2020).

Other minor design features that can affect crop production and land accessibility are related to the supporting structures. The encumbrance by pillars that support PV panels should be minimised by using piled foundations or special anchoring with Spinnanker© (Fraunhofer ISE, 2020), or by using tensile structures such as Agrovoltaico® (as described in Agostini et al., 2021), instead of using large concrete blocks with environmental repercussions (Agostini et al., 2021). Harvesting operations are strongly influenced by the presence of pillars and other structures due to manoeuvring problems, leading to a loss of yield because approximately 8% of the arable land cannot be used (Fraunhofer ISE, 2020).

3 Physiological and agronomical aspects of crop cultivation under agrivoltaic systems

Agrivoltaic systems constitute a complex cultivation environment. The PV panels generate a maze of microclimatic conditions, and their supporting structures limit field access and the performance of agricultural operations. Full exploitation of the potential productivity of AV systems entails very specific choices and requires very intensive agronomic management. A critical issue is the selection and cultivation of species that can thrive in the micrometeorological conditions generated by the AV system.

Beck et al. (2012) proposed a classification for the suitability of vegetable species for cultivation under AV systems based on the effect of shading on crop yield. Crops are divided into three groups:

1. crops tolerant to shade that do not show significant yield reduction or increase under shaded conditions;
2. neutral crops that are not significantly affected by light limitation, at least at a low level of shading; and
3. sensitive crops whose growth and productivity are significantly affected by shading.

Information on the classification of crops according to these three groups, or in general based on their suitability for cultivation under shaded conditions, is scarce. Additional criteria to inform the selection of suitable species are based on physiological and morphological traits (Dupraz et al., 2011; Marrou et al., 2013a,b). The main traits and shade ranges that have been investigated on a selection of crops in scientific experiments carried out under actual or simulated AV conditions are summarised in Table 1.

Considering that data on the ability of crops to produce sustainable yield under the shaded conditions of AV are scarce (Dupraz et al., 2011; Sekiyama and Nagashima, 2019), it can be argued that the selection of suitable vegetable species to match AV conditions should be based on results from research carried out in agroforestry or on agricultural species cultivated under artificial shade (Weselek et al., 2019).

However, the radiative micro-environment generated by an AV system, usually characterised by an average reduction of incoming radiation, is actually dynamic, in both space and time (Amaducci et al., 2018; Slattery et al., 2018). Therefore, selecting a genotype for a given AV system based on its capacity to grow at a specific and constant level of shading might not be a suitable strategy. Another limitation in selecting a species for AV systems based on shade tolerance is the consideration that this is the ability of a species to survive at low light levels (Valladares and Niinemets, 2008), whereas under an AV system, the aim is to grow crops that not only survive but that can contribute to the overall sustainability by producing a marketable yield. It is therefore argued that crop selection should not be limited to shade-tolerant species but should involve agricultural crops that can provide a sustainable production under a specific set of AV conditions. Therefore, the choice could include crops other than shade-intolerant species, such as maize (Sekiyama and Nagashima, 2019), that have the capacity to produce a sustainable yield under the dynamic environment of AV systems. The complexity of the AV environment is determined by the combination of a specific set of design features (panel density, panel height, tracking system, etc.) as well as climatic factors and soil conditions. This renders the classification of crops for their suitability to AV conditions particularly complex and potentially misleading.

Collection of field data on crop responses under actual AV systems is essential, but the results cannot be generalized by applying them outside of the specific conditions in which they were obtained. It is therefore relevant to define a set of objective criteria that can be used for determining crop suitability to specific AV conditions, such as CO_2 light-response curves, phenotypic plasticity, specific leaf area (SLA) (ratio between leaf area and leaf dry mass), radiation interception efficiency and crop cover rate.

An evaluation of the suitability of vegetable species to be cultivated under AV conditions based on their light-response curves can be used to describe how the rate of photosynthesis varies as a function of light (Wang et al., 2017; Sekiyama and Nagashima, 2019; Willockx et al., 2020; Frauhnofer ISE, 2020;).

Table 1 List of crops and crop parameters that have been investigated in AV system. The column "shade range" indicated the level of shading that was experienced by the crop in specific AV conditions reported by the authors

Crop	*Crop parameters*		*Shade range*	*Reference*
Lettuce	• Specific leaf area • Crop grow rate • Yield • Dry matter • Water use efficiency • Fresh biomass • Leaf temperature • Stomatal conductance • Crop temperature • Crop cover rate • Crop cycle length	• Leaves number and emission rate • Evapotranspiration • Water productivity • Water consumption • Photosynthesis/transpiration ratio • Leaf length, thickness, width, and dry mass • Radiation transmission efficiency • Radiation conversion efficiency • Radiation interception efficiency	20%-50%	*Marrou et al., 2013a; 2013b; 2013c. Valle et al., 2017; Elamri et al., 2018*
Cucumber	• Leaves numbers and temperature • Leaf emission rate • Evapotranspiration	• Water use efficiency • Soil cover rate • Dry matter accumulation • Crop cycle length	38%-63%	*Marrou et al., 2013a; 2013b*
Potato	• Marketable yield		40%	*Schindele et al., 2020*
Celeriac	• Diameter and weight of bulbs • Harvestable yield • Chemical composition	• Fresh matter • Dry matter • Leaf area index	30%-40%	*Schindele ed al., 2020; Weselek et al., 2021*
Cherry tomato, jalapeño, chiltepin pepper	• Cumulative CO_2 uptake • Total fruit production • Water use efficiency	• Net photosynthesis • Transpiration	N.D.	*Barron-Gafford et al., 2019*
Tomato	• Yield • Water productivity	• Dry biomass • Plant water content • Evapotranspiration	N.D.	*AL-agele et al., 2021*

Grass	• Yield • Dry biomass	• Water use efficiency	40%	*Hassanpour Adeh et al., 2018; Trommsdorff et al., 2021*
Corn	• Yield (grain and biomass) • Fresh weight	• Dry biomass • Crop revenues	5%-50%	*Amaducci et al., 2018; Sekiyama and Nagashima, 2019*
Wheat	• Phenological stages • Crop temperature • Yield	• Dry matter content • Crop cycle length	29%-57%	*Dupraz et al., 2011; Marrou et al., 2013b; Schindele et al., 2020*
Grape	• Crop cycle length • Fruit quality: coloration, sugar content	• Germination, bud sprouting period and growth of flower	30%	*Cho et al., 2020*
Flowers	• Bloom time	• Bloom abundance	25%-95%	*Graham et al., 2021*

In particular, CO_2 light–response curves are characterised by two meaningful parameters:

1. the point where photosynthetic activity of the plant equals respiration, defined as the light compensation point (LCP); and
2. the light saturation point (LSP) at which the photosynthetic rate reaches its maximum, above which further increments of light no longer increase assimilation.

Values of LCP and LSP vary among species, particularly depending on carbon assimilation pathways (C3, C4 or CAM), and within the same species at different phenological stages, in different environmental conditions (e.g. temperature), and in leaves present in different canopy layers (Kephart et al., 1992; Niinemets, 2007; Wang et al., 2017).

Plants with low LSP and LCP are light-demanding species that show low tolerance to shade conditions (Wang et al., 2017). Fraunhofer ISE (2020) hypothesised that crops with a low LSP are the most suitable for growing under an AV system. On this basis, the selection of species to be cultivated should be restricted to C3 plants that have a low LCP and LSP and are more shadetolerant, but are less photosynthetically efficient than C4 plants (Kephart et al., 1992). Different values of LCP and LSP for the major crops were reported by Tazawa (1999). Generally, shade-sensitive crops (a third group as proposed by Beck et al., 2012) need an average daily photosynthesis activation radiation intensity (PAR) greater than LCP to achieve marketable yield (Wang et al., 2017).

The relative yield reduction observed in various AV experimental conditions has been reported for several crops (Fig. 4). Data come from different conditions, which makes it difficult to compare results accurately, and only general conclusions on the relationship between crop production and shading can be drawn. In most cases, with a reduction of radiation intensity between 20% and 40%, yield reduction was between 20% and 25%. For grass, celeriac, potato and wheat crops, even with a radiation intensity reduction as high as 40%, a yield increment was observed. These data highlight that there is a strong variation in response to shading between crop species.

Maize is generally considered a shade-sensitive crop and is the only C4 species in the published literature that has been evaluated under AV systems in field experiments as well as in a simulation modelling study. The modelling study indicated that the yield of rainfed maize on average was higher under a set of AV conditions than under full light conditions, and the yield advantage under AV became highly significant under drought conditions (Amaducci et al., 2018). In the field trial (Sekiyama and Nagashima, 2019), maize was grown under two levels of shading at low and high PV panel densities and compared to plants grown under full light control. Surprisingly, the highest yield was obtained under the low panel density configuration, while at high density, the yield was slightly lower than under full light conditions. This confirmed the result of the modelling study and further validated the possibility of growing maize under AV conditions, especially considering that in the trial, the maize was irrigated and therefore not subjected to drought stress. These results indicate that a small fraction of the total incident radiation is required for plants to reach their maximum rate of photosynthesis (Sekiyama and Nagashima, 2019).

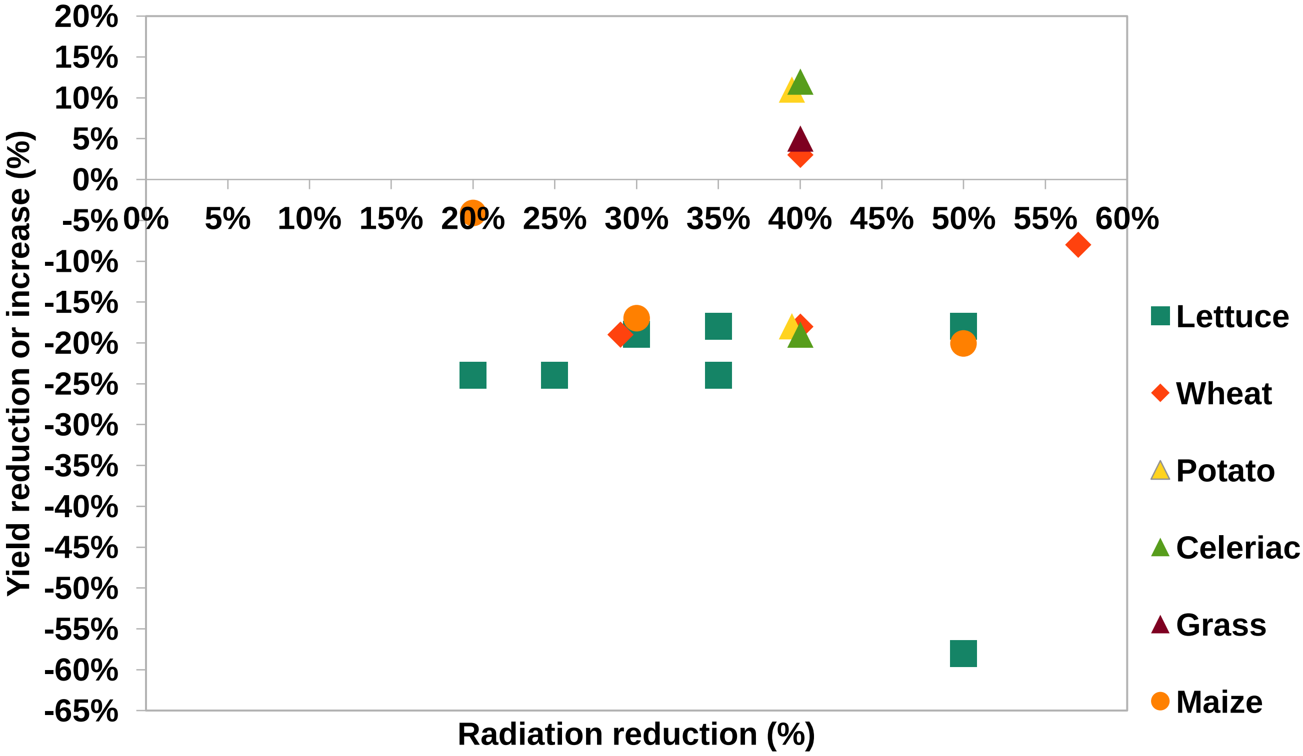

***Figure 4** Relative yield reduction (%) compared to radiation reduction (%) for selected crops cultivated under AV conditions. (Data obtained from cited references.)*

In a simulation similar to that conducted by Amaducci et al. (2018), maize grown in the Po Valley, Italy, showed yield reductions to be a function of the reduction in radiation obtained (Fig. 5). The radiation reduction level (RRL) was estimated from the relationship:

$$RRL = 100 * \frac{(rFL - rAV)}{rFL}$$

where rFl is the PAR intensity accumulated between crop emergence and harvest in full light conditions, and rAV is the mean PAR estimated in an AV system (https://www .remtec .energy/). The vertical bars represent the standard deviation of the relative yield reduction.

The simulation was conducted in the absence of water stress, to highlight only the effect of radiation. This simulated yield reduction for maize is in agreement with that reported by Sekiyama and Nagashima (2019) and confirms that, in conditions of high irradiation such as around the Mediterranean, a significant reduction in radiation can result in a crop yield reduction of less than 20%.

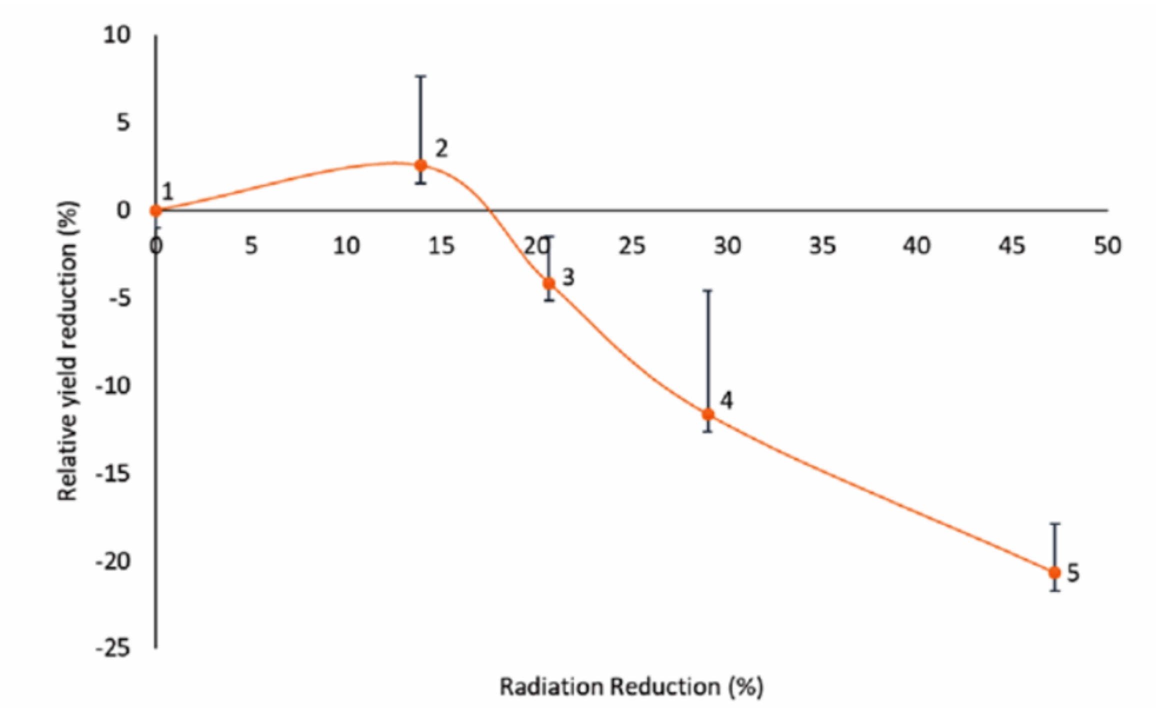

Figure 5 *Relationship between radiation reduction (%) from shade and the simulated relative yield reduction (%) for a maize crop cultivated in the Po Valle, Italy (Amaducci et al., 2018), with data taken from four AV systems with increasing panel area/ground area ratios between o.12 and 0.45.*

Therefore, the shading conditions that are generated under AV systems should be examined in the context of the topology of full radiation and shaded areas. Diffuse radiation plays a fundamental role in photosynthesis because, in most situations, crops use diffuse light more efficiently than direct light (Brodersen et al., 2008; Li and Yang, 2008).

Phenotypic plasticity (PP) is the phenotypic adaptation of a genotype to the variation of environmental conditions (Gratani, 2014; Sage and McKown, 2005; Valladares and Niinemets, 2008; Nicotra et al., 2010). It is relevant when selecting species to grow under AV conditions (Marrou et al., 2013c). The PP is related to leaf traits including radiation conversion efficiency, net photosynthetic rate, SLA, leaf chlorophyll content, leaf lifespan and leaf insertion angle. These change due to the light gradient along the canopy layers and the decrease of the red/ far red ratio (Gratani, 2014). Phenotypic plasticity in shade-tolerant species is generally lower than in shade-intolerant species, but it differs according to the leaf trait patterns (Portsmuth and Niinemets, 2007; Valladares and Niinemets, 2008).

Plasticity increases light capture by improving plant response in different environmental conditions such as adaptation to drought conditions or limited solar radiation (Valladares and Niinemets, 2008). A reduced potential in PP was reported for C4 species compared to C3 species. In fact, when the characteristics of acclimatisation to low light are considered, C4 plants seem to be lacking in one or more traits when compared to C3 species (Sage and McKown, 2005).

The adaptation of crops to shaded conditions consists of an increase in SLA (cm2 g−2), a decrease of the chlorophyll a/b ratio, and an increase in total chlorophyll content under low light conditions, which can increase the carbon gain in a shaded environment (Valladares and Niinemets, 2008). Leaves tend to show a high value of SLA in the shade to improve light interception (Gratani, 2014). The SLA reflects leaf thickness and the difference between sun leaves and shade leaves; it depends on leaf internal structure that performs an important role in light capture (Evans, 1999).

A relevant feature to consider under AV conditions is radiation interception, which depends on incident radiation, leaf area index and the extinction coefficient of canopy architecture (Sadras et al., 2016). In AV systems, the crop radiation interception efficiency (RIE) represents the major compensation mechanism to achieve high yield in shaded conditions (Marrou et al., 2013c).

The RIE is the plant's ability to cover the soil under the PV panels, also indicated as 'crop cover rate' (Marrou et al., 2013c). Crops that show high plasticity of cover rate (proportion of soil area covered by the crop) are able to intercept more light in shaded conditions (Valladares and Niinemets, 2008; Marrou et al., 2013c). In AV systems, selecting crops with a high soil cover rate increases light capture, increases photosynthetic efficiency when there is a light reduction and reduces soil evaporation (Marrou et al., 2013a). The cover rate of crops contributes to an increased water-use efficiency at certain stages of the crop cycle. At the onset of vegetative growth, the plants cover the soil less efficiently because the canopy is not fully developed. During the vegetative stage, crops cover the soil efficiently and help reduce soil evaporation. The cover rate also depends on the plants acclimatising to shaded conditions and to the rapidity of their vegetative growth (Marrou et al., 2013a).

Lettuce is an example of a crop that can exploit a high cover rate or a high RIE by increasing the total plant leaf area, optimizing leaf canopy architecture to harvest light more efficiently, and reducing leaf angle (if the leaf angle is close to horizontal orientation, the crop would cover a significant proportion of the ground and intercept more light) (Marrou et al., 2013b,c). Conversely, cucumber and wheat crops grown under AV conditions did not show a high cover rate or significant morphological changes, indicating low plasticity to shaded conditions (Marrou et al., 2013b).

Despite this, the adaptation of cropping practices in AV systems can contribute to finding the optimum solution to cultivate crops underneath an array of panels. For example, an increase in the RIE can be obtained by selecting the optimum planting distance (by increasing inter- and intra-row spacing) in order to avoid the leaves' self-shading (Marrou et al., 2013c).

Additional synergies between electricity production and agronomic management in AV systems are related to the cooling of the PV panels, the modification of surface albedo (the fraction of the total solar radiation that is reflected by a surface) and the reduction of soiling, which can all have significant effects on electricity production.

Soiling, which is the accumulation of material on PV panels that reducestheir power output and performance, is influenced by environmental conditions, and, in particular, by the presence of dust and its properties (i.e. the size, shape and weight of dust particles). Electricity output can technically be reduced from 2% to 50% by dust deposition on PV panels (Maghami et al., 2016). Agricultural management of AV systems can play a role in reducing the soiling effect by influencing the level of dust production and accumulation (Ravi et al., 2016). For instance, the implementation of conservation agriculture that promotes permanent soil cover and minimal or no soil disturbance (such as minimum tillage or no-tillage) can significantly reduce the production of dust and at the same time provide additional benefits such as increased water- and nutrientuse efficiencies and reduced land degradation (Baker et al., 2005)

The application of conservation agricultural practices could also contribute to the preservation or improvement of soil properties. Information on the effect of AV systems on soil conditions is limited. The impact of rain on the soil, which can be a major determinant of compaction in bare soils, can be influenced by the presence of overhead PV panels. In AV systems with one or two axes where the panel angles can be adjusted, Elamri et al. (2018b) indicated that keeping the panel horizontal during a rainfall event increases the spatial heterogeneity of rainfall distribution on the soil, with a potential increase in runoff and soil erosion.

Access to machinery can result in soil compaction (Soane et al., 1981). Under AV systems, this problem can be exacerbated by periodic maintenance operations that require heavy machinery. On the other hand, the presence of supporting infrastructures, which limit free movement in the field, confines all vehicles accessing the field to permanent traffic lanes. Implementation of controlled-traffic farming, which is a strategy to reduce the problem of soil compaction (Tim Chamen et al., 2015), could be particularly effective for AV systems.

Air temperature plays a key role in affecting PV module efficiency, and the implementation of cooling strategies can significantly increase electricity outputs (Dwivedi et al., 2020). In AV systems, crops generate a passive cooling effect on PV panels, thanks to plant transpiration (the release of water from aerial organs of the plant to increase heat dissipation). Transpiration is a natural cooling mechanism that can dissipate up to 32.9% of the total absorbed solar energy by the leaves (Othman et al., 2020). Barron-Gafford et al. (2019) demonstrated that during the cultivation of cherry tomato, chiltepin pepper and jalapeno under AV systems, the PV panel temperature was significantly cooler than in a traditional ground-mounted array. The temperature decrease documented by Barron-Gafford et al. (2019) in the growing months of May– July led to a 3% increase in electricity generation over those months and a 1% annual increase.

Another aspect that influences PV output, especially for bifacial modules, is the surface albedo. The performance of bifacial panels is positively affected by albedo and by the installation height of the panels.

Bifacial panels generate more electricity than similarly sized monofacial panels by producing electricity from both sides of the panels (Rodríguez-Gallegos et al., 2020; Guo et al., 2013). Crop albedo depends on leaf characteristics, such as colour, presence of surface waxes, orientation and trichome density (Doughty et al., 2010), plant height, agricultural practices, soil moisture and vegetation cover (Todd and Hoffer, 1998). It varies within the crop growth cycle among phenological stages (Oguntunde et al., 2007; Oguntunde et al. 2004). Mulching techniques can influence the surface albedo and thereby also the surface energy budget. Fan et al. (2014) showed that grassland albedo was increased by 23.5% and 33.9% on clear and cloudy days, respectively, when it was covered by agricultural white plastic film. Therefore, combining the use of a white mulch to avoid weed infestation and in conjunction having crops growing, and not bare ground, can be a strategy to increase albedo, and consequently electricity production. In turn, bifacial panels can improve the availability of sunlight for crops by multiplying the reflection of incoming light to the ground. Schindele et al. (2020) reported a gain in electricity generation of 8% for bifacial panels in an AV system with potato, wheat or celeriac crops in the first year of operation.

4 Crop modelling applications for the management of agrivoltaic systems

Since the 1970s, the application of modelling has complemented agronomic studies to support the understanding and interpretation of the physical and physiological phenomena (such as soil, nitrogen, water dynamics, radiation interception, photosynthesis) involved in crop production. However, the pioneering phase, in which crop models were mainly aimed at estimating crop production, has passed. The available modelling solutions enable the development of computing platforms. These are used for a multitude of scientific and technical applications, for example, to support decisions related to crop management (Thorp et al., 2008, Bonfante et al., 2019); to aid plant breeding (Cooper et al., 2014); and to perform scenario analysis, for example, when related to the impact of climate change.

Research on AV systems is in its infancy and the application of modelling to understand the response of crop growth and development under AV conditions has been extensive (Dupraz et al., 2011; Marrou et al., 2013a; Dinesh and Pearce, 2016; Valle et al., 2018; Elamri et al., 2018a; Amaducci et al., 2018). The complexity of AV systems and the trade-offs that exist between electricity generation and crop production suggest that the use of computing platforms should not be limited to the management of AV systems but should also include their design. This is particularly important when the construction and operation of AV systems is constrained by regulations or by specific agronomic requirements. In this context, modelling can be performed to simulate how various design parameters (such as PV panel dimension, height of the panels from the ground, panel density, sun-tracking configurations, plant layout and interaction with site topology) can affect the microclimate under the panels and particularly the level of radiation. Computing platforms using simulated micrometeorological data will therefore be able to simulate the potential physiological and productive responses of crops cultivated underneath the panels. In principle, it is not necessary to develop a new crop model specifically designed for an AV system, given that numerous crop models with varying levels of sophistication are available (Di Paola et al., 2015). Crop models to be used for applications related to AV systems can implement either complex mechanistic functions or simple empirical functions. Mechanistic models implementing sophisticated algorithms that simulate the response of individual physiological processes to environmental variables have been successfully applied to AV systems to model crop response to the daily variation in radiation.

The mechanistic model 'STICS' was used for the first time by Dupraz et al., (2011) to simulate crop productivity under the shade of PV panels. 'GECROS' was used by Amaducci et al. (2018) for a long-term simulation of maize cultivation under AV in Italy. For large-scale simulations that include a complex scenario analysis requiring high computational complexity, a simple model is appropriate. Campana et al. (2021) aim at developing a techno-economic optimisation model for AV systems with the 'EPIC' model, implemented for its low parameterisation requirements.

4.1 Simulation aspects in agrivoltaic platforms

What makes AV simulation particularly complex is the extreme dynamism of the environmental variables in the cultivation area under the panels. Shade conditions vary continuously throughout the day, with significant effects on the soil and microclimate. Marrou et al. (2013b) and Barron-Gafford et al. (2019) identified that the variability of micro-climatic conditions under the panels resulted with respect to full light, detectable both in hourly observations during a day as well as during the entire season. The reality is likely to be even more complex than reported by Marrou et al. (2013b) because the daily shading dynamics vary considerably with space and time at ground level. This appears in ground radiation maps (Dupraz et al., 2011, Amaducci et al., 2018, Elamri et al., 2018a) and has significant effects on the balance of ground radiation, temperature and evapotranspiration (Elamri et al., 2018a; Amaducci et al., 2018).

The capacity of a model to handle complex simulations should be evaluated considering the specific objectives of the simulations and the available resources (Liman Harou et al., 2021). Considering the modelling work with regard to the AV systems already performed in this context, for any modelling objective, good radiation estimations and an efficient system to map shading generated by the PV panels are essential prerequisites. Coupling radiation data (measured or simulated) with crop models enables an estimation of plant growth with a level of precision that is similar to that achievable under normal conditions in the open field.

Crop simulations under AV systems can be performed to verify whether certain construction choices, such as panel density or height from the ground, can guarantee the level of radiation necessary to achieve a certain production target. The simulation can be performed for specific crops or for entire cropping systems following defined agronomic management, while the target production level can be dictated by economic, social or political constraints. Simulation models could also greatly facilitate management operations, as presented in the work of Elamri et al. (2018a) who developed a model to support irrigation in an AV environment.

Regardless of the specific objectives of the modelling activity, the fundamental steps necessary to launch a simulation are:

1. create a radiation dataset for the specific AV environment;
2. complete the dataset with all other microclimate variables;
3. select soil and crop parameters; and
4. run the simulation.

The realization of time-related radiation maps and dynamic shading models implies computational strategies for:

- ray-tracing and shading;
- definition of the areas cultivated on the ground with an estimate of all the shading trajectories in each single portion (plot); and
- estimation of direct and diffuse radiation.

The above-mentioned steps use rather well-established computational technologies that rely on the light-interception literature for the estimation of electricity production of solar panels (Quaschning and Hanitsch, 1995, Khan et al., 2017, Mousazadeh et al., 2009) and calculation of ground radiation (Dupraz et al., 2011; Diaz et al., 2015; Riaz et al., 2020).

In the creation of a radiation dataset, an important feature is the spatial resolution for the simulations. In this regard, two options are available:

1. Create input datasets (hourly or daily) that spatially integrate the different radiation conditions. The calculations are considerably simplified but the simulation loses the possibility to distinguish the effects of contrasting values of radiation that are present within the same plot.
2. Create radiation (direct and diffuse) datasets for each element of a mosaic of small pixel-plots (e.g. 0.12 m) as performed by a multi-year study on maize (Amaducci et al., 2018). This could be performed on all or just a few 'representative' plots of the cultivated area, as performed for a lettuce simulation (Marrou et al., 2013b; Dinesh and Pearce, 2016). Both methods have advantages and disadvantages.

Here, the calculations are demanding in terms of computational resources, and time consuming, especially for hourly (or shorter) time steps. This option can be used in scientific studies that aim at understanding the effect of variability under an AV system when managed as vegetable gardens, with multiple crops present at the same time. In this case, the position of each crop under the PV panels can be decided according to the spatial variation of meteorological parameters and the specific requirements of each species.

Besides radiation, for other climatic variables needed for completing climate datasets (including air temperature, relative humidity, wind speed and rain), two solutions were adopted in the literature:

- To use actual data measured under AV systems in the specific positions where the simulations were carried out;
- To use the data of a weather station positioned nearby the AV system but in the open air, assuming that the influence of AV infrastructures on microclimatic conditions, with the exception of radiation, is negligible.

'Adjustments' can be made to this simplification, as done, for example, by Elamri et al. (2018a) who implemented a model to simulate a precipitation pattern modified according to PV constructive details. So far, no study has been published for the simulation of the microclimatic conditions under AV systems in which all the variables, including changes in air humidity, wind speed and their interactions with the AV system, are integrated into a microclimate-model, though a model similar to this was proposed for AV greenhouses by Fatnassi et al. (2015).

Another important limitation relating to the measurement of microclimatic variables in the literature on AV systems is that measurements have been carried out in pilot AV plants, which are probably too small to capture the effect that full-scale AV systems can have on meteorological variables.

Despite this limitation, once an appropriate climatic dataset is available, the simulations of crop growth under AV environments can be carried out in the same way as for normal crop models. However, the effectiveness of the model will depend on the parameterisation and the collection of sufficient data for the necessary operations of calibration and validation.

4.2 Design and optimisation

As already pointed out, model exploitation goes beyond the potential of simulating the effect of shading and microclimate on crop production. Advanced use of the models can be of value in the design phase to create an AV system design suitable for a given location (annual solar irradiation and its seasonality), a specific cropping system and a set of specific economic, environmental and social constraints. Altogether, these aspects can only be addressed with a calculation platform that combines simulation models (for the crops and for the meteorological parameters, including radiation) with multi-objective optimisation systems.

• A paradigmatic example addressing the optimisation problem in AV systems was proposed by Campana et al. (2021), in which a set of variables including the LER and economic and constructive features were used as driving variables to identify optimal AV solutions. To analyse most of the tradeoffs involved in the design and operation of AV systems, the optimisation algorithm maximises

LER, minimises the fluctuation of electricity injected into the grid in terms of annual standard deviation (STD) and maximises the annual electricity production. Although this study was carried out for a northern European environment in Sweden, with vertical panels, interesting conclusions emerged that underline the broad potential of this approach.

• By studying the contributions of LER (i.e. the crop yield and the electricity production contributions), it became evident that the optimal row distance varies according to the crop. This leads to important consequences in terms of the long-term optimal design of AV systems.

• An optimal design of AV systems should consider multi-year and multicrop simulations and optimisation based on conventional farm activities.

• LER cannot be used as the main variable for the optimal design of AV systems. More objective functions should be included for a better estimation of the synergies between crop and electricity production. Maximising the LER tends to drastically reduce electricity production, and this could undermine the economic sustainability of the system.

5 Conclusion and future trends in research

Agrivoltaic systems are expected to be resilient energy/food systems that, by combining the production of food with that of renewable energy, could provide valuable solutions to major future challenges for humanity. They have the potential to support the multiple Sustainable Development Goals (SDGs) mainly 'Affordable and Clean Energy' (SDG 7), 'climate action' (SDG 13) and, when applied in developing countries or where food production is insufficient, 'Zero Hunger' (SDG 1). In addition, the possibility of developing AV systems in urban and peri-urban areas (Majumdar and Pasqualetti, 2018) renders them relevant for 'Sustainable Cities and Communities' (SDG 11), while growing species under the shade of the panels that attract pollinators or that increase biodiversity, making AV systems compatible to 'Life on Land' (SDG 15).

There is an urgent need to transition to renewable energy sources, and AV systems appear to be a valid contributor within the renewable sector. Therefore, it is essential that additional research needed to validate their contribution to the above-mentioned SDGs is facilitated and accelerated.

This chapter has outlined the promising results obtained from preliminary research on AV systems. It has highlighted the need to co-optimise electricity and food production and evaluated the effectiveness of AV systems to help meet global environmental goals.

The benefits of AV systems have been found across the food–energy– water nexus, particularly where water is a limiting factor (Barron-Gafford et al, 2019). Future research and development will help to identify the conditions under which AV systems can increase water-use efficiency and mitigate water stress, particularly in areas that will be negatively affected by climate change (McAusland et al., 2016).

The availability of AV installations is limited and experiments to validate their potential under various environmental conditions, and with a large number of crops and cultivation systems, are expensive and time consuming. Therefore, at least in the short term, simulation studies will be used extensively. Future research is needed to calibrate and validate available models, which can thereafter be used to optimise AV systems and, more specifically, simulate the conditions under which they can:

- lower the impact of heat and high radiation stress to increase the resilience of the agricultural sector against the threat of climate change;
- stabilise and increase crop production;
- turn barren and degraded land into viable areas for agricultural production and ecosystem service provision;
- maximise land-use efficiency and energy gain from high solar radiation; and
- reduce GHG emissions by avoiding fossil fuel combustion.

Significant improvements in optimising AV systems will be achieved when modelling solutions developed specifically for the AV environment become available. They will enable simulation of the physical environment, particularly the microclimate and soil moisture dynamics, and the capacity of a crop to acclimatise to the AV system by adjusting its morphology and physiology.

These research goals are mainly focussed on the productivity of AV systems.

The impact that cultivation under AV systems can have on the quality of the crops can be evaluated. So far, only a few studies have addressed this issue (e.g. the chemical composition of celeriac by Weselek et al. (2021)). Cultivation of horticultural crops, fruit trees and even grapevines has high potential under AV systems, given the effect that AV conditions can have on quality parameters such as fruit colour and sugar content (Cho et al.,2020).

Most experiments to date have focussed on the effect of shading on crop production, on the water-use efficiency, and on the identification of shade tolerant species. Little attention has been paid to the modulation of other production factors such as plant nutrition or on the incidence of pests and diseases (Weselek et al., 2021).

Thus, AV systems can play a pivotal role in the transition toward the deployment of renewable energy systems. Guidelines for their development will require multi-disciplinary research. Engineers and plant scientists should work together to optimise AV system designs; agronomists must elaborate appropriate crop rotation and cultivation techniques; and landscape designers should propose strategies to integrate AV systems into the landscape so that they can respond to the ‘sustainable energy landscape approach’ and help meet the sustainable development goals.

6 Where to look for further information

Agrivoltaics conference: https://www.agrivoltaics-conference.org/

Agrivoltaics - Fraunhofer Institute for Solar Energy Systems ISE: https://www.ise.fraunhofer.de/en/key-topics/integrated -photovoltaics/agrivoltaics.html

Sustainable agrivoltaics – ENEA: https://www.agrivoltaicosostenibile.com/en/

The Colorado Agrivoltaic Learning: https://www.coagrivoltaic.org/

SANDBOX SOLAR: https://sandboxsolar.com/agrivoltaics/

Wikipedia: https://en.wikipedia.org/wiki/Agrivoltaic

RemTec https://remtec.energy/en

Sun'Agri https://sunagri.fr/en/

BayWa r.e. https://www.baywa-re.com/en/solar-projects/agri-pv

Next2Sun https://www.next2sun.de/en/homepage/

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Chapter 2: Agrivoltaic system and modelling simulation: a case study of soybean (*Glycine max* L.) in Italy

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Abstract: Agrivoltaic systems (AV) combine agricultural activities with the production of electricity from photovoltaic (PV) panels on the same land area. The concept of AV systems was introduced in 1981 by Goetzberger and Zastrow but only more recently increased environmental concerns and favorable economic and political frameworks stimulated a growing interest on this technology. A critical issue in the development of AV is the selection of crops that can grow profitably under the micrometeorological conditions generated by AV systems. This experiment studied the effect of 4 different shade depth treatments (AV1=27%, AV2=16%, AV3=9% and AV4=18%) on the morphology, physiology and yield of a soybean crop grown under a large-scale AV system. Field results were used to validate the output of a simulation platform that couples the crop model GECROS to a set of algorithms for the estimation and spatialization of shading, radiation, and crop-related outputs. Crop height, Leaf Area Index (LAI) and Specific Leaf Area (SLA) all increased under the most shaded AV areas compared to full light (FL, control) conditions. On average, under AV sys-tem, grain yield and number of pods per plant were reduced by 8% and 13% and only in one area (AV2), a slight increase in grain yield (+4.4%) was observed in comparison to FL. The normalised root means square error (nRMSE) value of predicted grain yield differs from the observed grain values of 12.9% for FL conditions, 15.7% in AV1, 16.5% in AV2, 6.71% in AV3, 2.82% in AV4. Although the model simulated yield satisfactorily results on RMSE revealed that the model tends to underestimate the yield with increase of shade in particular for AV1 and AV2 conditions.

Keywords: Soybean, Agrivoltaic system, Modelling, shading, yield

Citation: Potenza, E.; Croci, M.; Colauzzi, M.; Amaducci, S. Agrivoltaic System and Modelling Simulation: A Case Study of Soybean (*Glycine max* L.) in Italy. Horticulturae 2022, 8, 1160. https://doi.org/10.3390/horticulturae8121160

1. Introduction

In 2015, the United Nations General Assembly [1] defined the 17 Sustainable Development Goals (SDGs). Among these SDG 7, which targets the production of sustainable energy, aims at i) ensuring universal access to affordable, reliable, and modern energy services; ii) increasing substantially the share of renewable energy in the global energy mix and iii) doubling the global rate of improvement in energy efficiency [2]. In addition to these targets, SDG 7 also intends to stimulate investment in energy infra-structure and clean renewable energy technologies.

The use of renewable energy sources provides multiple benefits to society, as they reduce CO2 emissions, improve air quality, and economic growth, and can help to move forward to more efficient and cleaner power production. In 2021 solar energy, among renewable energy sources, reached a capacity of 849 GW, increasing by 18% compared to that of 2020 (716 GW) [3]. At the same time, an effective energy transition strategy would require an increase in the use of renewables bigger than the projected growth in energy demand, in order to curtail the share of non-renewable energy employed. Many countries still strive for this goal, despite dramatic increases in their share of renewables for generating electricity [3].

Implementation of renewables can also have negative sides, and a major concern relates to the high land requirement of most renewables, which can compete with agricultural activities on land use, potentially resulting in a reduction of food production [4]. Agrivoltaic (AV) systems, combining food and energy production on the same land, can represent a win-win strategy that can increase land-use efficiency [5,6,7,8,9], while reducing water use by crops, especially in drought-prone environments [10]. In these environments, sustainability of agrivoltaic systems could be further increased by using wastewaters [11] or biostimulants [12].

The concept of AV was first formulated in 1981 [13], but only more recently in-creased environmental concerns and favorable economic and political frameworks stimulated a growing interest in this technology. The main driver of the current interest in AV is the development of sustainable renewable energies that have a low impact on soil consumption [14].

In the last decade, a growing number of studies have investigated different topics related to AV system. Most of the studies have addressed the impact of AV conditions on crop yield [5,6,14,15,16,17,18,19], but many others have recognized that AV systems tend to reduce crop evapotranspiration [18,20,21,22], protect the crop against extreme weather events (for example, drought stress [10]) and increase Land Equivalent Ratio (LER), which is an index used to evaluate a dual-use purpose compared to a mono-use (only photovoltaic panels or only crop) [5,6,7,8,9]. Despite this, studies are still insufficient to assess the impact of AV on the productivity and development of a large number of crops and only very few studies analysed the crops' physiological and morphological responses [13, 17,18,19,23,24,25] to the dynamic shading conditions generated by the AV system.

Height, vigour, stem potential, transpiration, photosynthesis, chlorophyll content (SPAD), Leaf Area Index (LAI) and Specific Leaf Area (SLA) are amongst the crops' physiological and morphological traits most influenced in low light conditions and shaded conditions [25].

The vigour of crops growing under shaded conditions tends to be greater to in-crease light interception and this trait reflects an adaptation of crops to shade [26,27,28,29,30].

In addition, in low light conditions, the adaptation of crops consists of an increase in SLA, a decrease in the chlorophyll a/b ratio, and an increase in total chlorophyll content, which can increase the carbon gain in a shaded environment [31]. A high value of SLA in the shade tends to increase light interception [32] and leaves appear thinner than those growing in sunlight conditions. The difference between sun leaves and shade leaves depends on the leaf internal structure which performs an important role in light capture [31]. Therefore, it can be assumed that even in the AV environment plants similarly behave as crops growing under low light or shaded conditions by modifying their leaves structures and by exhibiting physiological adaptation mechanisms, for example by changing stomata size and density and reducing transpiration as in cloudy days [33,34,35,36,37,38,39].

Furthermore, crop physiological and morphological traits can influence crop development by affecting the processes of light interception, photosynthesis, and transpiration as already demonstrated for LAI [25,41,42,43]. For example, LAI of celeriac [16], wheat, grass-clover, and potatoes [24] was higher under AV system than in full light conditions.

Information on the performance of industrial crops cultivated under AV systems is scarce, and limited data are available on soybean (*Glycine max* L.) cultivation under AV. Namely, two modelling approaches have been investigated for soybean [45,46]. Adoption of crop modelling approach allows an insight into the microclimatic conditions that are generated under AV systems by considering multiple micro-meteorological conditions (i.e., solar radiation, temperature, CO2 concentration, soil nutrients, and water), the management of the crops (i.e., plants number per m2 or fertilisation) and the crop yield response to the shading environment [46,47].

In a recent work, the response of soybean to an AV environment was modelled by coupling a crop model with a solar power generation model to obtain data on the effect of AV system both on crop yield and on net revenue for the landowners [46]. In another study carried out in Korea [45], field trials were carried out on rice, barley and soybean to collect the data needed to calibrate and validate three crop models (CERES-rice, CERES-barley, and CROPGRO-soybean) and to predict the impact of shade on crop yield.

In 2018, a pioneering AV simulation work on maize [6] had already demonstrated the importance of using models to study how crops respond to the microclimatic conditions generated in an AV system and how this response interacts with weather conditions that change from year to year. In the abovementioned study, for example, model simulations indicate that maize yield is more stable under AV conditions than under full light and that in dry and hot years rainfed maize yield under AV is higher than under full light.

In order to study the response of soybean cultivated under an AV system, a field experiment was set up and an improved version of the model previously run for maize [6] was used to simulate soybean growth under AV. In particular, the objectives of this research were: 1) to measure the morphological, physiological and yield response of soybean cultivated under the dynamic shading environment of a large-scale Agrovoltaico ® system [48] and 2) to use the experimental data to validate the capacity of the modelling platform to accurately simulate the response of soybean under such conditions.

2. Material and Methods

2.1 Study area and experimental design

The study was carried out under a large commercial AV plant (Remtec, Agrovoltaico® [48]) in Monticelli d'Ongina (Italy, 45°04'10''N - 9°55'40''E) where PV panels are stilt mounted on a biaxial full sun-tracking system. The experimental set-up included a control area "full light" (FL, 180 m^2) located just outside the AV system and 8 experimental areas (Figure 1) characterised by 4 different shade depth (SD) treatments (see section 2.4): 27%, 16%, 9% and 18% (by considering the average value of SD over the crop growing cycle), which are indicated respectively as, AV1, AV2, AV3 and AV4. Each area included 4 soybean rows for a total of 16 rows and an area of 144 m^2 for single replicate (2 replicates for each AV area).

Figure 1. *Experimental set-up of the soybean trial in Monticelli D'Ongina (2021). Different colours represent the different shade depth (SD) levels, and the four SD levels are indicated as follows: AV1= 27%, AV2=16%,AV3= 9% and AV4= 18%.*

Leaf Area Index (LAI) and yield data (pods number and pods fresh weight) were collected by using the quadrat-sampling methods [49] with a modification for the AV environment. The quadrats of the SD treatments were obtained by using a PVC quadrat frame (100 x 100 cm, 1 m^2) placed directly on top of the vegetation.

2.2 Agronomic management

The experimental field was ploughed (30 cm depth) to a fine tilth in March 2021. The soybean (Glycine max, L.) cultivar Namaste (Venturoli, maturity group 1/1+ [40]) was sowed on April 29, 2021. Sowing density was 50 plant m-2. The seeds were planted by a pneumatic seed drill (Gaspardo, Pinta [51]) at a depth of 3-4 cm. The inter-row spacing was 70 cm and the distance among seed on the row was 3 cm. To control weeds hoeing was performed on June 7, 2021, on inter-rows. Soybean plants were fully irrigated at 100% of crop evapotranspiration (ETc) with a sub-irrigation system with 15-day intervals (July 5 and July 20, 2021, and August 4, 2021). ETc was calculated by using the Irriframe cloud services developed by Water Boards Italian Association (ANBI)[52]. Harvesting was carried out on September 27,2021.

2.3 Field data collection

2.3.1 Crop height

Crop height is a morphological and shade-adaptive trait most affected under shaded environment [26,27,28,29,30] and under AV system [17,24] since crops tend to elongate their stems when light decreases. To study the effect of AV system on soybean height measurements were carried out throughout the growing cycle on four occasions: June 28, July 15 and 30, and August 9, 2021. Height was measured on 12 plants per treatment with 1 mm resolution.

2.3.2 SPAD Chlorophyll content

Chlorophyll content in leaves, which determines their photosynthetic capacity [53], is linked to the N-nutrition status of the plant and is affected by shading. According to studies carried out in moderate-shaded environments with peony [54] and red rice [55], under low light conditions for a large number of species [31] and in intercropping system (maize-soybean) [56], chlorophyll content tends to increase as light availability decreases.

Measurements of chlorophyll content in leaves were carried out in this study with the SPAD chlorophyll meter SPAD-502 plus (Konica Minolta) to measure the dynamics of leaves chlorophyll content throughout the phenological cycle. SPAD values were measured on 4 leaves of 3 different plants per treatment to obtain a representative mean value. Measurements were carried out on the following dates: June 23, July 7,15 and 30, August 9 and September 3, 2021.

2.3.3 Leaf Area Index (LAI) and Specific Leaf Area (SLA)

Leaf Area Index (LAI) was monitored throughout the growing season to evaluate crop adaptation under AV conditions. LAI was measured by using an AccuPAR LP-80 PAR/LAI ceptometer from METER Group. A total of 4 LAI measurements were carried out per shade depth treatment in the selected quadrat (12 measurements in total) in 4 development phases (early crop establishment: June 16; flowering stage: June 30; the full pods stage: August 9 and the maturity stage: September 3, 2021).

In addition to LAI, Specific Leaf Area (SLA) was also monitored. SLA is the ratio of leaf area to leaf dry mass ($cm^2\ g^{-1}$). SLA increase under low-light conditions [57,58,59] and in shaded conditions is an indication of the shade-adaptive mechanism of most plants [31,60]. SLA was measured under the AV system by randomly selecting 12 plants for each treatment (4 plants x 3 replicates for each treatment). Samples were collected on June 30, July 15 and August 9, 2021, during flowering, beginning and full pods development respectively. Samples of 15 leaves per plant with a fresh weight ranging from 4.5 g to 11 g were collected. Leaves samples were subsequently analysed with a desktop scanner for total surface estimation (cm^2). Leaves samples were then dried in a forced-air oven at 65°C until constant dry weight (g).

2.3.4 Crop yield parameter: fresh and dry weight of pods

All the plants in the quadrat were sampled and soybean pods were collected from the plants and immediately weighted in the field to record the fresh weight with a precision scale (Figure 2).

A) B)

Figure 2. *A) Soybean plant on September 27, 2021 (harvest date) under AV system and B) Sample of soybean pods after the harvest used to determine the pods number, fresh and dry weight of the pods and grain yield.*

The samples were subsequently oven-dried at 65°C until constant weight for determining the dry matter and the water content of each sample (following the method indicated by Kenig et al. [61]). The dry weight of the pods per quadrat was estimated from the fresh weight of the pods harvested in the quadrat and from the water content of the samples (Equations 2 and 3).

$$DW = FW - W_{c_{tot}} \cdot FW \qquad (2)$$

$$W_c = \frac{(FW - DW)}{FW} \qquad (3)$$

Where:

DW is the quadrat dry weight (g); FW is the quadrat fresh weight (g) and W_c is the water content of the pods.

Biomass productivity was then calculated from the quadrat dry biomass and expressed in t ha^{-1}. Once the DW of the pods was obtained, soybean seeds were separated from the pods and weighted to obtain the grain yield (g m^{-2}).

2.4 Simulations

Simulations were performed with an updated version of the modelling platform described in [6]. The system couples a crop growth model (GECROS [62]) to a set of algorithms for estimating and spatialising shading, radiation, and crop-related outputs.

The system can simulate the entire growing cycle of the crop, including phenology, carbohydrate partitioning and grain yield. Simulations were conducted on a 12m x 12m test area covering all shading conditions of the AV system used. Calculations were iterated in the test area on cells of size 0.5m x 0.5m allowing mapping of results.

Radiation mapping was calculated on cells with a resolution of 0.12m x 0.12m and 30 min time step. The mapped values of radiation were then used to compute the Shade Depth (SD) map (Figure 3).

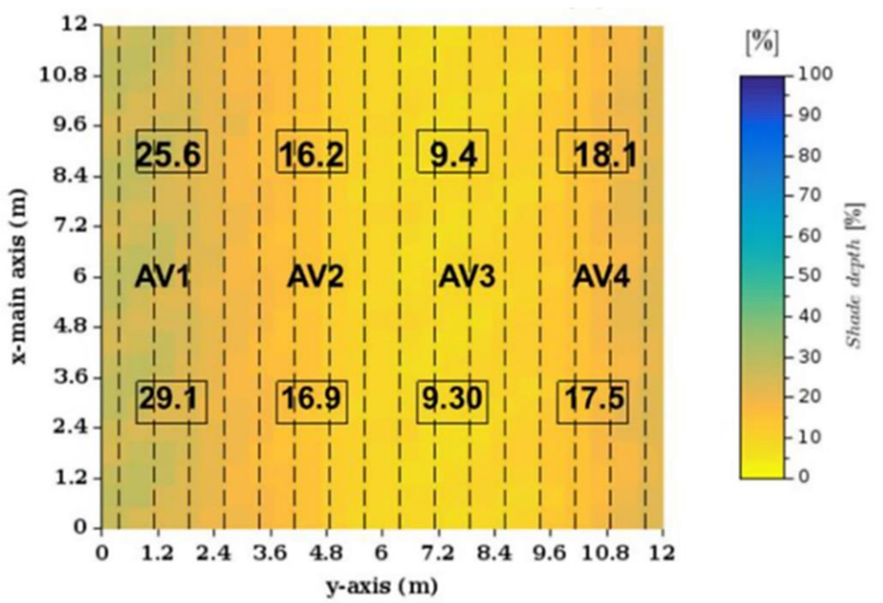

Figure 3 *Mapped values of radiation reduction "Shade Depth (%)". The vertical dotted lines represent crop rows and the boxes represent the plots positioning and size.*

SD indicates the reduction percentage of global radiation compared to full light, calculated as:

$$SD(i,j) = 100 * \frac{I_{FL} - I(i,j)_{AV}}{I_{FL}} \qquad (4)$$

Where I_{FL} is the Cumulated radiation in full light:

$$I_{FL} = \int_{t_{start}}^{t_{end}} g_{FL}(t)dt \qquad (5)$$

and *I(i j)* is the cumulated radiation in a cell *i, j* of the AV area:

$$I(i,j) = \int_{t_{start}}^{t_{end}} g(i,j)(t)dt \qquad (6)$$

SD values were estimated as mean values in the 1.5m x 1.5m plots (Figure 3). Simulated and observed grain yield values on the experimental plots were then plotted against SD values estimated at plots locations.

2.5 Statistical analysis

Statistical analysis was performed using Rstudio, R version 4.2.1 (R Core Team, 2022).

The statistical analysis of the physiological and morphological traits of the crop was carried out using two-way ANOVA to identify statistically significant differences among the experimental factors shading levels (FL, AV1, AV2, AV3, AV4) and time (dates) for the variables considered (LAI, SLA, SPAD etc.) (see Supplementary material). The two-way ANOVA for the SLA was carried out only on 2 dates: July 15 and August 9, 2021. One-way ANOVA was carried out for crop yield data.

The ANOVA test was followed by the post hoc Tukey's Honestly Significant Difference test. Simulation data were analysed through Root Mean Square Errors (RMSE) and Normalised RMSE (nRMSE, %) to measure the differences between simulated and observed values of soybean grain yield. The nRMSE was calculated by comparing the 4 simulated grain yield and the 4 observed grain yield in FL conditions, and, in AV system the 2 simulated grain yield and the 2 observed grain yield.

3. Results

3.1. Crop height

Average plant height (cm) (see Table 1 of supplementary material), measured during the whole growing cycle, of AV1 plants (98.25 cm) was significantly higher (p-value <0.05, see Table 2 of supplementary material) than that of FL plants (87.8 cm) and all other AV treatments (AV2= 86.95 cm, AV3=85.04 cm and AV4=90.81 cm), which indicates that only the most severe conditions of shade depth significantly affected stem elongation. Height of plants grown in AV2, AV3 and AV4 did not statistically differ from that of FL plants, but plants in AV1 were significantly higher than AV2, AV2 AV3 and AV4 (Figure 4).

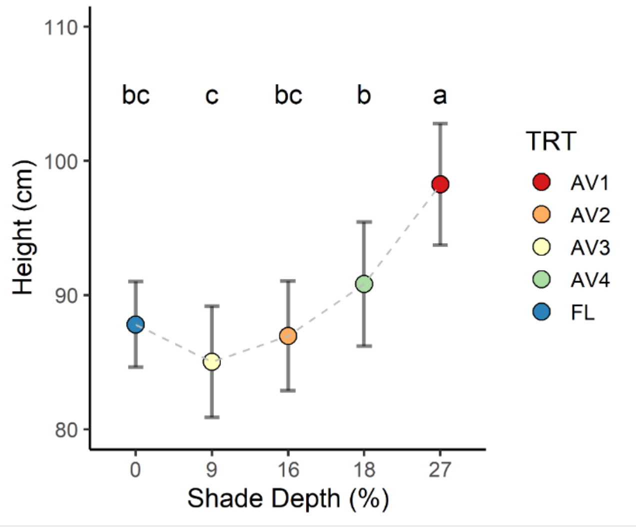

Figure 4 *Physiological response of soybean in terms of crop height (cm). Different letters (a, b, c, d) at the top of the graphs indicate statistically significant differences according to Tukey HSD-test.*

3.2. SPAD chlorophyll content

Differences in chlorophyll content among treatments were very limited and apparently not directly related to shading depth. SPAD value of the FL treatments (43.58) was statistically higher (p-value < 0.05, Figure 5, see Table 1 and Table 3 of supplementary material) than that measured on the AV2 treatment (41.87). The level of shading of the other three treatments did not affect SPAD compared to FL conditions (AV1=43.41, AV3=42.87, AV4=42.33).

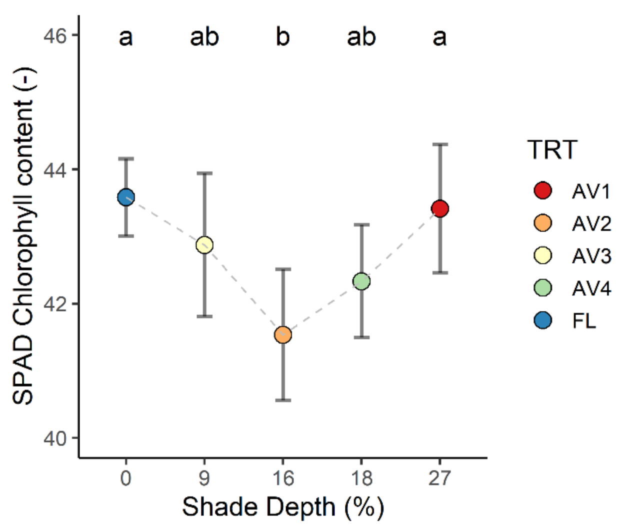

Figure 5 *SPAD values for different Shade Depth. Different letters (a, b, c, d) at the top of the plot indicate statistically significant differences according to Tukey HSD-test.*

3.3. Leaf Area Index and Specific Leaf Area

The highest LAI was found under the most shaded conditions (AV1) (Figure 6). Mean LAI at FL (2.78) was significantly lower (p-value < 0.05, see Table 4 of supplementary Material, Figure 6) than at AV1 (3.63).

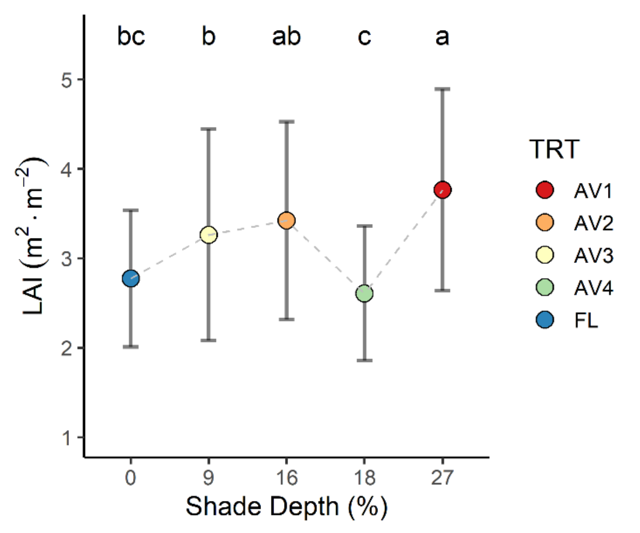

Figure 6 *Leaf Area Index (LAI, m2 m-2) value for different Shade Depth. Different letters (a, b, c, d) at the top of the plot indicate statistically significant differences according to Tukey HSD-test.*

LAI of the AV2 (3.42), AV3 (3.26) and AV4 (2.64) SD treatments were not different from that of FL (see Table 1 of supplementary material). However, LAI of the AV2 and AV3 treatments showed a tendency to increase compared to FL, which indicates that soybean adapted its canopy to shade progressively by increasing leaf area. This morphological adaptation is also supported by the measurement of SLA which increased by 9% (216 cm^2 g^{-1}) under AV1 compared to FL conditions (198 cm^2 g^{-1}) even though this difference, was not statistically significant (p-value ≥ 0.05, see Table 1 and Table 5 of supplementary material). The other treatments showed the following SLA values: 201 cm^2 g^{-1} (AV2), 159.12 cm^2 g^{-1} (AV3), 194.90 cm^2 g^{-1} (AV4).

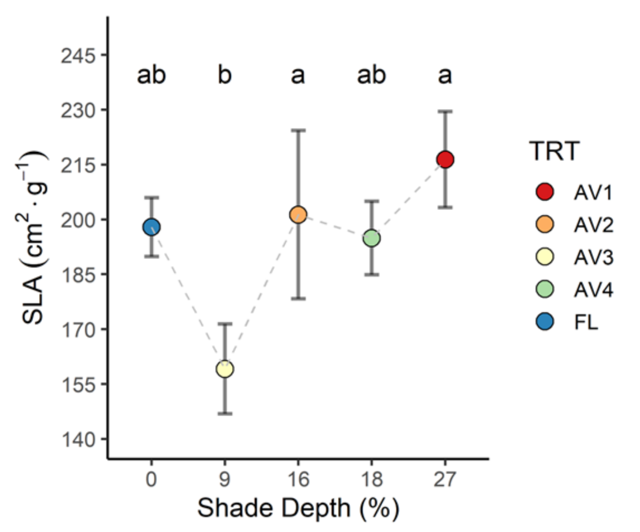

Figure 7 *Specific Leaf Area (SLA, cm^2 g^{-1}) for different Shade Depth. Different letters (a, b, c, d) at the top of the graphs indicate statistically significant differences according to Tukey HSD-test.*

3.4. Crop yield parameters

Pods number and grain yield showed a decreasing trend with increasing SD levels (Figure 8A and 8B, see Table 1 of supplementary material). In particular, in the most shaded treatments (AV1 and AV4) pods number was reduced by 19.4% (1983, AV1) and 18,2% (2011, AV4) compared to FL conditions (2461) (Figure 8A) and, in AV2 and AV3 treatments the number of pods was reduced by 3.3% (2379) and 11.5% (2177) respectively. Total pod number reduction compared to open field conditions was on average 13% considering the whole AV conditions.

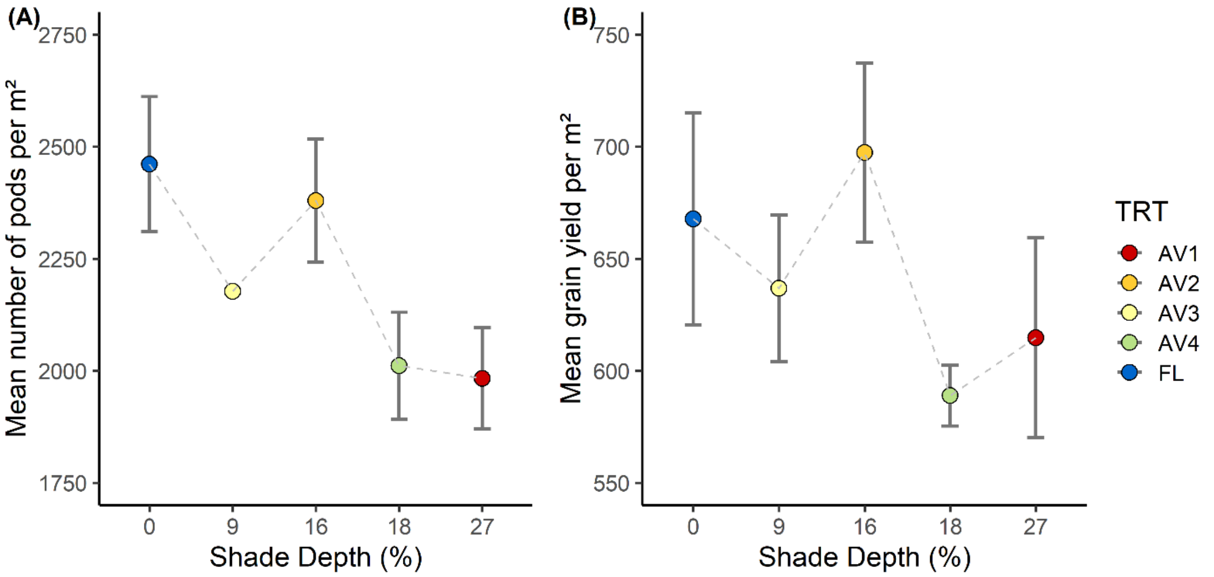

Figure 8. *Effect of shading depth on soybean yield response in terms of number of pods m-2 (A) and grain yield per g m-2 (B). Data variability within treatment is indicated by the standard deviation bars (Figure 8A and 8B, see Table 8 and 9 of supplementary material).*

While not statistically significant (see Table 6 and Table 7 of supplementary material) the grain yield reduction compared to FL (667 g m-2) was 8% (614 g m-2), 4.6% (636 g m-2), and 11.8% (588 g m-2), respectively, for treatments AV1, AV3 and AV4, while for AV2, a slight increase (+4.4%, 697 g m-2) was observed (Figure 8B).

3.5. Modelling results

The normalised root means square error (nRMSE) value of predicted grain yield differs from the observed grain values of 12.9% for FL conditions, 15.7% in AV1, 16.5% in AV2, 6.71% in AV3, 2.82% in AV4. The results on RMSE revealed that the model underestimate the grain yield in particular in AV2 and AV1 conditions (>15% nRMSE) (Table 2).

Table 2. *Root mean square error value (RMSE) and Normalised RMSE (nRMSE) between simulated and observed grain yield (g m-2).*

TRT	SD (%)	RMSE	nRMSE
FL	0%	86.2	12.9 %
AV1	27%	96.3	15.7 %
AV2	16%	115.00	16.5 %
AV3	9%	42.7	6.71 %
AV4	18%	16.6	2.82 %

The simulation platform showed a good correspondence between observed and simulated values (Figure 9).

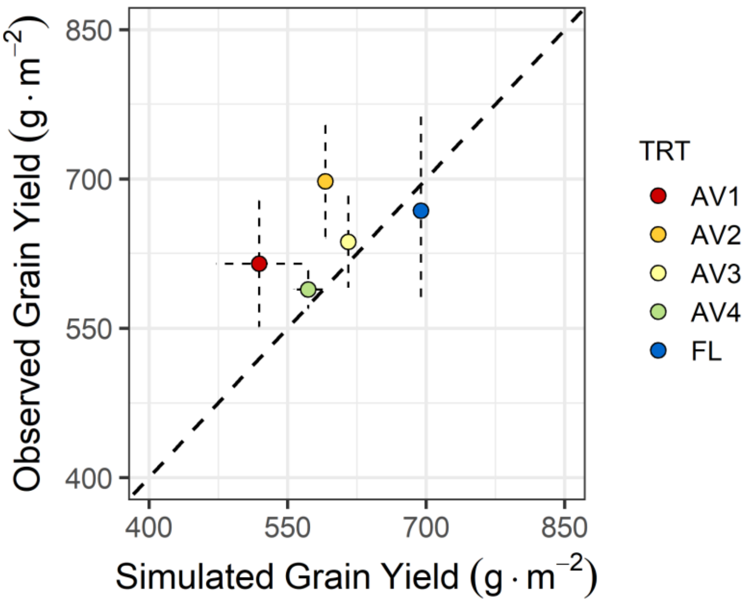

Figure 9 *Scatterplots between observed and simulated grain yield (g m-2) per different Shade Depth treatments*

4. Discussion

One of the main limiting factors to the development of sustainable AV solutions is the lack of information on the response of the main field crops to the shading conditions generated by the AV system. In this work, for the first time, soybean crop was cultivated under a largescale AV system and, field results (morphological and physiological traits and yield) were used to validate a simulation model to forecast soybean yield.

Soybean physiological and morphological traits were affected by shade depth levels. Plant height and vigour increased linearly with shading depth levels (Figure 4), which is a normal response of plants growing under shading conditions [25,26,27,28,29,30] that was previously reported for soybean in intercropping system [63,64] and for other field crops such as durum wheat, potatoes and grass-clover under AV system [17].

Leaf physiological and morphological traits investigated in this study were the Leaf Area Index (LAI), the Specific Leaf Area (SLA) and the chlorophyll content (SPAD).

LAI and SLA data were collected not exclusively to evaluate the physiological and morphological mechanisms of shade adaptation but also for modelling purposes. In fact, LAI is an important trait, along with SLA [65,66,67], to predict crop photosynthesis and its growth response during the growing cycle.

LAI and SLA were higher in the most shaded AV areas than in FL conditions across all sampling dates. An increase in LAI under AV system was found in celeriac [17], wheat, potatoes and grass clover [24]. The SLA of soybean increased with SD treatment, which confirms the response of this trait to shading already found in lettuce [14] and apples [19] grown under AV systems and for soybean grow in intercropping system [63,64].

Chlorophyll content, which in this study was estimated with the SPAD index, was not affected by SD levels under AV system as the range of data collected varies by ± 2 between treatments. These SPAD results were unexpected as chlorophyll content usually increases in crops grown under low light, under shade and for soybean in intercropping conditions [31,52,55,56,63,68,69]. In the AV system studied in this work, soybean SPAD values were similar to those of plants growing in full light conditions, which is probably a consequence of the low shading depth and of the fact that level of shading was not constant but changed dynamically throughout the day. For this it seems not correct to the response of soybean grown under AV conditions to that of soybean cultivated in intercropping systems or of experiments where the level of shading is constant throughout the day. In fact, the results obtained for SPAD under AV system with a maximum shade <30% were different to that obtained in the shading condition for other crops growing under a moderate shade environment where the shade can reach values >50% [54,55].

Regarding yield potential, it is considered that soybean is among the crops that suffer from shading conditions the most [70] but, without on field observations in AV system, this assertion can only be based on basic knowledge of the crop or trials where, shading conditions are features of the experimental setup e.g., intercropping systems [71].

Taking into account cropping in AV systems it is interesting to analyse how the conditions of reduced radiation affect grain yield. In a previous study, it was reported that shading conditions negatively affect the reproductive stages of soybean (flowering and pod set) as they are directly related to the photosynthetic process [72,73,74,75]. It was also reported that continuous shade affects soybean pods number by increasing pod abortion [75]. Our results are in agreement with the bibliographic evidences and confirmed that in soybean the yield reduction experienced under the shade of AV is associated with a negative impact of shade during the pod set stage (Figure 8A). The inversely proportional relationship between shade depth and grain yield (Figure 8B) is, to a good extent, explained by the depressive effect of shade on pods number, as revealed in Figure 8A. This is particularly evident for the AV1 and AV4 treatments.

In view of the aforementioned, the particular results observed for the treatment in AV2 are, to some extent counter-intuitive, in that AV2 yields do not fit well in the relationship with shade depth. Our interpretation must refer to a non-uniform distribution of irrigation water. In fact, the treatment in AV2 was located near the drip irrigation and this may have affected the yield performances compared to the other treatments.

The average grain yield reduction for the whole AV system was 8%, which is largely under the limits of the yield reductions indicated by the DIN standards in Germany ([77], for which at least 66 % of the reference yield needs to be achieved under the AV system). In a Korean study [35], which investigated soybean cultivation under an AV system, grain yield was reduced by 20% with a shade depth of 25%, while, in the present work a similar shade depth (27% in AV1) determined a yield reduction of only 8%. These results confirm that, considering the conceptual model proposed by Laub et al. [70], soybean is shade tolerant. The yield reduction measured in this work is lower that what previously reported in literature [35,64,70,78,79,80], which could be a consequence of pedoclimatic conditions or variety choice, considering that the effect of shading in soybean varies largely with the genotype [64]. Considering the large effect that genotype, environmental factors and AV system design have on crop yield, it would be necessary to run multiple long-term studies to provide the information needed to support the design and management of sustainable AV systems. On this regard, the use of models such as GECROS [62], implemented in the modelling platform of this study, offers a great contribution to the development of AV systems. The experimental data obtained in this study were used to validate the modelling platform and the values of nRMSE (<7% and 16.5% respectively best and worst performing) indicated that the simulation platform can predict satisfactorily soybean grain yields under AV.

5. Conclusions

In this work the morphological and physiological traits and yield responses of soybean growing under a commercial large scale AV system were investigated both on field and using a crop model.

The main morphological and physiological traits that increased significantly under the most shaded areas were plant height, LAI and SLA. These results highlight the capacity of a soybean crop to adapt its morphology under an AV system to improve light capture, in particular by increasing leaf area (both LAI and SLA increased with shading level) and by increasing stem elongation.

Under the large-scale AV system tested in this study, soybean yield was on average reduced by 8%, due to a reduction in pod number, which was proportional to shade depth level increase. The simulation platform developed by Amaducci et al (2018) was validated in this study and thus confirms to be a valuable tool for testing the potential of different AV scenarios. This could be of great practical use when studying the impact that a given AV design, in a particular environment and with a specific crop, has on a set of pre-defined key performance indicators or to achieve a target level of crop yield On this regard, regulations in France, Japan and Germany have set the maximum level of yield reduction that can be achieved underAV systems (compared to full light) as 10%, 20% and 34%, respectively. In addition, the simulation platform can be used to study the effect of specific agronomic choices (e.g., fertilisations and irrigation) on crop yield and in general on AV performance

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table 1: Values of crop height, LAI, SPAD, SLA, number of pods and grain yield and Tukey's HSD letters; Table 2: The Two-way ANOVA table for Height; Table 3 The Two-way ANOVA table for SPAD; Table 4: The Two-way ANOVA table for LAI; Table 5: The Two-way ANOVA table for SLA; Table 6: One-way ANOVA for number of pods; Table 7: One-way ANOVA for grain yield. Table 8: Summary of the standard deviation and standard error of pods number measured per each treatment. N= number of samplings per area. Table 9: Summary of the standard deviation and standard error of grain yield measured per each treatment. N= number of samplings per area

Author Contributions:

E.P. (Eleonora Potenza): conceptualization, investigation, data curation, methodology, formal analysis, original draft preparation; M.C. (Michele Croci) data curation, review and editing, formal analysis; M.C (Michele Colauzzi): conceptualization, software, review and editing; S.A. (Stefano Amaducci) conceptualization, review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: Emilia-Romagna Region European Social Fund (ESF) POR-FESR 2014-2020 bando “Alte competenze”.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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Supplementary material

Table S1 Values of crop height, LAI, SPAD, SLA, number of pods and grain yield and Tukey's HSD letters

TRT	Shade depth % (SD)	Height (cm)	LAI (m^2 m^{-2})	SPAD	SLA (cm^2 g^{-1})	Number of pods m^2	Grain yield (g m^{-2})
FL	0%	87.80 bc	2.78 bc	43.58 a	197.93 ab	2461 a	667.82 a
AV1	27%	98.25 a	3.63 a	43.41 a	213.36 a	1983 a	614.73 a
AV2	16%	86.95 bc	3.08 ab	41.87 b	201.31 a	2379 a	697.36 a
AV3	9%	85.04 c	2.97 b	42.87 ab	159.12 b	2177 a	636.80 a
AV4	18%	90.81 b	2.31 c	42.33 ab	194.91 ab	2011 a	588.81 a

Table S2 The Two-way ANOVA table for Height.

	Df	Sum Sq	Mean Sq	F-value	P-value
TRT	4	2642	660.4	19.71	<2.2e-16
Date	3	55944	18468	556.5	<2.2e-16
TRT: Date	12	1917	159.76	4.76	<2.2e-16
Residuals	121	4055	33.51	-	-

Table S3 The Two-way ANOVA table for SPAD.

	Df	Sum Sq	Mean Sq	F-value	P-value
TRT	4	118.5	29.61	5.744	0.0002
Date	5	4586	917.1	177.9	<2.2e-16
TRT: Date	20	483.7	24.18	4.691	<2.2e-16
Residuals	180	928	5.5155	-	-

Table S4 The Two-way ANOVA table for LAI.

	Df	Sum Sq	Mean Sq	F-value	P-value
TRT	4	5.67	1.418	13.33	<2.2e-16
Date	2	171.9	85.93	808	<2.2e-16
TRT: Date	8	6.138	0.7673	7.215	0.0002
Residuals	18	1.914	0.1063	-	-

Table S5 The Two-way ANOVA table for SLA.

	Df	Sum Sq	Mean Sq	F-value	P-value
TRT	4	8061	2015	4.524	0.0085
Date	1	10690	10690	24	<2.2e-16
TRT: Date	3	244.1	81.36	0.1827	0.907
Residuals	21	9355	445.5	-	-

Table S6 One-way ANOVA for number of pods.

	Df	Sum Sq	Mean Sq	F-value	P-value
TRT	4	479025	119756	2.307	0.1577
Residuals	7	363436	51919	-	-

Table S7 Summary of the standard deviation and standard error of pods number measured per each treatment. N= number of samplings per area

SD	TRT	N	Pods number per m2	sd	se
0	FL	4	2461	301.01	150.50
9	AV3	2	2177	6.72	4.75
16	AV2	2	2379	193.70	136.96
18	AV4	2	2011	168.79	119.35
27	AV1	2	1983	159.82	113.01

Table S8 Summary of the standard deviation and standard error of grain yield measured per each treatment. N= number of samplings per area

SD	TRT	N	Grain yield $g\ m^{-2}$	sd	se
0	FL	4	667	94.60	47.30
9	AV3	2	636	46.29	32.73
16	AV2	2	697	56.62	40.04
18	AV4	2	588	19.09	13.50
27	AV1	2	614	63.17	44.67

Table S9 One-way ANOVA for grain yield.

	Df	Sum Sq	Mean Sq	F-value	P-value
TRT	4	15822	3955	0.7574	0.5843
Residuals	7	36556	5222	-	-

Chapter 3: Effect of simulated agrivoltaic system on phenology, ecophysiology, fruit yield and quality of processing Tomato (*Solanum lycopersicum*, L)

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Abstract: Agrivoltaics (AVs) is gaining attention as renewable technologies due to the combination of electricity production with agricultural production. To date, experiments are needed to cover the knowledge gaps that exist on the response of crops to agrivoltaic conditions. The main objective of this study was to collect experimental evidence on the physiological response and crop performance of a processing tomato variety grown in different radiation regimes during the crop cycle. Different shading regimes were realized with a mock AV system using a dense shading net over potted tomatoes. Pots were spatially arranged to obtain four shading treatments: full light (FL), shade during morning time (SH_M), full shade (FS), and shade during afternoon (SH_A). Main morphological and physiological traits were affected by shading conditions in particular, the chlorophyll content (SPAD) was lower under shading conditions, the crop's photosystem was not under stress despite shading treatments (Fv/Fm value), the performance index (PI) values in FL and SH_A treatments reflects a heat stress condition compared to FS treatment. The PN (Net photosynthetic rate) and stomatal conductance (gs) under FS treatment decreased compared to FL treatments. The instantaneous WUE decreased in FS and SH_A treatments. The highest specific leaf area (SLA) was found in FS treatment. Regarding phenology, shade mainly affected the flowering phase, as the fruit set rate was lower in shade than in FL and this affected both the yield and the number of fruits. The yield reduction of commercial fruits (CF) compared to FL treatment was 43.5%, 13.2% and 12.8%, respectively for FS, SH_A and SH_M treatments. The total fruit number, including commercial and green fruits of FS and SH_A treatments were statistically lower than FL and SH_M. Compared to FL treatment the number of fruits was reduced by 55%, 24% and 15% respectively for treatments FS, SH_A and SH_M. Fruit quality characteristics (pH and °Brix) were not affected by the shading treatments, dry weight of fruits was lower under shading conditions.

Introduction

Climate change will be the plausible cause of undernourishment, malnutrition, and food insecurity by impacting agricultural food production, biodiversity, socio-economic aspects, water resources, forest systems and human livelihoods (Muluneh, 2021). The industrial revolution and the progress in urbanisation have increased greenhouse gas have increased the greenhouse gases emissions (GHGs) which consequently caused an intensification in the global warming process (Farooq et al., 2022). Climate change will negatively impact agriculture in the coming decades by events such as low and high temperature stresses, change in precipitation frequency and intensity, drought, salinity, sea level rise, and floods (Iniguez-Gallardo et al., 2021, Raza et al., 2021; Ullah et al., 2021), availability of water for irrigation and other agricultural resources (Davidson, 2018). The photosynthetic process of plants will be affected by climate change events such as drought and high and low temperature stresses (Davidson, 2018, Jin et al., 2021; Zhang et al., 2022) and this will increase the abiotic stress sensitivity of plants (Shah et al., 2020b). Abiotic stress will impact the morphological and physiological process of crops, dry-matter accumulation and distribution, crop production and quality of the products, threatening food security (Nurhasanah Ritonga and Chen, 2020; Aazami et al., 2021; Ahmad et al., 2021).

To deal with the effect of climate change communities need to ensure food security and to produce energy from renewables to favour the decarbonisation process and a sustainable solution to mitigate the climate change effect is represented by the Agrivoltaic (AV) system (Weselek et al., 2019, Barron-Gafford et al., 2019; Agostini et al., 2021; Walston et al., 2022).

AV systems combine agricultural and energy production on the same land, which is a “new” concept, particularly relevant in high light environment (e.g., Mediterranean areas) because it provides energy and green biomass (for food, energy, or industrial purpose), whilst allowing to reduce crop water requirements and limiting light stress. AV systems would make possible to cope with the effects of climate change as a resilient system against climate change due to its effects on increasing water use efficiency of crops (Marrou et al., 2013a; Hassanpour Adeh et al., 2018; Elamri et al., 2018) and reducing water evaporation from soil (Ali Abaker Omer et al., 2022), avoid heat stress for crops due to the shading conditions under photovoltaic panels especially in warmer seasons and drought-prone environments (Amaducci et al., 2018; Barron-Gafford et al., 2019; Othman et al., 2020), and protecting crops from other adverse climatic events (e.g. hail, Weselek et al., 2019).

However, as a new concept the interaction effects between the photovoltaic system and the agriculture (e.g., crop yield × AV configurations, crop ecophysiology impact under AV system) need to be assessed. The cultivation and management of plants of agricultural interest in AV environment depends on the complex interaction of agronomic factors related to the growth of plant under limiting light conditions. Considering that data on the ability of crops to produce sustainable yield under the shaded conditions of AV are scarce (Dupraz et al., 2011; Sekiyama and Nagashima, 2019), it can be argued that the selection of suitable plants species to match AV conditions should be based on results from research carried out in agroforestry or on agricultural species cultivated under artificial shade (Artru et al., 2017; Weselek et al., 2019; Weselek et al., 2021). Plants in fact, change their morphology and physiology to cope with the AV environment characterised by shading conditions generated by the PV panels, microclimate differences such as air and soil temperature, wind, soil moisture, incident radiation (Marrou et al., 2013b, 2013c, Hassanpour Adeh et al., 2018; Elamri et al., 2018; Barron-Gafford et al., 2019; Othman et al., 2020; Weselek et al., 2021; Altyeb Ali Abaker et al., 2022) and different water distribution under the PV panels (Dupraz et al., 2011a, Elamri et al., 2017; Hassanpour Adeh et al., 2018).

Usually, under shading environment there is an increase in the fraction of diffuse light (Sinclair et al., 1992; Rochette et al., 1996; Gu et al., 1999; Greenwald et al., 2006). Diffuse light can increase leaf CO_2 uptake, photosynthesis and plant growth (Healey et al., 1998; Gu et al., 1999, 2002; Cohan et al., 2002). Changes in light such as direct or diffuse light influence the photosynthetic process and the carbon use efficiency and affect yield (Bell et al., 2000; Jiang et al., 2002; Greenwald et al., 2006; Zhang et al., 2007). Furthermore, the change in light quality in a shading environment are referred to the increase in the fraction of blue light (400–500 nm) and a decrease in red light (600–700 nm)

(Bell et al., 2000), which might affect both morphological parameters (e.g. by increasing height of crops (Gommers et al., 2013, Ruberti et al., 2012, Smith et al., 1997) and physiological parameters (e.g. photosynthesis and chlorophyll synthesis (Blackwell, 1966), stomatal conductance (Munzner and Voigt, 1992;Zandomeni and Schopfer, 1993; Furuya et al., 1997).

The main modifications of morphological and physiological traits are change in leaf size, leaf thickness, leaf mass and chlorophyll content (Rozendaal et al., 2006; Valladares and Niinemets, 2008; Legner et al., 2014). The adaptation to shading condition determines a decrease of the chlorophyll a/b ratio, and an increase in total chlorophyll content under low light conditions, which can increase the carbon gain in a shaded environment (Zhang et al., 1995; Hikosaka, 1996; Evans and Poorter, 2001; Valladares and Niinemets 2008, Dai et al., 2009). However, adaptation strategy is univocal, and in plants, chlorophyll a/b ratios have been found to increase (Jiang et al., 2004). Another common plant adaptation to shade is related to increase of Specific Leaf Area (SLA, Gratani et al., 2014).

This study was carried out to simulate the shading effect of a fixed PV system on the growth and development of an industrial tomato cultivar. The cultivation of tomato has a worldwide relevance, however, information on its physiological and productive response to growth under shading conditions and AV systems is limited. The study aims at improving the knowledge on AV systems and on how crops are influenced by different shading conditions and how the shading conditions influence yield, fruit quality, physiological and the morphological response of tomato.

The objectives of the study were to study the effect of shading on: (1) A selection of morphological and physiological traits; (2) The formation of tomato yield throughout the crop growth cycle, and (3) Main fruit quality parameters.

Materials and methods

Experimental site and crop management

The experimental site was located at the Università Cattolica del Sacro Cuore in Piacenza, Italy, (lat=45.037238 N, long= 9.725722 E). The industrial tomato cultivar used for this experiment was 'HEINZ 1648'. 40-day-old plants were purchased from the nursery and each single plant was transplanted in a pot of 12 litres (28cmx24cm) for a total of 60 pots. The potting soil used was 'Ortaggi Supernutriente' (Vigorplant), each pot was filled with 4,250 Kg of soil. The trial started on the 1st of July 2021 and tomato was harvested on the 13th of September 2021. Shading was obtained with a tightly meshed shading net (90%), mounted on a pre-existing greenhouse structure (Figure 1). The shading net was mounted 2.10 m above the soil. Potted tomato plants were arranged in arrays in different position with respect to the shading net to obtain four different light treatments: full light (FL), shade during morning time (SH_M), full shade (FS), and shade during afternoon (SH_A).

Each treatment included 15 pots (Figure 1). The plants were arranged in rows with a distance between rows of 45 cm and of 25 cm between plants along the row.

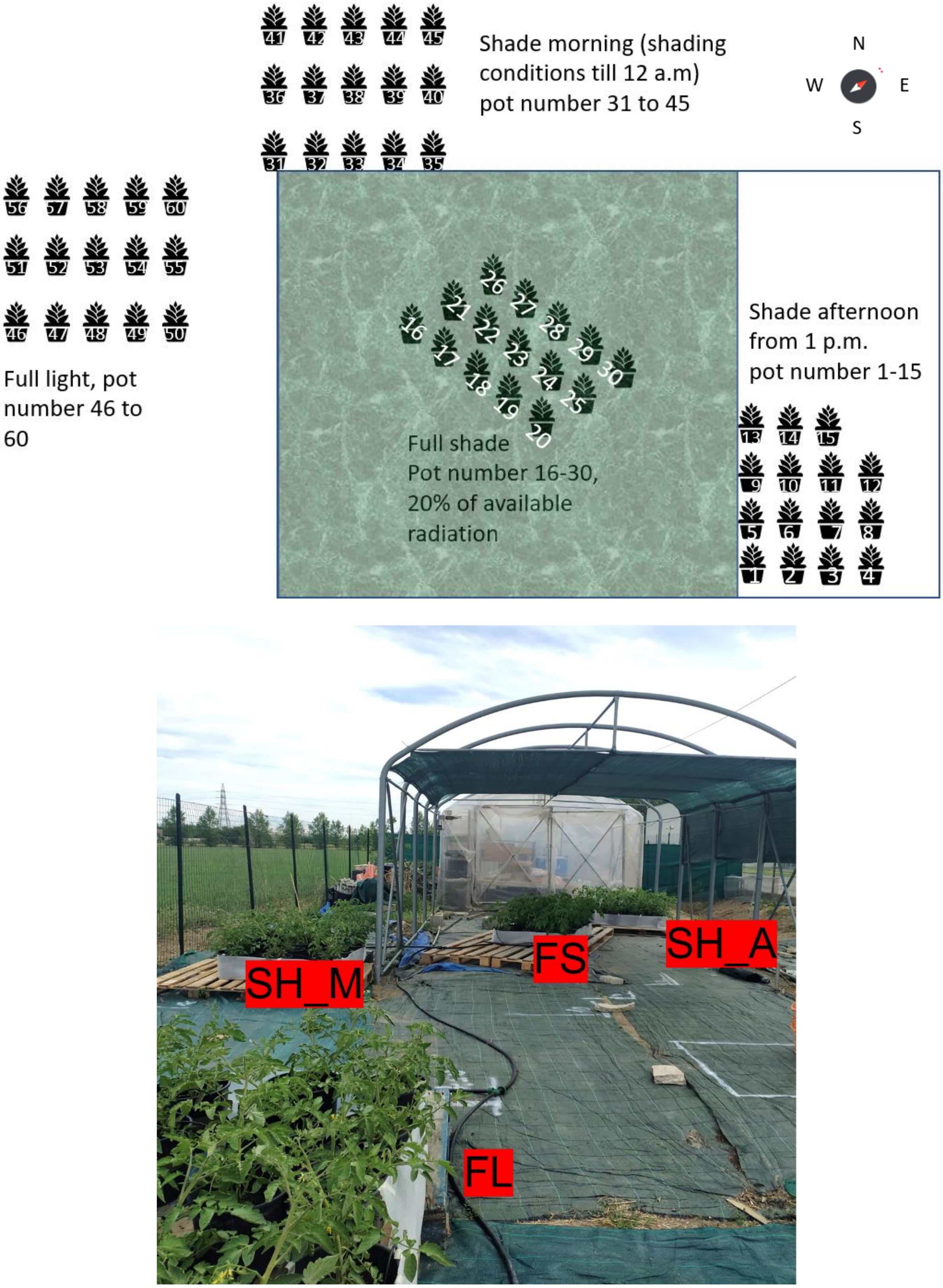

Figure 6 *Experimental design and shading treatments: FL= Full Ligith, SH_M= Shade Morning, FS= Full Shade, SH_A= Shade Afternoon*

In the full light treatment (FL) the plants had no shading. In the full shade treatment (FS) plants were in shaded conditions from 8 a.m. to 4.30 p.m. Shade morning (SH_M) and Shade afternoon (SH_A) treatments had a prevailing condition of shade at specific times of the day. In the case of the SH_M treatment the plants were shaded from 8.00 a.m. until 12 a.m., for the SH_A treatment from 1 p.m. until sunset.

A micro-irrigation system was used to provide irrigation based on crop water consumption, calculated by weighting the pots three times a day for one week starting on 10/07/21. Considering that each treatment had a different radiation and therefore plants had different evapotranspiration, irrigation level was different among treatments. The FL treatment received a mean of 2.4 L per day per pot (the irrigation was set up 6 times per day starting at 7.30 a.m and stopped at 7 p.m.), the SH_A and SH_M treatment received a mean of 2.0 L per day and the FS treatment 1.8 L.

During the growing season a universal fertiliser (title: NPK 7-5-6, Compo concime liquido universale) was applied 4 times (6-16-30 of July, 4 August). 9.8 ml (11 g, 0.75 g of nitrogen) of fertilizer was diluted in 400 ml of water per each pot every application to reach a total of 3gr of nitrogen per plant. During the growing cycle copper hydroxide treatments (1.2 g diluted in 1 L of water, COBRE NORDOX 50) were carried out to prevent the formation of mold.

Plants in flowering stage and with fruits

All plants were checked periodically to determine the number of plants that were in the flowering stage or that had at least one fruit truss with fruits (minimum diameter of 2mm). Data were collected on 4 dates: 13, 16, 20, 23 July.

Height

Plants height was measured randomly on five plants per treatment from the ground to the latest fully expanded leaf with a 1 mm precision. Plant height was measured on two dates on the 13th and 23rd of July, after which the plants showed a prostrate habitus ad it was no longer possible to collect height data.

SPAD

Chlorophyll content (SPAD) was estimated by using the chlorophyll meter SPAD-502 plus (Konica Minolta, USA). Measurements were carried out on 3 dates (23 and 29 July 2021, 5 August 2021) on 4 fully expanded leaves of 3 different plants per treatment.

SLA

SLA, which is the ratio of area to leaf dry mass (cm^2 g^{-1}), plays an important role in the active response of plants against environmental stress or reduced resource availability (Van Kleunen and

Fischer, 2005). SLA values were obtained by randomly selecting 3 plants for each treatment. 15 leaves per plant were collected on 2nd of August to obtain SLA value. They were first separated from the stems, put in a plastic bag to keep leaves flat and stored in a freezer at -18°C until the leaf area were determined. All leaves were scanned (EPSON Expression 10000 XL) and leaf area was determined from the scans using R (v 4.1.2., packages 'EBImage', 'nnet', 'NeuralNetTools').

Once the leaf area was calculated the leaves samples were dried in a ventilated oven at 65 °C until a constant dry weight weighed with a 0.01 mg precision scale. Values of leaf area (cm2) and dry weight (g) were then used compute SLA (ratio of area to leaf dry mass $cm^2\ g^{-1}$).

Chlorophyll fluorescence and leaf photosynthesis

Chlorophyll molecules respond to the incoming radiation in three ways: (i) driving photosynthesis; (ii) re-emitting radiation as heat; or (iii) re-emitting radiation as light (fluorescence) (Murchie et al., 2013). Chlorophyll fluorescence is a measure of re-emitted light (in the red wavebands) from photosystem II.

Fluorescence parameters reflect plant health status, acclimatization to various abiotic factors such as temperature, drought, nutrient level, soil properties, as well as biotic factors (Kalaji et al., 2018). The main measured parameters for chlorophyll fluorescence using a fluorimeter are the Fv/Fm ratio (which indicates the maximum quantum efficiency of photosystem II) and the performance index (PI). The PI quantifies the overall functionality of the electron flow through PSII. PI is a very reliable and sensitive parameter to indicate the onset and progress of drought stress (Ceusters et al., 2019). The Fv/Fm ratio (where Fm = maximal fluorescence, Fv = variable fluorescence (Fm-F0(initial fluorescence) indicates the physiological state of the photosynthetic system in plant leaves and have a narrow range (0.832 ± 0.004) among leaves of many different species (Krause and Weiss, 1991). Environmental stresses that affect PSII efficiency led to a characteristic decrease in Fv/Fm (Krause and Weiss, 1991).

The maximum quantum yield of PSII (Fv/Fm) ratio and the performance index (PI) values of tomato were obtained by using a pocket pea chlorophyll fluorimeter (Hansatech Instruments, Norfolk, UK). Prior to measurement, samples were dark adapted for at least 30 minutes using leaf clips provided by the chlorophyll fluorimeter's manufacturer. Fluorescence measurements were realised on three different fully expanded leaves of four plants per treatment (leaves were randomly selected but the same four plant were used per each treatment) on 4 dates: 13th,23rd, 29th July and 5th of August. Leaf photosynthesis was measured on plants of all four treatments to assess the effect of shading conditions, using a portable photosynthesis system (CIRAS-2, PPS Co. Ltd., England). 3 fully expanded leaves (on the bottom, middle and top parts of the canopy) were randomly selected for 4 plants per treatment to measure leaf photosynthesis. The same plants used to collect data on fluorescence were used for the CIRAS-2 measurements. For the trials where used a PLC with an insert of 25 x 7 mm Ø and the light intensity was set up at 1000 µmol m^{-2} s^{-1}.

In this study, among the calculated variables (see Table 1 and supplementary material), net photosynthetic rate (PN, µmol m^{-2} s^{-1}) and stomatal conductance (gs, mmol m^{-2} s^{-1}) were taken into account to analyse the photosynthetic data in response to shading conditions. Furthermore, the ratio between PN and the transpiration rate (E, mmol m^{-2} s^{-1}) was used to calculate the leaf instantaneous Water Use Efficiency (WUE) (Farquhar & Richards, 1984). Water-use efficiency (WUE) is a measure of the carbon gained by plants through photosynthesis relative to the water lost through transpiration and it is an ecological trait that is important to evaluate plant drought response (Kenney et al., 2014).

***Table 2** Ciras-2 measured and calculated variables (see supplementary material for further information)*

Measured parameters		
Symbol	**Description**	**Unit**
Cr	Reference CO_2	Ppm
Hr	Reference H_2O	Mb
Tc	Cuvette air temperature	°C
Q	PAR	µmol m^{-2} s^{-1}
Ap	Atmospheric pressure	Mb
Cd	Differential CO_2	Ppm
Hd	Differential H_2O	Mb
Tl	Leaf temperature	°C
V	Chamber flow rate	ml min^{-1}
RH	Relative Humidity (Calculated)	%
Calculated Variables		
Symbol	**Description**	**Unit**
Ci	Substomatal CO_2 concentration	Ppm
E	Transpiration Rate	mmol m^{-2} s^{-1}
gs	Stomatal Conductance	mmol m^{-2} s^{-1}
Pn	Net Photosynthetic Rate	µmol m^{-2} s^{-1}
VPD	Vapor Pressure Deficit	Mb

Harvest method and fruits analysis

The tomatoes were harvested on the 13th of September. After harvest, fruits were divided into commercial fruits (CF, red fruits), green fruits (GF) and non-marketable fruits (fruits with rot).

The number of fruits trusses were counted for each plant. Successively, the fruits were weighted to obtain the fresh weight and counted to obtain the number of tomatoes per plant. 6 fruits samples were taken per treatment (24 samples in total) to determine the water content and successively the fruits dry weight in each treatment, whilst other 24 samples were taken to measure the pH and

°Brix. The weight of each subsample varies from 350 gr to 500 gr. Fruits were dried in a ventilated oven at 65 °C until constant weight, to obtain the fruit dry weight.

pH was measured with the pH meter (Hach Lange Sension+) and the soluble solids (°Brix) with a digital refractometer (ATAGO DBX-55, Tokyo, Japan).

Statistical analysis

Data in text, figures and tables are always represented as the mean (per dates of sampling where there are multiple sampling dates) of the variables calculated: SPAD, SLA, height, Fv/Fm, PI, Pn, gs, WUE.

All analyses were carried out with R (version 4.1.2, 2021-11-01).

To estimate the effects of shade conditions and sampling dates on dependent variables, the data were analysed by one-way and two-way ANOVA. One-way ANOVA was used for SLA, WUE, PN Yield and °Brix. Two-way ANOVA was used for performance index (PI). Assumptions of normality distribution of residuals and homoscedasticity were analysed by Shapiro-wilk test and Levene's test respectively. When the assumptions were respected a post-hoc tests were performed (Tukey's Honest Significance Difference Test, HSD). When the assumptions were not fulfilled, non-parametric tests of Wilcoxon and Friedman were used. The Wilcoxon test was used to assess the effect of the shading treatments on height, SPAD and pH.

Fv/Fm values were analysed throughout the Friedman test followed by the Conover post-hoc test. For Fv/Fm values the package 'multcompView' version 0.1-8 was used to convert a vector of p-values into a character-based display in which common letters identify levels or groups that are not significantly different.

The number of fruits (only commercial fruits and both green fruits + commercial fruits) were analysed throughout Generalized linear model (GLM) with a Poisson distribution. A Tukey post-hoc test was carried out using the R package "emmeans" and the package 'multcompView' was used as previously described for Fv/Fm values. Results are given as the response scale after convert the log scale results obtained by the statistical analysis.

A p-value < 0.05 was used to indicate significant difference across treatments.

Results

Height

Plant height during the two-sampling date was never affected by shading treatments (Wilcoxon test, p-value > 0.05, Table 2).

Table 3 *Average tomato height in cm per treatment on the two sampling dates. se= standard error*

TRT	Height (cm)	se	p. value
FL	45.5	1.335415	
FS	47.2	1.443761	0.293
SH_A	44.5	1.688194	0.916
SH_M	44.8	1.540563	1

Phenological stage: fruit set and ripening

On the 13th of July, in all the treatments, plants showed 2 well-opened flower trusses with the third trusses being almost open, indicating that there were no variations in the initial phenological phases of flowering.

On the 16th of July, the number of plants having fruits of at least 2 mm Ø was 4/15 in FL treatment, 6/15 in FS treatment, 5/15 in SH_M treatment, and 6/15 in SH_A treatment. On this date, the lowest number of fruits was found in FL treatment.

On the 20th of July, the plants in the FL treatment reached the 100% fruit set stage (fruits of at least 2 mm Ø), in FS treatment, the fruit set stage was 86%, in SH_M 86% and in SH_A 80%.

On the 23rd of July, 3 plants showed symptoms (flower abortion, yellow and curly leaves, reduced leaflet size) of tomato yellow leaf curl virus (TYLCV) in SH_A, 1 plant in SH_M and 1 plant in FS treatment. All remaining plants of the 4 treatments had fruits with a diameter superior to 2 mm.

Tomato fruits started to ripen on the 7th of August and the number of plants showing red fruit were 4/15 in FL treatment, 4/14 for the FS treatment, 11/12 in SH_A treatment and 8/14 in SH_M treatment.

SPAD

Sampling date did not significantly affect SPAD value (p-value >0.05), but a statistically significant difference was observed among shading treatments (p-value <0.05, Table 3).

Table 4** Wilcoxon test result for SPAD where the p-value is ’*’ <0.001 ‘***’= 0.001 ‘**’ =0.01 ‘*’ =0.05*

Group 1	*Group2*	*p-value*	*p-signif*
FL	SH_M	0.35	ns
FL	FS	0.00008	****
FL	SH_A	0.19	ns
SH_M	FS	0.016	**
SH_M	SH_A	0.48	ns
FS	SH_A	0.19	*

The mean SPAD value were 53.6 in FL, 52.3 in SH_M, 51.6 in SH_A, and 48.8 in FS. The lowest SPAD value was found in FS and the Wilcoxon test revealed statistically significant differences between the SPAD value of the FS and FL (Figure 2) and, between FS and SH_A and FS and SH_M (Table 3). No significant difference exists between the SH_A, SH_M and FL treatments.

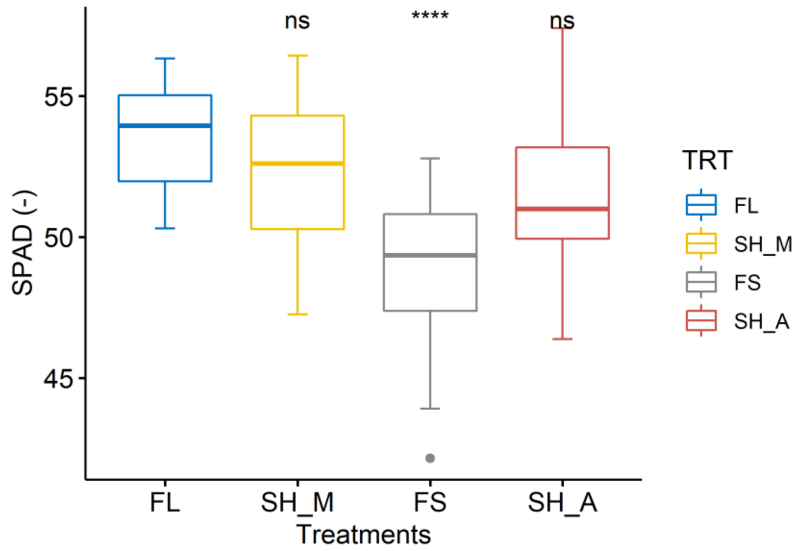

Figure 2 *Mean SPAD value and standard deviation error bars. Wilcoxon test significance stars where the p-value is '****' <0.001 '***'= 0.001 '**' =0.01 '*' =0.05.*

SLA

Statistically significant differences (p-value< 0.05) were observed for SLA with the following mean values across the four shade treatments: FL=329 cm^2 g^{-1}, SH_A= 315 cm^2 g^{-1}, SH_M=323 cm^2 g^{-1}, FS= 607 cm^2 g^{-1}. Tukey test showed that the FS treatment was significantly different from the other three treatments (Figure 3).

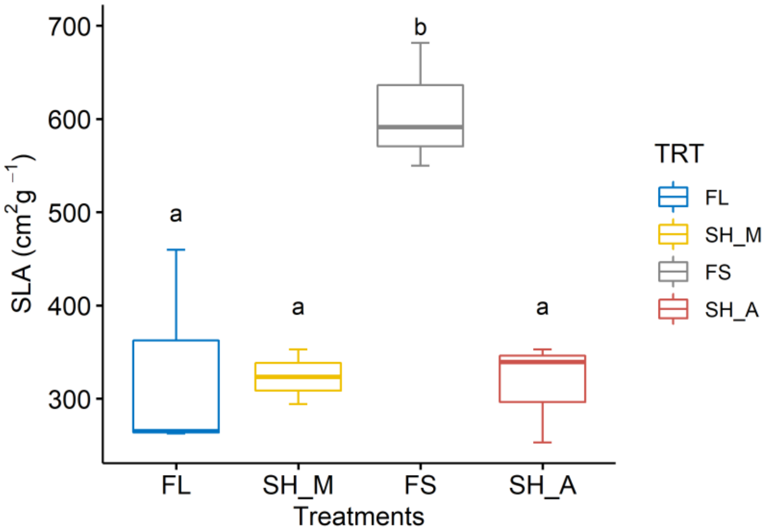

Figure 3 *Mean SLA value per treatment (2/08/2021) with standard deviation error bar and Tukey's HSD letters.*

__Table 5__ Standard deviation and standard error of SLA

TRT	*SLA (cm^2 g^{-1})*	*sd*	*se*
FL	329.09	113.02	65.25
FS	607.54	67.36	38.89
SH_A	315.17	54.13	31.25
SH_M	323.49	41.62	29.43

Chlorophyll fluorescence and gas exchange measurements

FS treatment (Figure 4A, grey line) showed absence of PSII stress, as Fv/Fm values above 0.83 were maintained, while a condition of photosystem stress with Fv/Fm < 0.80 occurred for FL (Figure 4A, blue line) and SH_A (Figure 4A, red line) treatments in all dates considered in the growing cycle, excluding on the 13th of July when all plant had the same Fv/Fm (Figure 4A). SH_M treatment did not show stress on PSII (Fv/Fm value > 0.80).

By using the Friedman test the Fv/Fm p-value was significant across sampling date and shading treatments (<0.05). Conover post-hoc test showed significance difference between FS and SH_A treatment (Figure 4B). The lowest value that corresponds to the highest stress was found for SH_A treatment.

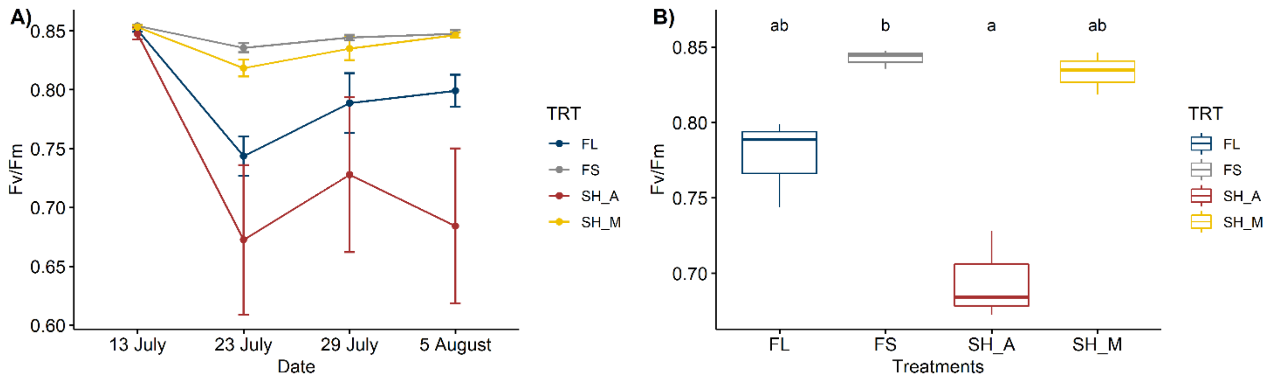

***Figure 4** A) Fv/Fm mean value per date of sampling with standard deviation bars and B) Mean Fv/Fm values, standard deviation bars and Conover post hoc letters. Fv/Fm means followed by a common letter are not significantly different.*

***Table 6** Conover Test result on Fv/Fm per treatments. p-value <0.05 indicate significance difference between treatments*

TRT	*FL*	*FS*	*SH_A*
FS	0.279	-	-
SH_A	0.808	0.037	-
SH_M	0.808	0.808	0.279

The performance index (PI) on FS treatment (Figure 5A) presented relatively constant values during the growing season, which was not the case for the other treatments.

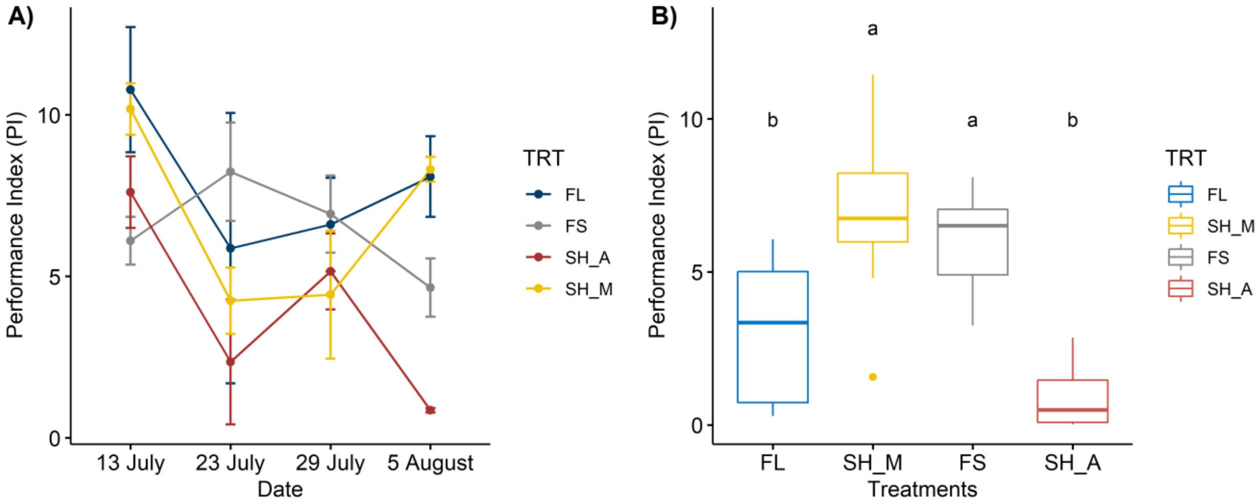

Figure 5 *A) PI mean value per date of sampling and standard deviation bars B) Mean PI values and Tukey's post hoc letters. PI values followed by a common letter are not significantly different.*

Tukey's post hoc analyses showed that the treatments SH_M and FS significantly differ from the other two treatments, as the plants under SH_A and FL treatments displayed clearly lower PI values (figure 5B).

Significant differences between FL and the shaded treatments were observed for both PN and gs (Figure 6A and 6B, p-value < 0.05). The mean PN values for the four treatments were 30.55 µmol m^{-2} s^{-1} under FL, 29.65 µmol m^{-2} s^{-1} in SH_M. 26.56 in SH_A and 26.75 µmol m^{-2} s^{-1} in FS. The highest gs value was found under FL treatment (6.10) followed by 5.51 in SH_M, 2.65 in SH_A and 2.31 in FS. In FL and SH_M treatments, plants showed an increase in gs and a higher PN value compared to the other 2 treatments. Low values for PN and gs were found in FS and SH_A treatments.

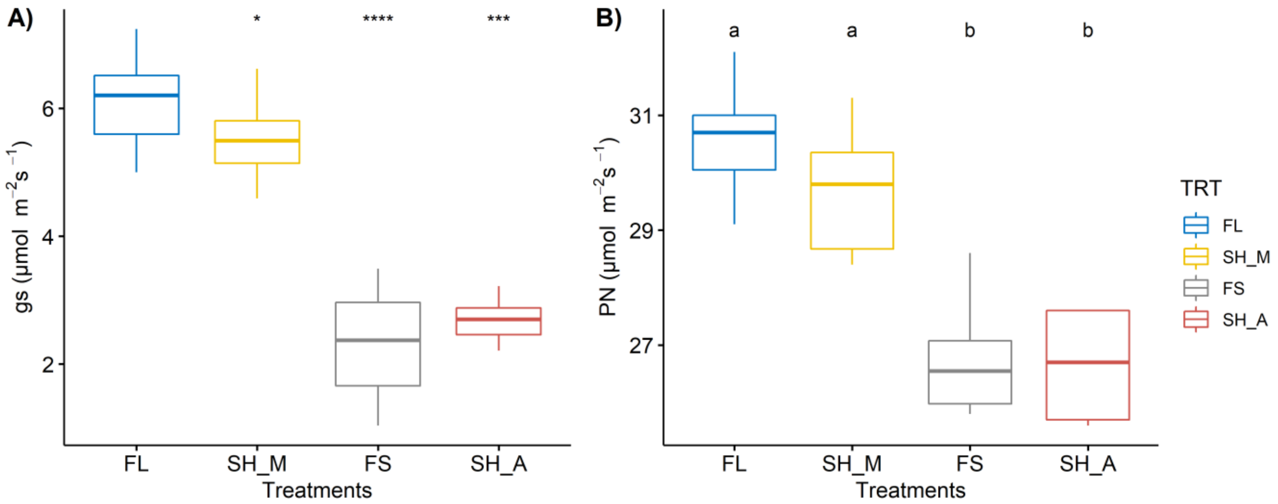

Figure 6 *A) gs values and Wilcoxon significance stars where the p-value is '****' <0.001 '***'= 0.001 '**' =0.01 '*' =0.05 B) PN values and Tukey's post hoc letters. Gs and PI values followed by a common letter are not significantly different.*

Instantaneous WUE values (WUE , PN/E) range from 5 to 25 µmol CO_2 mol^{-1} H_2O, average WUE values per treatments were under FL treatment 0.15 mol CO_2 mol^{-1} H_2O, 0.13 mol CO2 mol-1 H2O under FS, under SH_M treatment 0.14 mol CO_2 mol^{-1} H_2O, and in SH_A 0.13 mol CO_2 mol^{-1} H_2O. Post-hoc analysis showed that the treatments SH_A and FS were similar between each other but significantly differ from the treatments SH_M and FL as these last had a clearly higher WUE (Figure 7).

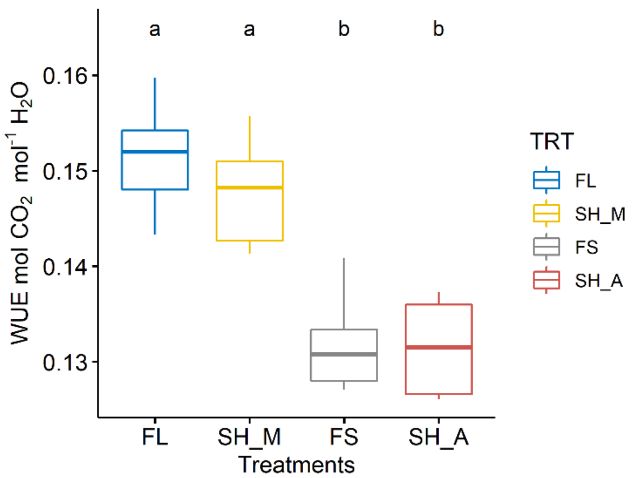

Figure 7 *Mean leaf instantaneous water use efficiency (WUE) and Tukey's post hoc letters. WUE values followed by a common letter are not significantly different.*

SH_M reported the behaviour most similar to that of the standard conditions under which a plant grows (FL conditions) while gas exchanges pattern differed markedly under FS and SH_A conditions. The lowest WUE were found for FS and SH_A although the difference is not critical compared to that of SH_M and FL treatments (the value differs for ±0.02 CO_2 mol^{-1} H_2O).

By considering the irrigation amount, FL treatment received 2.4 L per day and per pot whilst plants in SH_M and SH_A treatments received about 2.0 L per day and per pot, indicating a reduction of 17% of water consumption. For the FS treatment, the reduction in water consumption per day was 25% lower than that of the FL treatment.

Yield

ANOVA results showed significant differences for yield. GLM results showed significant differences for commercial fruits number across treatments (Table 6).

Table 7 *GLM results, Poisson regression, Signif. stars '***' 0.001, '**' 0.01, '*' 0.05, '.' 0.1, ' ' 1*

TRT	se	p-value	Significance stars
Intercept (FL)	5.923e-02	<2e-16	***
FS	9.919e-02	<2e-16	***
SH_A	8.885e-0.2	1	
SH_M	8.969e-02	0.0387	*

Individual comparisons among treatments with Tukey's test showed significant differences between FS and the three treatments FL, SH_A and for SH_M (Figure 8A and 8B, Table 7 for fruits number). The mean yield of commercial fruit (CF) per plant was 1.29 Kg for the FL treatment, 0.73 Kg for FS, 1.12 Kg for SH_A and 1.13 Kg for SH_M (Figure 8A). The yield reduction per single treatment compared to FL was 43.5% for FS treatment, 13.2% for SH_A and 12.8% for SH_M.

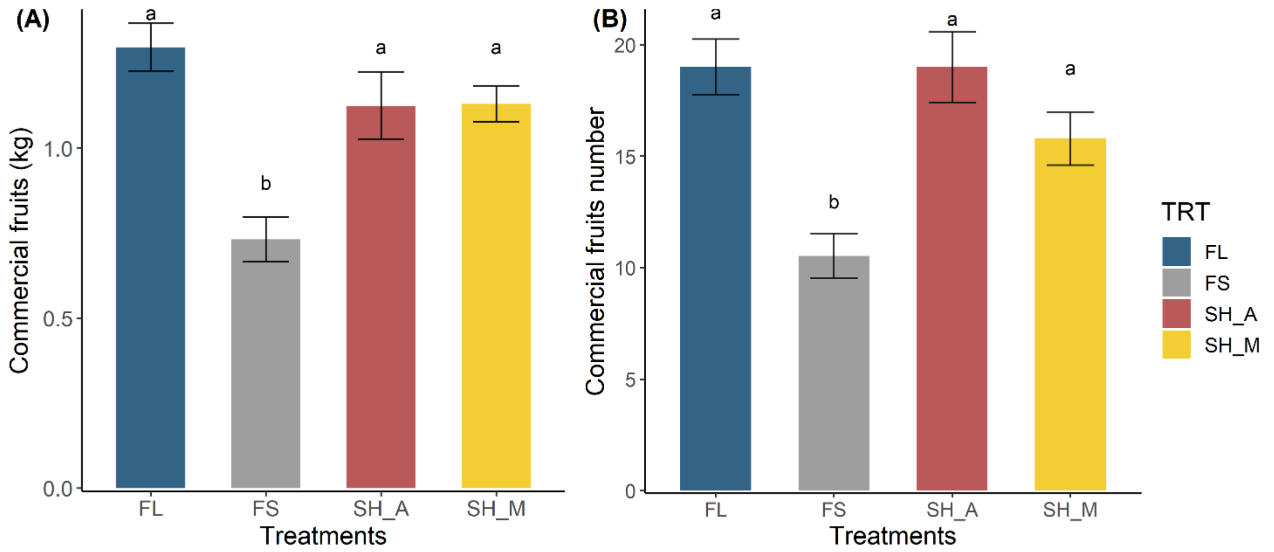

Figure 8 *A) Yield of commercial fruits for each treatment and Tukey post-hoc letters B) Number of commercial fruits for each treatment and Tukey post-hoc letters. Bars and error bars represent the mean ± standard error.*

The mean number of commercial fruit (CF) per plant was 19 for the FL treatment, 10 for FS, 19 for SH_A and 15 for SH_M (Figure 8B). When compared to FL, the number of CF per single treatment was reduced of 44.5% for FS treatment, of 20% for SH_A and of 16.9% for SH_M.

Table 8 *Post-hoc results for GLM (log scale) on fruits numbers (CF). Tukey method for comparing TRT. Signif. stars '****' < 0.001, '***' 0.001, '**' 0.01, '*' 0.05, '.' 0.1, ' ' 1*

Contrast	se	p-value	Significance stars
FL-FS	0.0992	<0.0001	****
FL-SH_A	0.0889	1	
FL-SH_M	0.0896	0.1637	
FS-SH_A	0.1035	<0.0001	****
FS- SH_M	0.1042	0.0006	***
SH_A-SH_M	0.0944	0.2020	

To better characterize the effect of shading conditions on total plant yield (its influence on fruit number in particular) total weight (fresh weight) and total number of fruits were also analysed: marketable fruits (CF) + green fruits (GF). The ANOVA and GLM results showed significant differences for both total fruit weight and total number of fruits (ANOVA p-value <0.05, GLM Table 7). Subsequent analysis with Tukey's test revealed that with the inclusion of green fruits, FL and SH_M treatments differed significantly from FS and SH_A (Figure 9A and 9B). The total yield per plant (CF+GF) were, in the four treatments: 2.0 Kg for the FL treatment, 1.0 Kg for FS, 1.5 Kg for SH_A and 1.9 Kg for SH_M (Figure 9A).

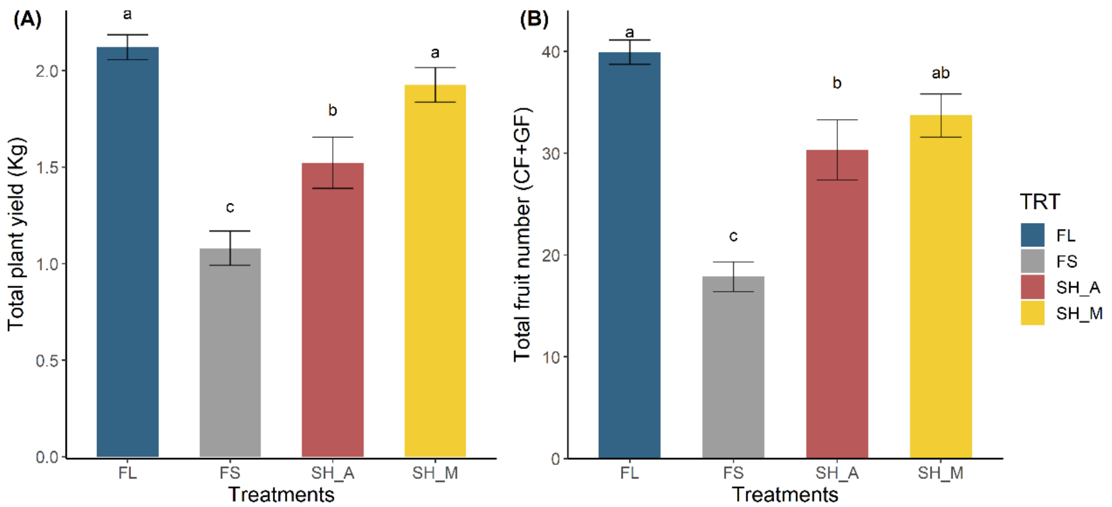

Figure 9 *A) Total plant yield (GF+CF) with standard errors bars and Tukey's HSD test letters B) Mean tomatoes number (GF+CF) with se bars and Tukey's HSD test letters*

Table 8 *GLM results on Total fruits number (CF+GF), Poisson regression, Signif. stars '***' 0.001, '**' 0.01, '*' 0.05, '.' 0.1, ' ' 1*

TRT	se	p-value	Significance stars
Intercept (FL)	0.04086	<2e-16	***
FS	0.07349	<2e-16	***
SH_A	0.06646	<2e-16	***
SH_M	0.06155	0.00595	**

*Table 9 Post-hoc results for GLM (log scale)on total fruits number (CF+GF). Tukey method for comparing TRT. Signif. stars '****' < 0.001, '***' 0.001, '**' 0.01, '*' 0.05, '.' 0.1, ' ' 1*

Contrast	se	p-value	Significance stars
FL-FS	0.0735	<0.0001	****
FL-SH_A	0.0665	0.0002	***
FL-SH_M	0.0615	0.0303	*
FS-SH_A	0.0805	<0.0001	****
FS- SH_M	0.0765	<0.0001	****
SH_A-SH_M	0.0698	0.4285	

The pattern was similar for the yield of all fruits, with reductions from FL treatment of 55% under FS conditions, 24% under SH_A treatment, and 15% under SH_M treatment. There was significant difference between FL and SH_M conditions for either of these two parameters after the post-hoc analysis (Table 9), whilst SH_A and especially FS treatments significantly differed from FL conditions (Table 9).

Fruits dry weight

ANOVA results for fruit dry weights showed significant differences among treatments. The Tukey test showed that the two treatments FL and SH_M were statistically different from FS and SH_A (Figure 10). The mean dry weight (Kg) per plant was 0.15 Kg for the FL treatment, 0.07 for FS, 0.09 for SH_A and 0.10 for SH_M (Figure 10, table 10).

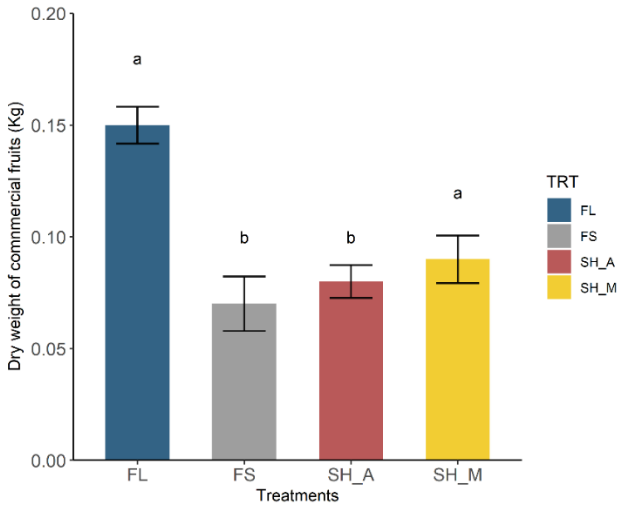

Figure 10 *Commercial fruits dry weight across the four light treatments. Bars and error bars represent the mean ± standard error, respectively. Letters above the bars represent Tukey's HSD results and different letters indicate significantly different values at α = 0.05.*

Table 10 *Standard deviation, standard error and Tukey's HSD results for dry weight of fruits*

TRT	DW_kg	Sd	se
FL	0.15 a	0.020	0.008
FS	0.07 b	0.029	0.012
SH_A	0.09 b	0.017	0.007
SH_M	0.10 a	0.026	0.010

Fruit quality: pH and °Brix

The one-way ANOVA for pH did not show significant difference for the 4 treatments considered (the p-value was >0.05, Tukey HDS letters on Table 11).

Table 11 *Mean pH value with Tukey's HSD test letters, sd and se value*

TRT	pH	sd	se
FL	4.27 a	0.046	0.018
FS	4.27 a	0.029	0.012
SH_A	4.24 a	0.045	0.018
SH_M	4.24 a	0.019	0.007

Wilcoxon test showed that the two treatments FL and SH_M (4.71° and 4.62°) were statistically different from SH_A (4.08°, Figure 11, Table 12). A lower value was found in FS (4.38°) and SH_A (4.08°) compared to FL and SH_M but this value was not significant different from these treatments. The highest value of °Brix was found in FL conditions.

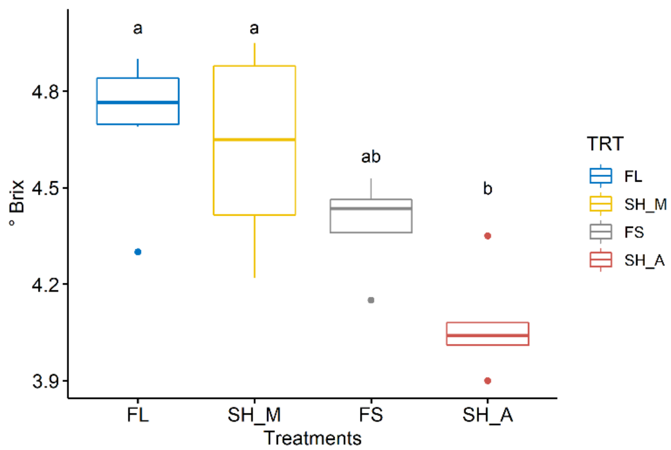

Figure 11 *°Brix and Tukey's HSD test letters. Different letters indicate significantly different values at α = 0.05*

Table 12 *Mean °Brix value with Tukey's HSD test letters, sd and se value*

TRT	°Brix	sd	se
FL	4.71 a	0.216	0.08
FS	4.38 ab	0.164	0.08
SH_A	4.07 b	0.167	0.07
SH_M	4.62 a	0.302	0.12

Discussion

Industrial tomato is a typical crop grown in Italy, where radiation is particularly intense in summer. Tomato fruit set, yield and main crop parameters were significantly affected by shade. Assessing the phenological response of plants is important to investigate the influence of shade treatments on the reproductive stages of the plant. Shading treatment did not delay the flowering stage of tomatoes as already reported for tomatoes grows in shading conditions (El-Gizawy et al., 1993; Angmo et al., 2021) and for other species (Qin et al., 2022, Munir et al., 2004; Colberg and Voldeng 2001; Faust et al., 2005). Fruits set and ripening of tomato was slightly influenced by the shading conditions as tomato in FL reached fruit set earlier than under varying shading conditions.

To assess the physiological and morphological responses of tomato to shade treatments, data were collected for height, Specific Leaf Area (SLA), maximum quantum yield of the PSII (Fv/Fm) and PI (performance Index) parameters and on net photosynthetic rate (PN), stomatal conductance (gs) and instantaneous Water Use Efficiency (WUE).

It was reported by several authors that under shading condition or under AV environment plant height was significantly affected by shading conditions, which increases stem elongation (Gommers et al., 2013, Ruberti et al., 2012, Smith et al., 1997, Niinemets, 1997; Nguyen et al., 2022; Weselek et al., 2022; Potenza et al., 2022) to increase light interception. However, in the present work, height was not significantly affected by different shading conditions probably due to the fact that other factors have constrained plant height, such as pot size.

In this work, SPAD measures were used to estimate leaf chlorophyll content. Previous works suggested that SPAD tends to increase as light availability decreases (Niinemets and Valladares, 2004; Ilić et al., 2014; Muhidin et al., 2018; Li et al., 2018; Wan et al., 2020). SPAD in shading condition was not higher than under full light conditions. SPAD value in FS was lower compared to the other 3 treatments analysed, which confirms what already found in other research on eggplant growing under shading nets (Nguyen et al., 2022), for purple pak-choi under low-light treatments (Zhu et al., 2017), soybean under AV conditions and inter-cropping system (Fan et al.,2018; Potenza et al., 2022). It can be hypothesized that this response is due to 1) the different allocation of leaf nitrogen to chlorophyll because nitrogen is susceptible in shading conditions (Xiong et al., 2015) and 2) to the different distribution of tissue layers and a different structural organization of leaves that cause different light reflection and/or scattering effect (Fukshansky et al., 1993, Xiong et al., 2015). The dynamic shade for SH_A and SH_M treatment did not significantly decrease the leaf chlorophyll content compared to FL treatment, which was favourable for tomato growth.

One of the main mechanisms that plants adopt in shading conditions are related to increasing leaf area to increase light interception (Gratani, 2014). To achieve a higher light interception by increasing leaf area, plants usually tend to increase their SLA to maximise ground coverage (Rozendaal et al., 2006; Valladares and Niinemets, 2008; Legner et al., 2014). Tomato plants usually increase SLA under shading conditions (Sandri et al., 2003). In this study, SLA measurements were in accordance with what reported in literature, in particular higher SLA values were found for plants grown in FS conditions than for plants grown in FL conditions. Interestingly, the SLA measured under dynamic shading conditions (SH_A and SH_M) did not differ from the FL condition, suggesting that the SLA increment does not respond to temporary shading, but is rather induced if the plant is shaded during the whole day. Leaves in FS treatments were thinner compared to leaves grown in FL conditions, this difference between sun leaves and shade leaves depends on leaf internal structure that performs an important role in light capture (Evans, 1999). No significant difference was found between FL and SH_A and SH_M treatments.

Chlorophyll fluorescence parameters (Fv/Fm, PI, PN, gs) were used to investigate photosynthetic systems and reactions and how they are affected by shading. Both PN and gs analysed in this study were lower in FS condition than in FL conditions. Carbohydrate accumulation and consequently crop yield depends on leaf photosynthesis (Peoples et al., 1980). Net photosynthetic rate (PN) under shading conditions tends to decrease (Li et al., 2010, Mu et al., 2010, Yang et al., 2020). Previous studies have shown that shading conditions during the crop growth cycle decrease leaf PN and inhibit carbon assimilation, resulting in the reduction of yield (Hashemi-Dezfouli & Herbert, 1992; Bellasio & Griffiths, 2014). Limitation of PN under shading conditions depends on the decreasing of irradiance (Da Matta, 2004). Stomatal conductance (gs) affect photosynthesis (Ohsumi et al., 2007) and under shading conditions tends to decrease resulting in a limitation to the diffusion of CO_2 from the atmosphere into the leaves and decreasing the PN (Wu et al., 2018, Yang et al., 2020).

Furthermore, shading affects physiological traits of tomato (e.g., SLA increase under FS conditions) and thus leads to a modification of gas exchanges (Merano et al., 2015) and to a reduction of PN due to the modification in leaf thickness, leaf tissue and chloroplast morphology and the ultrastructural organization of plant cell (Tateno & Taneda,2007; Huang et al., 2016; Cui et al., 1991; Sheue et al., 2015). Despite this, the dynamic shading treatments underlying a photosynthetic response different for shading intensities and durations, in SH_A the PN and gs was lower than SH_M condition where plants response was similar to the FL conditions.

The leaf scale ratio of net carbon assimilation (PN) to transpiration (E), (i.e., WUEinst) was lower in FS and SH_A treatments than in FL and SH_M treatments. Despite this, the observed differences across treatments remained small, indicating that it is possible to assume a high WUEinst of tomato in all the treatments considered.

Fluorescence parameters were significantly different for FS conditions and FL conditions. PI (performance index) is a. PI indicates the plant performance (Strasser et al., 2004; Žlvčák et al., 2008) under stress conditions for example drought stress conditions (Ceusters et al., 2019) and it is referred to the functionality of photosystem I and II (Strasser et al., 2000). The values of PI in FL were lower than in the FS treatment, reflecting a stress condition due both to the heat stress caused by high solar radiation and to the greater evapotranspiration of the crop, which led the plant to increase the water consumption. The highest values of PN were measured in FL and in SH_M treatments and, the plants growing in these light conditions showed also an increase in stomatal conductance (gs) to allow leaf temperature reduction (leaf cooling). The influence of high temperature on crop photosynthesis was already reported for tomato by Poudyal et al. (2019).

Reduction in marketable fruits yield, fruits number, fresh and dry weight were found in shading treatments, which was also found in other research for tomato grow in shaded environments (Lopez Diaz et al., 2020; Sandri et al., 2003). In the severe conditions of the FS treatment the reduction of yield and of commercial fruits (CF) number was higher than 40% when compared to FL conditions. In SH_A and SH_M treatments, yield and number of fruits was lower than under FL conditions, but higher than under FS conditions. The impact on yield and fruit number for the shading treatment analysed (Figure 9) may be linked to i) a reduction in photosynthesis and in increase in allocation of assimilate for vegetative organs than that of assimilates to fruits as showed for bell pepper in greenhouse under shading conditions (Díaz-Pérez 2013), ii) to a lower fruit set as already reported for sweet pepper growing under various shading conditions (12-47% of shading rate, Rylski and Spigelman, 1986). In addition, considering commercial fruit (CF) + green fruit (GF), it was confirmed that the fruit set in FS was lower than under FL and in fact the highest number of GF were found in FL, SH_A and SH_M, this result is linked to a high fruit set rate of the plant due to the higher radiation availability.

Regarding the fruit dry weight, data in this study showed that fruit dry weight was reduced by 54% in FS, 40% in SH_A and 44% in SH_M treatments. A similar result was obtained for tomato growing in a greenhouse environment under shading conditions (Sandri et al., 2003) where with a 52% of shade led to a total fruit dry weight reduction of 20%. This indicates that the lack of solar radiation limited the allocation of assimilates for the fruits.

Referring to the two fruit quality parameters (pH and °Brix) assessed in this study, pH was not significantly affected by any of the 4 treatments considered, which is in line with previous research carried out on tomato grown in moderate-shaded environment (Aroca Delgado et al., 2019; Cossu et al., 2018; López-Díaz et al. 2020). °Brix was lower in the fruits produced under FS and SH_A than that obtained under FL conditions. Similar results were obtained for tomato growing in a shading environment where the shade led to a decrease in °Brix (Callejón-Ferre et al. 2009, López-Díaz et al., 2020). Usually, °Brix ranges from 4% to 9% and it is inversely related to fruit yield (Stevens and Rudich, 1978; Atherton and Rudich, 1986). In this study the lowest °Brix was found under shading condition, but the value obtained were always above the lower threshold indicated by the industry as the limit for accepting processing tomato (4.2 °Brix and a pH value up to 4.5 according to the D.D.L 3462 art.2; D.M 23 Settembre 2005 art.1).

Conclusion

In this study the effect of the agrivoltaic system on phenology, ecophysiology, fruit yield and quality of processing tomato was investigated. Continuous shade throughout the day greatly affected both morphological and physiological aspects of tomato plants. Regarding phenology, shade mainly affected the reproductive stage as the fruit set rate was lower in shade conditions than in FL and this affected both the yield and the number of fruits. The chlorophyll content (SPAD) and the height of plants were not affected by the shading conditions of the three shading treatments considered compared to FL conditions. Results showed that tomatoes adapted to shading conditions by increasing SLA, despite this, this plant adaptation response to shading conditions did not satisfy the requirement of the plant in terms of net photosynthetic rate (PN) to achieve a yield similar to the full light conditions. In fact, the lowest PN values were measured in shading conditions.

The lowest yield was found in FS conditions, but this result was influenced by both shading and the reduced irrigation volume given to the plant, which may have affected production. In SH_M treatment, where shading was provided in the morning hours (8-12am), an overall daily reduction of radiation of resulted in a yield reduction by 12.8%, while daily water consumption was 16% lower compared to plant grown under full light (FL). Plants in full lights were stressed by the high radiation and high temperatures compare to FS conditions as it was confirmed by the lower performance index (PI) measured throughout the crop cycle. Regarding fruit quality, pH and °Brix were not affected by shading, which indicates that tomatoes can maintain a high fruit quality also under agrivoltaic conditions. Fruit dry weight instead was significantly affected by shading and the lowest value was recorded under FS.

Result obtained in this study should be validated in “real” open field agrivoltaic systems in order to fully evaluate the effect of the dynamic changes of radiation and of other meteorological parameters that occur under an agrivoltaic system.

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Supplementary material: Photosynthesis Equations Used in CIRAS-2

The first step is to calculate the mass flow of air (**W**) per unit leaf area entering the cuvette. The CIRAS-2 mass flowmeter is calibrated to read the volume flow at 20 °C and 1013.25 mb (**V_{20}**). Molar volume is 22.414 at 0 °C and 1 standard atmosphere (STP). Therefore:

$$W(mol\, m^{-2}s^{-1}) = \left(\frac{V_{20}}{60\ \times 10^3}\right) \times \left(\frac{1}{22.414}\right) \times \left(\frac{273.15}{293.15}\right) \times \left(\frac{1000}{1013.25}\right) \times \left(\frac{10^4}{\alpha}\right)$$

Where $\boldsymbol{\alpha}$ is the projected leaf area (cm^2). The V_{20} term is calculated above using $cm^3\ sec^{-1}$, but displayed by CIRAS-2 as ml min^{-1} and is the mass flow of dry air into cuvette at STP.

The second step is to calculate the transpiration rate (E) from the partial pressure of water vapor of the air entering ($\mathbf{e_{in}}$) and leaving ($\mathbf{e_{out}}$) the cuvette.

$\mathbf{e_{in}}$ is defined as the partial pressure of water vapor of dry reference air supplied to the cuvette, but not yet inside the cuvette, and therefore uninfluenced by the cuvette stirring fans or the leaf itself. Its partial pressure is determined by the Reference H_2O IRGA.

$\mathbf{e_{out}}$ is defined as the partial pressure of water vapor of air inside the cuvette, surrounding the leaf. This air is both highly mixed by the stirring fans and influenced by transpirational water vapor. Its partial pressure is determined by the Analysis H_2O IRGA.

(2.1) The molar flow of water vapor (mol $m^2\ s^{-1}$) into the cuvette is:

$$W \times \left(\frac{e_{in}}{P}\right)$$

Where **P** is the Atmospheric pressure expressed in mb.

(2.2) The molar flow of air out of the cuvette (due to the addition of transpired water) is (**W+E**). Therefore, the molar flow of water vapor out of the cuvette is:

$$(W + E) \times \left(\frac{e_{out}}{P}\right)$$

(2.3) However, the difference between the molar flows into and out of the cuvette must equal the transpiration, so:

$$E = \left[(W + E) \times \left(\frac{e_{out}}{P}\right)\right] - \left[W \times \left(\frac{e_{in}}{P}\right)\right]$$

(2.4) Therefore:

$$E(mmol\, m^{-2}s^{-1}) = \left[W \times \left(\frac{e_{out} - e_{in}}{(P - e_{in})}\right)\right] \times 10^3$$

The third step is to calculate the leaf temperature ($\mathbf{T_{leaf}}$) from the energy balance. The difference between air and leaf temperature is defined by Parkinson (1983) as:

(3.1)

$$\Delta t = \left[\frac{H - \lambda \times E}{\left(\frac{0.93 \times M_a \times C_p}{r_b} \right) + [4\sigma \times ((T_c + 273)^3)]} \right]$$

Where:

H= incident radiation absorbed by the leaf

λ = latent heat of vaporization of water

E = transpiration rate

M_a = molecular weight of air

C_p = specific heat at constant pressure

r_b = boundary layer resistance to water vapor transfer, empirically determined for each cuvette by the pseudo-leaf (filter paper) method. 0.93 converts it to that for heat transfer.

σ = Stefan Boltzmann constant

T_c = cuvette air temperature

H is calculated from the photon flux incident on the cuvette (Q), taking into account the ratio of infrared to PAR in the light source, transmission through the cuvette window (Trans), and reflection/absorption by the leaf: (H = Q x Trans).

The following approximation is made in the program :

$$4\sigma \times ((T_c + 273)^3) \cong (4.639 + (0.5834 \times T_{c)}$$

(3.2) From this we derive:

$$T_{leaf} = T_c + \Delta t$$

Where Δt is the temperature difference between the air and the leaf expressed in °C.

The fourth step is to derive i) saturated vapor pressure at leaf temperature (e_{leaf}) from T_{leaf} and ii) stomatal resistance (r_s) as defined by Buck (1981) as:

(4.1)

$$e_{leaf} = 6.1121 * exp\left[\frac{T_{leaf} \times \left(18.564 - \left(\frac{T_{leaf}}{254.4}\right)\right)}{T_{leaf} + 255.57}\right]$$

(4.2) Stomatal resistance (to water vapor) is derived by:

$$r_s = \left[\left[\frac{(e_{leaf} - e_{out})}{\frac{(e_{out} - e_{in}) \times (P - e_{out})}{P}}\right] \div W\right] - r_b$$

(4.3) Another expression of (2.4) is:

$$E = \left[\frac{(e_{leaf} - e_{out})}{P \times (r_s + r_b)}\right]$$

(4.4) because

$$\left[\frac{(P - e_{out})}{W \times (e_{out} - e_{in})}\right] = \frac{1}{E}$$

(4.5) Then:

$$r_s(m^2\ s\ mol^{-1}) = \left[\frac{(e_{leaf} - e_{out})}{(E \times P)}\right] - r_b$$

(4.6) It follows that stomatal conductance is the inverse of stomatal resistance:

$$g_s(mmol\ m^{-2}s^{-1}) = \frac{1}{r_s} \times 10^3$$

The fifth step is to determine the rate of net photosynthesis (**A**) from the difference between CO_2 concentrations entering (C_{in}) and leaving (C_{out}) the cuvette

(5.1) IRGA CO_2 readings are corrected for water vapor, temperature, and atmospheric pressure. The addition of transpirational water vapor dilutes the air leaving the cuvette (C_{out}), and this is compensated for in the calculation:

$$A = (C_{in} \times W) - [C_{out} \times (W + E)]$$

Therefore:

(5.2)

$$A = \left[\left((C_{out} - C_{in}) \times W\right) + (C_{out} \times E)\right]$$

CIRAS-2 calculates and displays the CO_2 difference (C_{out} - C_{in}). As relates to the calculated values in the CIRAS-2 display:

$$C_{out} = \left(C_{ref} + C_{dif}\right) = C_{analysis}$$

The sixth step is to calculate CO_2 concentration in the sub-stomatal cavity (Ci) using the equation derived by von Caemmerer & Farquhar:

(6.1)

$$C_i(\mu mol\ mol^{-1}) = \frac{\left[\left(g_d - \frac{E}{2}\right) \times C_{out}\right] - A}{\left(g_c + \frac{E}{2}\right)}$$

(6.2) Where:

$$g_c(mmol\ m^{-2}s^{-1}) = \left[\frac{1}{(1.585 \times r_s) + (1.37 \times r_b}\right] \times 10^3$$

Please note: These calculations are based on the following assumptions:

i) the leaf is exposed on both upper and lower leaf surfaces

ii) the upper and lower boundary layer resistances are similar

iii) stomata are evenly distributed on both upper and lower leaf surfaces.

Table 1. *Symbol definition (Ciras-2 Manual). *Determined by IRGA. Temperature and pressure corrected for water vapor effects on measurement and analyzer temperature*

Measured parameters		
Symbol	**Measured parameter**	**Unit**
V_{20}	Mass flow of dry air into cuvette at STP	$cm^3\ sec^{-1}$
A	Projected leaf area	cm^2
r_b	Boundary layer resistance to water vapor	$m^2s\ mol^{-1}$
P	Atmospheric pressure	mb
Q	Photon flux density incident on cuvette	$\mu mol\ m^{-2}\ s^{-1}$
T_c	Cuvette air temperature	°C
Calculated parameters		
Symbol	**Calculated parameter**	**Unit**
W	Mass flow of dry air per unit leaf area	$mol\ m^{-2}\ s^{-1}$
e_{in}	Partial pressure of water vapor of air entering cuvette	mb
e_{out}	Partial pressure of water vapor of stirred cuvette air	mb
E	Transpiration Rate	$mmol\ m^{-2}\ s^{-1}$
e_s	Saturated water pressure at cuvette air temperature	mb
e_{leaf}	Saturated water pressure at leaf temperature, inside the leaf	mb
Tleaf	Leaf temperature	°C

Δt	Temperature difference between the air and the leaf	°C
H	Radiation absorbed by leaf	W m^{-2}
Rs	Stomatal resistance to water vapor	m^2s mol^{-1}
Gs	Stomatal conductance to water vapor	mmol m^{-2} s^{-1}
C_{in}	CO_2 concentration of air entering cuvette	µmol mol^{-1} *
C_{out}	CO_2 concentration of air inside and exiting the cuvette	µmol mmol $^{-1}$ *
A	Rate of CO_2 assimilation (Net Photosynthetic Rate)	µmol m^{-2} s^{-1}
Gc	Total conductance to Co2 transfer	mmol m^{-2} s^{-1}
C_I	CO_2 concentration of sub-stomatal cavity	µmol mol^{-1}

Physical Constants Used in Equations (Ciras-2 Manual)

- Volume of one kg mole of gas= 0.0224 m^3, at 1013.25 millibars of pressure and 273.15 °K
- Latent hear of vaporization of water (λ)= 45064.3-(T_c x 42.9)
- Molecular weight of air (Ma)= 28.97
- Specific heat at constant pressure (Cp)= 1.012 kJ kg^{-1} K^{-1}
- Stefan Boltzmann constant (σ)= 5.6704 x 10^{-8} W m^{-2} K^{-4}

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Chapter 4: Modelling the effect of crops albedo for energy conversion on bifacial agrivoltaic systems

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Abstract : Agrivoltaic (AV) systems combine agricultural activities and energy conversion from solar photovoltaic (PV) panels in the same land area. In AV systems, the interaction between energy conversion and crop production is synergistic because crops can benefit from the presence of the panels and the PV system benefits from the vegetative cover. In particular, the crop albedo can increase the PV energy conversion on bifacial AV systems. Among the variables that can affect the energy conversion of the PV modules (for example cooling, soiling etc.) this study aimed to assess the impact of the measured crop albedo from different crops on the energy conversion of two AV systems with bifacial PV modules (vertical and 2-axis tracking). A simulation platform was used to evaluate the effect of crop albedo (field-derived and satellite-derived data) on the energy conversion compared to the albedo of the bare soil conditions. Average albedo values measured in field conditions during the entire growing cycle were bare soil (BS)=0.2, lemon balm (LB)= 0.22, oregano (O)=0.30, rosemary (RM)=0.27, thyme(T)=0.25 and Miscanthus mulching (MM) =0.31. A fixed value for the white mulching film (WM) was set at 0.45. Average albedo derived from satellite data were BS=0.2, LB= 0.25, O= 0.25, RM=0.26, and T=0.26. The simulated PV energy converted was estimated by using albedo from field data and albedo from satellite. In the vertical system by considering the albedo field data, the increase of the total simulated PV energy conversion (kWh) compared to bare soil was 6.7% for O, 4.2% RM, 3.8% T ,2.8% LB, 4% MM and 16.8% WM. For the albedo satellite data, the simulated PV energy converted compared to that of the field albedo measurement was reduced by 3.5% for O and 0.3% for RM, while a slight increase of 0.2% for the PV energy converted was estimated for T and LB. In the bi-axial system, by considering the albedo field data the increase of the total simulated PV energy conversion (kWh) compared to bare soil was 4.6% for O, 3.1% RM, 2.8% T, 1.7% LB, 5.3% MM and 11.3% WM. By considering the satellite-derived albedo data the PV energy conversion result reduced for O by 3.4% and for RM by 0.7% compared to that reported for the field measurements. For the T and LB, the simulated PV energy conversion was slightly overestimated by 0.1% and 0.5% respectively, compared to the results obtained with field data. In addition, the increase of energy conversion for the rear side of the PV modules compared to the bare soil condition ranged between 15% to 93% for the biaxial system and between 3.8% to 23.3% for the fixed vertical system.

Introduction

Goetzberger and Zastrow (1981) were the first to introduce the concept of coexistence between cultivation and solar energy conversion. However, for a long time this possibility remained almost unexplored in both the research and commercial fields, and the scientific community's interest in

AV systems has only grown since the last decade. The term 'agrivoltaic system' was used for the first time in 2011, when Dupraz et al. (2011) predicted a significant increase in the overall productivity of agricultural land when combined with photovoltaic panels and, in the last decade there is a growing number of related publications (Amaducci et al., 2022; Mamun et al., 2022, Weselek et al., 2019).

The cultivation and management of plants of agricultural interest in an agrivoltaic (AV) environment depend on the complex interaction of agronomic factors related to the growth of plants under limiting light conditions. In AV systems the interaction between electricity generation and crop production is synergistic, not only do crops benefit from the presence of the panels, but the PV system also benefits from the vegetative cover (Amaducci et al., 2022). In particular, transpiration from crops cultivated under PV panels lowers the air temperature, thereby significantly increasing the performance of the solar cells (Barron Gafford et al., 2019) and the crop albedo can increase the electricity yield of PV panels, mainly for bi-facial modules (Fraunhofer ISE, 2022, Schindele et al., 2020). The performance of photovoltaic panels is positively influenced by high albedo values of the underlying surfaces, especially when bifacial panels are used, i.e., those capable of generating energy from both sides of the photovoltaic module (Krenzinger & Pigueiras, 1986). The albedo (α) is an indicator of a surface's reflective power and is the ratio of reflected solar radiation to direct solar radiation at a surface (Philander, 2012). The albedo is a dimensionless measure between 0 and 1, the higher this value, the more reflective power the surface will have. The albedo value of the surfaces below the panels can influence the power output of bifacial photovoltaic modules by up to several tens of percentage points (Guerrero-Lemus et al., 2016)

The albedo is generally expressed through the ratio:

$$\rho = \frac{Eu}{Eg}$$

Where ρ = albedo, Eu = global reflected radiation and Eg= global radiation in the horizontal plane (descending), both typically measured through a pyranometer (facing downward and upward, respectively) (Gueymard et al., 2019).

For crops, the albedo depends on the agricultural management and crop cultivation cycles (for example annual cycle) and on rapid changes in vegetation and the fraction of exposed soil (Cescatti et al., 2012; Gao et al., 2005). Among the agricultural practices the most that influenced the albedo are tillage and fallowing (Davin et al., 2014; Liu et al., 2021), organic amendments, cover cropping or intercropping (Carrer et al., 2018; Miller et al., 2016; Seneviratne et al., 2018).

From an agronomic point of view, several possibilities lead to modifying the albedo of one or more surfaces, these can be related to the choice of crops, to the different phenological phases and growing season (Jacobs and Van Pul, 1990, Song, 1999) and to morphological modification of the crops (Oguntunde et al., 2004; Song, 1999; Doughty et al., 2011). Furthermore, the optical proprieties of leaves influence the albedo for example, biochemical and biophysical characteristics such as mesophyll, internal interfaces, proteins, sugars, and pigments (Hollinger et al., 2010, Ustin and Jacquemond, 2020). Chlorophyll and other pigments in leaves absorb a large amount of radiation in the optical wavelengths of 400–700nm (Gates et al., 1965). Leaves contain air-filled intercellular spaces interspersed with mesophyll cells, radiation is reflected and refracted many times, leading to higher reflectance and lower transmittances from NIR spectral (Gates et al., 1965; Woolley, 1971). Pigments in leaves absorb poorly in the infrared wavelength, so leaves reflect and transmit most incoming NIR radiation (780 nm to 2500 nm). The increasing scattering of light at the upper boundary of the canopy results in a direct improvement of canopy albedo. In the lowest part of the canopy the radiation changes in terms of transmittance from the above canopy layers and for the multiple reflections, thus leading to an enhanced leaf scattering and the albedo becomes small (Hollinger et al., 2010).

The main differences in crop albedo are due also to the crop morphological and physiological traits (i.e., height and Leaf Area Index), the soil texture and organic matter content, and local meteorology (Bonan, 2015; Bright et al., 2015; Sieber et al., 2019), to the nitrogen content and chlorophyll concentration in leaves, leaves trichomes, glaucousness and waxiness (Genesio et al., 2021; Hollinger et al., 2010; Singarayer & Davies-Barnard, 2012).

Using highly reflective crops in AV systems can considerably influence energy production, especially when bifacial photovoltaic modules are used. In fact, for the same panel density, the use of bifacial modules positively affects electricity production per square metre, as the radiation reflected by vegetation and soil is intercepted from the rear side of the panel (Kreinin et al., 2011). Consequently, the use of bifacial modules makes it possible to decrease the density of photovoltaic panels by using larger distances between support structures, increasing the level of solar radiation available to crops, while maintaining the same energy output per unit area (Schindele et al., 2020). Furthermore, this type of photovoltaic module is characterised by greater transparency due to the presence of small gaps between the individual solar cells (Trommsdorff et al., 2021), therefore, the use of bifacial panels allows for an increase in the level of diffuse radiation available to crops.

In addition to the presence of vegetation, a possible means of increasing albedo in the AV environment is to cover the ground with materials with a high reflective capacity. In an experimental trial conducted by Fan et al. (2015), using a white plastic mulching film, on clear days the albedo of bare soil increased by 16.6% and that with grass by 23.5%. Therefore, the use of mulching techniques can increase the amount of solar radiation reflected from the soil, affecting the energy performance of an AV system.

As the bifacial PV technique increases in popularity, it becomes necessary to evaluate how surrounding factors and system configurations, such as albedo value, tilt angle and azimuth angle, influence the energy conversion. Various researchers have investigated how different a static albedo value affect the energy yield of monofacial or bifacial PV systems (Sreenath, Sudhakar, & Yusop, 2021; Lindsay et al., 2015; Asgharzadeh et al., 2018) but, there is a lack of sufficient research on the impact on the power output when simulating with a dynamic albedo compared to a static albedo value. The need to fill the information gap regarding the influence of albedo on the energy production of AV systems is therefore evident and to do so by means of a simulation model would reduce both the time and resources required (Maria, 1997) and make experimentation reproducible under different scenarios in terms of crops, latitude, climate and other variables of interest.

Several software tools have been developed to evaluate bifacial PV performance. PVsyst is one of these tools. However, in PVsyst the albedo values can only be adjusted at the highest frequency each month (Mermoud & Wittmer, 2016; PVsyst). Considering a constant albedo is not sufficient when simulating some photovoltaic applications (Chiodetti et al., 2016) for example, the energy conversion of bifacial PV modules. OptiCE software is an open-source code with a PV simulation tool and during the last years Campana et al., (2021) improved the simulation model to predict the shading generated by the AV system and they integrate the albedo variable as dynamic factor that can change depending on the data collected for example in field or by satellite-derived data.

This study aims to:

- Measure the albedo values of crops in field to have data on how crops reflect the light;
- Evaluate among 4 aromatic crops (rosemary, lemon balm, thyme and oregano) which crop show the best albedo performance under the photovoltaic panels;
- Evaluate the phenological impact on crop albedo throughout season in perennial crops;
- Evaluate which conditions most affected the value obtained (e.g., bare soil, mulching film);
- Use the field albedo data and satellite-derived data to simulate the energy conversion of 2 bifacial systems: 1 Vertical and 1 Biaxial system.
- Assess what system configurations are most optimal to maximise the energy output.

Matherial and Methods

Experimental site, crops and agronomical management

The experimental site to collect albedo of the crop was Cooperativa Agricola Sociale Gli Spinoni located in Piacenza (29122), Italy, lat= 45.027484 N, lon= 9.723368 E. The crops cultivated in the experimental site were aromatic plants (Figure 1).

141-152 Lavandula angustifolia	134-140 *Melissa officinalis141-152*	128-133 *Origanum Majorana*	*107-127 Thymus vulgaris Tujanolo*	*89-106 Rosmarinus Officinalis Verbenone*	78-88 *Timo*	65-77 *Salvia sclarea*	63-64 Origano	56-62 *Timo*	50-55 *Origano*	47-49 Lavanda	44-46 Rosmarino	21-43 *Melissa Officinalis*	15-20 *Salvia Officinalis*	12-14 *Salvia sclarea*	1-11 *Salvia Officinalis*

Figure 1 *Experimental design of the field. Crops rows chosen for albedo measurements are 132 -133 for Oregano, 134 for Lemon Balm, 107-108 for Thyme and 106 for Rosemary*

The crops selected to measure the albedo were thyme (*Thymus vulgaris* cv. Tujanolo), rosemary (*Rosmarinus officinalis* cv. Verbenone), oregano (*Origanum majorana*), lemon balm (*Melissa officinalis*) (Figure 1). In the same field were also carried out the measurement in the bare soil and for the Miscanthus mulch. Crops rows chosen for albedo measurements are 132 -133 for oregano, 134 for lemon balm, 107-108 for thyme and 106 for rosemary (Figure 1).

The plants in the site are grown according to the organic method. An adequate weed control in the field was done by using a with mulching film (Figure 2).

Figure 2 *White plastic mulching film on crop rows*

The plastic mulch covering a planting bed with a width of 110 cm and the inter row distance between plants is 15 cm and 30 cm between rows (double rows per single bed). Plants were fully irrigated using a drip irrigation system with pipes placed under the mulching films close to the plants roots.

Albedo field measurement

Albedo measurements were carried out according to the guidelines described in ASTM E1918-06 (ASTM international 2015). This procedure allows the measurement of albedo on horizontal surfaces of different nature and low slope. The ASTM E1918-06 is a pyranometer test method (using only one pyranometer) but can also be used with an albedometer (Li et al., 2013).

The measurements were conducted from October 2021 to May 2022 using six Light Scout Silicon Pyranometers (Spectrum Technologies, Inc, UK) that measure solar radiation between 300 to 1100 nm with ± 5% of accuracy. The six pyranometers used in this trial were south oriented to minimise the influence of shadow. Five pyranometers were turned downward and each of them were mounted in a horizontal rod parallel to the measurement surface and stand at the height of 50 cm from the surface to minimise shadow and the effect of surrounding surfaces on the measured reflected radiation. One pyranometer was turned upward to collect measurements of horizontal global radiation. Albedo was estimated as the ratio of reflected solar radiation (W m^{-2} downward pyranometers) to the global solar radiation (W m^{-2} upward pyranometer).

The dimension of each plot for the downward pyranometers was 1 m^2 (the ASTM method require a minimum size of plot of 1 m^2 so that albedo can be evaluated precisely). In order to correctly position the pyranometers the crop height per plot was measured.

The tests were performed on clear days to collect at least 3 days of data for each plot and pyranometers were positioned in each plot for 5-6 days (depending on the weather conditions). The measurements considered to obtain albedo data from the incoming and reflected radiation was taken every 4 minutes from 10 a.m. to 4 p.m. The selected crops and field pyranometers positioning are represented in Figure 3 and Figure 4.

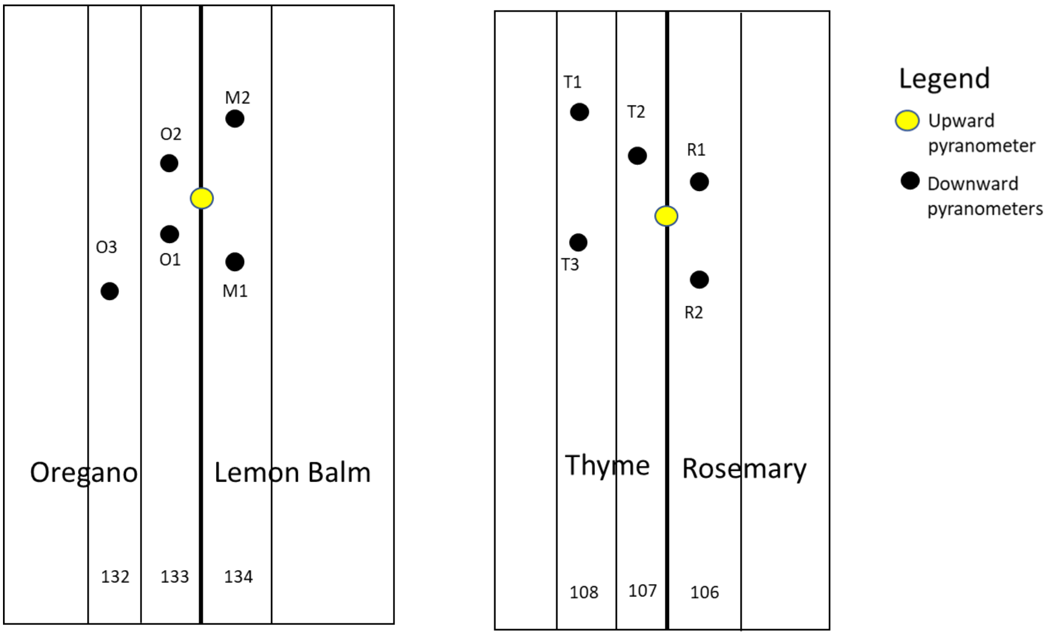


Figure 3 *Position of pyranometers in field for the crops chosen. O= oregano, M= lemon balm, T= thyme, R= rosemary. Each number represent the replicate pyranometer for a single crop.*

Figure 4 *Pyranometers on rosemary and thyme (top) and on oregano and lemon balm (bottom)*

Albedo changes with the phenological stages of the crop for example vegetative stage or senescence of the canopy (Richardson et al., 2013). The albedo during the season changes due the combined changes in reflectance of photosynthetically active (PAR) and near-infrared (NIR) radiation. For example, the reflectance of the canopy in PAR range decrease with the development of the canopy because plant absorbs an increasing amount of PAR for the photosynthetic process (Moore et al., 1996, Burba and Verma, 2001, Ryu et al., 2008). In contrast, the NIR reflectance of the plants tends to increase with the development of the canopy due to the increase of multiple scattering within the canopy (Gates, 1965). Due to the influence of phenological stage on crop albedo the field measurements were collected in three different season to obtain the albedo data for 2 main crop phenological stages: vegetative and reproductive stage and to show the seasonal change of albedo due to canopy development.

The albedo data were collected for thyme (T) and rosemary (RM) from 26/10/21 to 02/11/2021, for oregano (O) and lemon balm (LB) from 05/11/2021 to 09/11/2021, for the bare soil (BS) from 26/11/2021 to 02/12/2021 and for the Miscanthus mulching (MM) 18/03/2022 to 26/03/2022. Albedo data for bare soil and Miscanthus mulching were collected only once in the period between October 2021 (BS) and April 2022 (MM) because, the same albedo value was assumed throughout the year. Another fixed albedo data used for this study relates to the white mulch (for more information, see the section Simulation platform: description and set up).

The crops during the autumn months are in vegetative stage (Figure 5). Among the crops selected, LB during the winter month started to lose the leaves (Figure 5).

Figure 5 *Pyranometers on crops: 1) rosemary 2) thyme 3) oregano 4) lemon balm*

During winter the albedos data for T and RM were collected from 21/02/2022 to 28/02/2022, the albedos data for O and LB were collected from 08/02/2022 to 16/02/2022. The crops during these months are in still in vegetative stage but the LB was leafless (Figure 6).

Figure 6 *Lemon Balm February 2022*

In spring the albedo data were collected for T and RM from 10/05/2022 to 19/05/2022, for O and LB from 19/05/2022 to 26/05/2022. The crops in spring are in flowering stage.

Data collection in field

Measurements of crop height and Leaf Area Index (LAI) were carried out to characterise crops morphology, to collect data on the development of the crop and to show how the development of the crop can influence the albedo. The crop height was estimated as the mean of the heights (cm) from the ground to the top of the raised leaves of each plant (in total 3 plant per plot).

As a quantitative measure of canopy size, LAI measurements were taken to characterize the growing features of the involved crops. LAI affects the processes of light interception, photosynthesis, and transpiration (Oguntunde et al.,2004, 2007, Bsaibes et al., 2009) and it is an important quantity for modelling purposes (Breuer, 2003). LAI was estimated using an ACCUPAR LP-80 PAR/LAI ceptometer from METER Group. The LP-80 measures photosynthetically active radiation (PAR, 400-nm to 700-nm) and can use these readings in a model to give a leaf area index (LAI) for a plant canopy. A total of 12 LAI measurements per plot were taken and mean value and standard deviation were computed per each set of readings.

Weather variables (air temperature, relative humidity, wind speed and direction, rainfall, and solar radiation) were collected with WatchDog 2000 Series Weather Stations and, were also downloaded by the regional RIRER survey network operated by Arpae-Simc (https://simc.arpae.it/dext3r/).

Satellite-derived data

Data from Sentinel-2 were used to calculate crop albedo values from satellite images. The Sentinel-2 mission of the European Space Agency's Copernicus programme consists of a pair of satellites launched in 2015 and 2017. Both satellites carry a multi-spectral sensor capable of covering an area of 290 km and provide data in 13 spectral bands ranging from the visible and near-infrared to the short-wave infrared region, with a spatial resolution of 10 m (four bands: Red, Green, Blue and NIR), 20 m (six bands) and 60 m (three bands), providing data every 2-3 days at mid-latitudes (Croci et al., 2022). To calculate the daily mean albedo Sentinel-2 level 2A surface reflectance data freely accessible from the Google Earth Engine platform were used with a resolution of 10 metres produced by three visible bands (Red, Green and Blue) and one NIR spectral band, net of clouds and cloud-generated shadows (Lin et al., 2022). Following the procedure described by Silva et al. (2019), the daily albedo was extrapolated from the surface albedo (α0), by first calculating the planetary albedo (αP) for the visible and infrared partition of the electromagnetic spectrum as the total sum of the different narrow-band reflectance values (rband) weighted for each band (wband), according to the formula:

$$\alpha P = \Sigma wband rband$$

in which the weights for the different bands were calculated as the ratio of the amount of incoming shortwave radiation from the sum in each band to the sum of incoming shortwave radiation for the bands in the upper atmosphere. The different wband values were therefore 0.32, 0.26, 0.25 and 0.17 for the Red, Green, Blue and NIR bands, respectively. The daily albedo values were then obtained according to the equation:

$$\alpha 0 = b\alpha P + c$$

where b and c are regression coefficients used to estimate the value over a 24-hour period. Therefore, the final equation used to calculate the daily albedo value was:

$$\alpha 0 = 1.0223 * (0.6054 * ((0.32 * \text{Red}) + (0.26 * \text{Green}) + (0.25 * \text{Blue}) + (0.17 * \text{NIR})) + 0.0797) + 0.0149$$

This formula was used to calculate the albedo value of each pixel contained in the images of the experimental site, extracted from Sentinel-2 and covering the period between 26/10/2021 and 26/05/2022. The daily albedo value of each crop was estimated as the median of the value of the pixels contained in the area that included a single crop.

Simulation platform: description and set up

The albedo data collected in the experiment and extracted from satellite images were used to feed a simulation model (Figure 7) for bifacial PV panels based on the open-source code Opti-CE, described in Campana et al. (2017), with the aim of assessing the impact of albedo, both static and dynamic, on the energy production of an AV system equipped with bifacial modules.

The Opti-CE package is an open-source code written in the Matlab language (The MathWorks Inc., Natick, MA, USA), equipped with a photovoltaic environment simulation tool that, in its original version, does not include bifacial modules as a simulation option.

The inputs to the improved version of Opti-CE model are the AV system configuration, meteorological data, irradiance, albedo and photovoltaic module characteristics. The model uses meteorological data and system information to simulate the front and rear irradiance of a bifacial photovoltaic module. The software is able to calculate the position of the sun and its energy and uses these values together with the previously mentioned inputs to calculate the angle of incidence on the module, reflection losses and irradiance components. Opti-CE functions (based on equations obtained from PVLIB Toolbox, as described in Stein et al., 2016) and PV module parameters are subsequently used in the model to calculate the energy conversion. Compared to the original version, the developed model implemented row-to-row shading for both the vertical and the biaxial systems to be able to distinguish the diffuse and direct components of solar radiation.

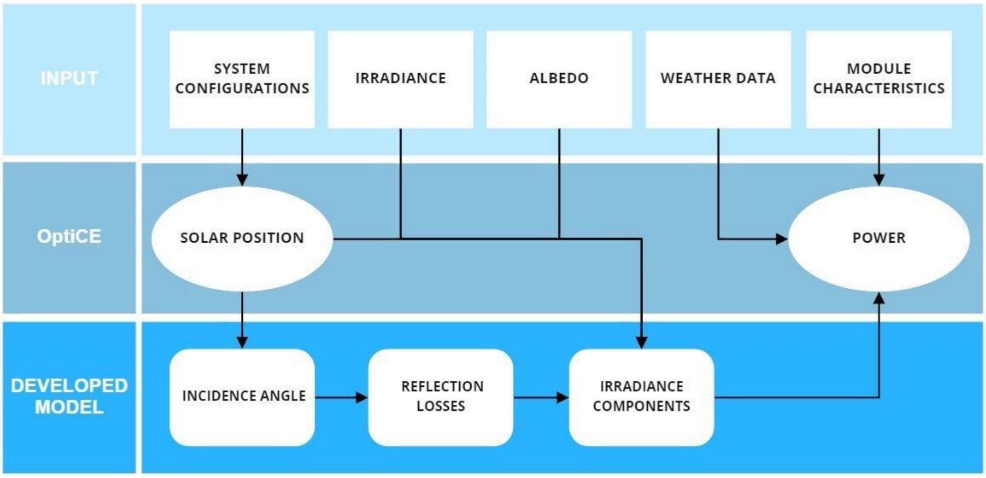


***Figure 7** Overall model framework*

In simulation software, bifacial photovoltaic modules are characterised by a bifaciality factor, which is the ratio between the nominal efficiency on the back side and the nominal efficiency on the front side of the panel (Sreenath et al., 2021; Deline et al., 2017). Thus, the irradiance on the rear side of the module, after being multiplied by the bifaciality factor, is added to the front irradiance to obtain the total energy conversion value. For the simulations, the bifaciality factor for bifacial photovoltaic modules was chosen to be 0.85. The total energy conversion (PVe) was calculated as:

$$PVe = PVef + PVer * 0.85$$

Where $PVef$ is the energy conversion of the front side of the bifacial module; $PVer$ is the energy conversion of the rear side of the bifacial module and 0.85 is the bifaciality factor selected for the simulations.

The total irradiance for each side is calculated as the contribution of the direct, diffuse and reflected (albedo) components of solar radiation. The outputs of the simulation platform consist of the irradiance received from the front and rear side of the photovoltaic module (W) and its conversion to total electrical energy (kWh).

The validation results of the modified Opti-CE model were obtained in an experiment conducted by Nygren & Sundström (2021), showed a coefficient of determination R^2 of 93% and 91% for the front and rear sides, respectively, when simulated with a dynamic albedo value on an hourly basis and based on a single-axis bifacial tracker system.

The albedo data were used on an hourly basis from 8:00 a.m. to 5:00 p.m., referring to solar time, for a period between 26 October 2021 and 26 May 2022, adding data obtained by interpolation for the missing dates to the values measured in the field. Similarly, the satellite-derived albedo was supplied to the model as a daily average and used on an hourly basis for the four selected crops through interpolation.

The albedo data used for the white mulch cloth was estimated to be 0.45 as described in Brault et al. (2002). This value was measured on a white/black coextruded polyethylene sheeting, very similar to that used at the experimental site, using an instrument capable of evaluating wavelengths in the 400-1100 nm range, a range comparable to the operating range of the pyranometers used in the experiment.

Agrivoltaic systems configurations

The model was modified to simulate the performance of bifacial photovoltaic panels and evaluate the effect of the albedo value on the performance of an AV system both in terms of irradiance on both sides of the modules and by calculating the energy output of the system. The modification to the simulation model was based on the characteristics of two types of AV systems: a fixed vertical bifacial system installed at Kärrbo Prästgård (59.5549° N, 16.7585° E), Västerås, Sweden, described in Campana et al. (2021); and a bifacial system with biaxial solar tracking technology (AGROVOLTAICO®, REM Tec srl, Mantova, Italy).

The vertical AV system installed in Kärrbo Prästgård has a capacity of 22.8 kWp and consists of 60 bifacial PV modules arranged in three rows of 20 m each and spaced 10 m apart. Considering the three tracker rows of the vertical system, the agricultural area covered by the photovoltaic modules is 600 m^2. The biaxial system has a capacity of 16.8 kWp per tracker and a total capacity of 33.8 kWp was chosen to simulate a total of 48 bifacial photovoltaic modules arranged in two rows, each 14 m long and with 12 m pitch, covering a total agricultural area of 336 m^2.

Statistical Analysis

Statistical analysis was performed using with Rstudio, R version 4.2.1 (R Core Team, 2022).

The statistical analysis of the albedo of the crop was carried out using the Wilcoxon signed-rank test for a non-parametric statistical hypothesis. For the satellite-extracted albedo data, LAI and height measurements and energy conversion, no statistical analysis was performed due to the lack of an adequate number of replicates for the crop measurement and the time series analysed.

Results

Height and LAI Autumn

The average crops heights in autumn for O were 18 cm, for T 32 cm, for RM 30 cm and for LB 27 cm (Figure 10). LAI mean values in autumn for the crops were: 2.36 for T, 2.71 for RM, 0.4 for LB and 1.3 for O. The highest LAI value in autumn was found for RM and plant canopy completely covered the mulching film. Oregano canopy did not entirely cover the white plastic film. LB plants were almost leafless in October and at the beginning of November.

***Figure 10** Mean value of Albedo, Height and LAI for the season considered. The dotted lines represent the albedo value of bare soil (0.21) and Miscanthus mulch had an albedo value of 0.30, both albedo values were assumed for all the three seasons considered.*

Height and LAI Winter

The average crop height in winter for LB was 10 cm due to the leafless plants and consequently the LAI value was 0 for all the plants (Figure 10). Oregano average height was 20 cm and no changes were found in the canopy during the winter months compared to the autumn months and this was also confirmed by a reported average LAI of 1.15 (Figure 10). Average height of 27 cm was measured for T and, a mean LAI of 2.2 indicates a slightly decrease compared to the LAI value measured in autumn (Figure 10). RM plants reported a mean height of 30 cm and an average LAI of 2.64 which is similar to the previous LAI measured in the autumn, this indicates that the crop has not changed its canopy (Figure 10).

Height and LAI Spring

The plants in spring were in the flowering stage. The LB and O plants were the ones that changed their canopy the most as they not only increased their height (45 cm and 38 cm, respectively) but they also developed leaves and both crops started to increase their canopy presenting a LAI of 1.8 (LB) and 2.52 (O). RM and T showed a mean height of 33 cm and 35 cm respectively. The average LAI value was 1.53 for RM and 1.2 for T. In spring RM and T have reduced their LAI.

Albedo data per seasons

Albedo in autumn

The mean albedo values of the involved crops for the autumn season were: 0.32 for oregano, 0.29 for rosemary, 0.24 for thyme and 0.21 for lemon balm (Figure 10 and 11).

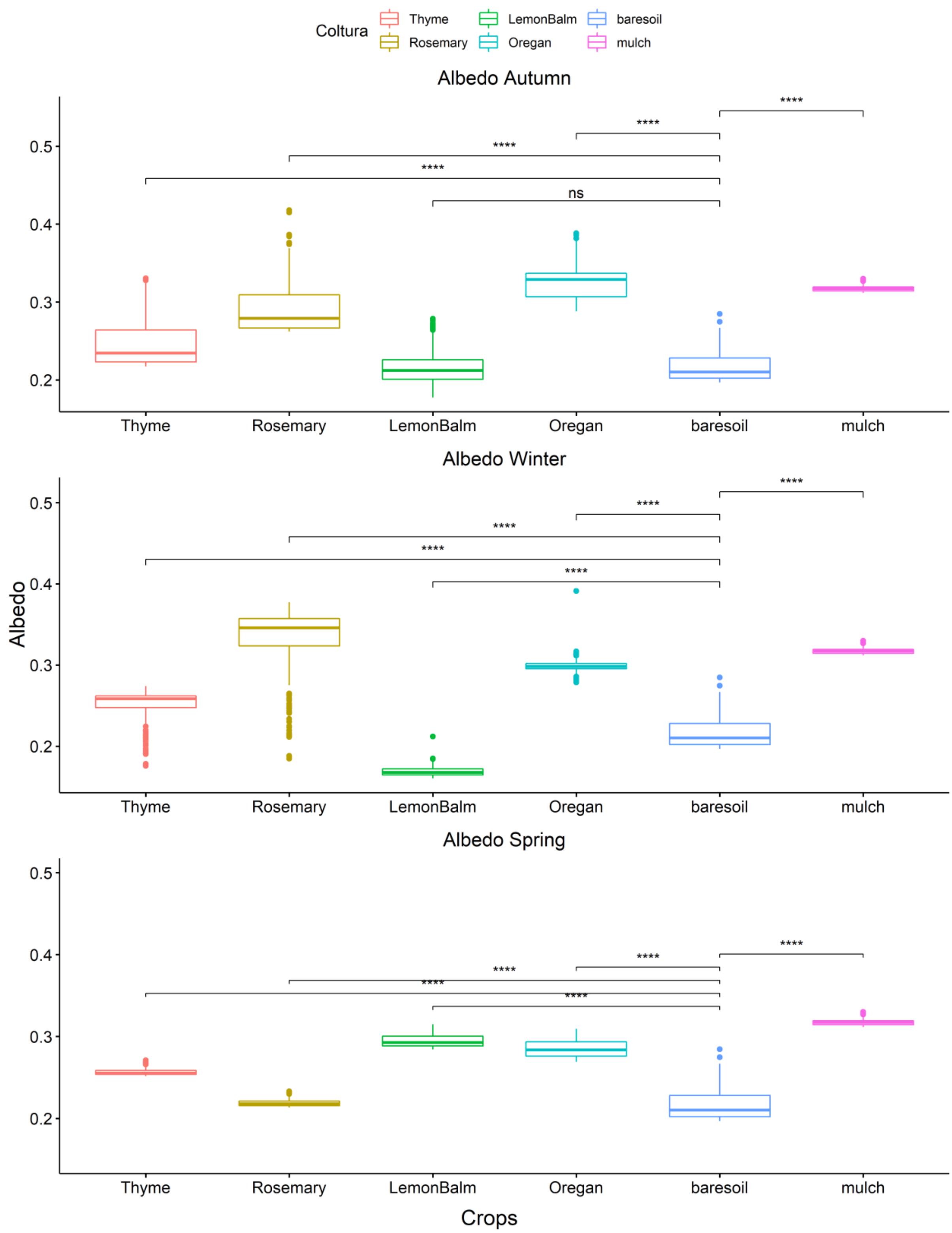


Figure 11 *Albedo mean value for crops, Miscanthus mulch and bare soil in three seasons (Autumn, Winter and Spring). The thick continuous line within the individual boxes of the plot showed the mean albedo. Albedo data were collected from 10 a.m. to 4 p.m.*

Albedo of bare soil was 0.21 and the albedo of miscanthus mulch was 0.31 (Figure 11) for all the season considered (Figure 11). The average albedo of the crops in this season and of the MM was higher compared to bare soil (Figure 11, p-value <0.05) excepting for LB that reported a value of

0.21 that was the same of the bare soil during this season. The highest albedo value in autumn was found for oregano (0.32) and, during this season, as already reported by the LAI value, the crop did not fully cover the row in which it was transplanted (Figure 5) and the white mulching may affect the reflectance of the surface by increasing the albedo.

Albedo in winter

The average albedo values of the crops for the winter season were: 0.29 for O, 0.32 for RM, 0,25 for T and 0.16 for LB (Figure 11). A significant difference was found between crops and BS and MM and BS (p-value < 0.05).

In winter LB reported a value of 0.16 that was lower than that measured for BS (0.21). LB was leafless during this season, and from these values it can be seen that the colour of the fallen leaves on the mulch sheet was darker than the reference soil (Figure 6) and consequently with less reflective power despite the presence of the white mulch sheet at the bottom.

All other crops and the mulching film reported higher values compared to bare soil and therefore this indicates higher reflectance. The highest albedo value in winter was found for RM (0.32). Considering the albedo measured in autumn and winter, the crops with the best reflectance during the vegetative stage were oregano and rosemary. Furthermore, both RM and T maintained the same albedo for the autumn and winter. For T, the average albedo increased slightly from 0.24 to 0.25 but there was not significance difference compared to the results obtained in autumn.

Albedo in spring

The average albedo values of the crops for the spring season were: 0.28 for O, 0.21 for RM, 0.25 for T and 0.29 for LB (Figure 11). Mean crop albedo for all crops and MM compared to bare soil value showed significant differences (p-value < 0.05).

In spring LB started the vegetative and flowering phenological stage, in fact, the monitored plants showed flowers and leaves and the plants canopy well covered the soil (Figure 12A and see section Height and LAI in spring for the LAI value of LB). The highest albedo value during the year for the LB was found in spring, when the plants showed an increase in height and in LAI that influence the albedo value to be higher than the previous seasons.

O showed a slighter decrease in albedo compared to the other 2 seasons, but in this case, it was influenced by a greater plant’s height especially for the flower-bearing stems, began to elongate and thus change the reflection of light conditioned by the flowering phase of the crop (Figure 12A) and the white mulching film is covered by the crops, and this may affect the albedo decrease.

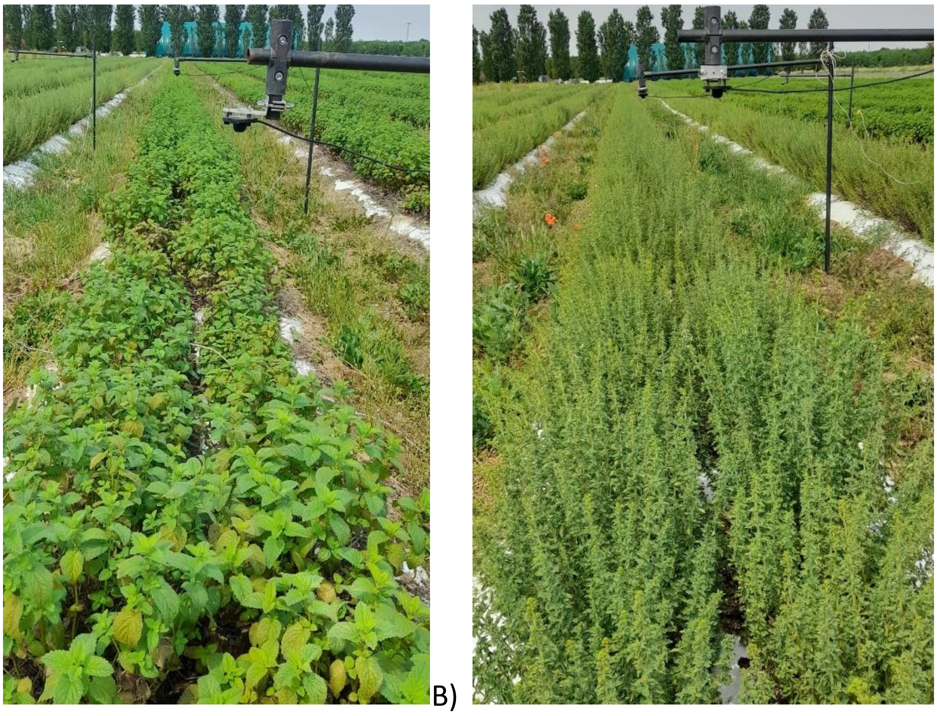
A)  B)

Figure 12 *A) Albedo measurement of lemon balm in spring B) Albedo measurement of Oregano in spring*

The lowest albedo of rosemary was measured in spring, this happened because the plant's growth was affected by the winter frosts (see figure 13A) occurred between January-March 2022, which resulted in most of the plants having a less developed canopy which lowered their ability to reflect light. The rosemary during the data collection in spring was in the flowering stage (figure 13A).

Thyme was also affected by the winter frosts (Figure 13B) but it showed the same albedo value during all three seasons considered, this indicates that the albedo value remains stable during the crop growth cycle despite the different phenological stages (as can be seen from figure 13B thyme was in flowering stage) and the changes in LAI and height.

A)  B) 

Figure 13 *A) Albedo measurement on rosemary in spring, on the right side of the picture the frost damage on plants; B) Albedo measurement on thyme in spring. Both crops were in flowering stage.*

Satellite-derived data

The average albedo values extrapolated from satellite images for the four aromatic crops were always above the average values recorded by the pyranometer for bare soil (0.21). During the seven months considered in the trial, the highest average albedo was found in RM (0.26) and T (0.26), followed by LB (0.25) and O (0.25). The satellite-derived values for RM and T slightly varied from the albedo measured in the field, -4% and +4% respectively. O and LB showed more significant variations, -20% and +12% respectively. The average albedo values obtained for the seven-month period, when compared to the albedo measured on bare soil in the field, represent a percentage increase of 23.8% for RM and T and 19.0% for O and LB.

Energy conversion: Vertical system

Using the albedo data measured in the field of the different crops, the increase in total energy conversion compared to bare soil (16617 kWh) was, in descending order, 6.7% for O (17734 kWh), 4.2% for RM (17317 kWh), 3.7% for T (17246 kWh) and 2.8% for LB (17080 kWh) (Figure 14 and 15).

Using the albedo value of MM (0.31) in the simulation for the fixed vertical system resulted in a total energy conversion of 17277 kWh (Figure 14). This value, when compared to the energy output of bare soil (16617 kWh), marks a conversion increase of 4.0%. For the albedo of the WM (0.45), a total energy conversion of 19410 kWh was obtained over the seven-month period considered (Figure 14). WM report an increase of 16.8 % of energy conversion compared to BS.

Using satellite-derived albedo the increase in total energy conversion compared to the albedo of bare soil was, 4.0% for RM and T (17286 kWh), 3.1% for LB (17132 kWh) and 2.9% for O (17099 kWh) (Figure 14 and 15).

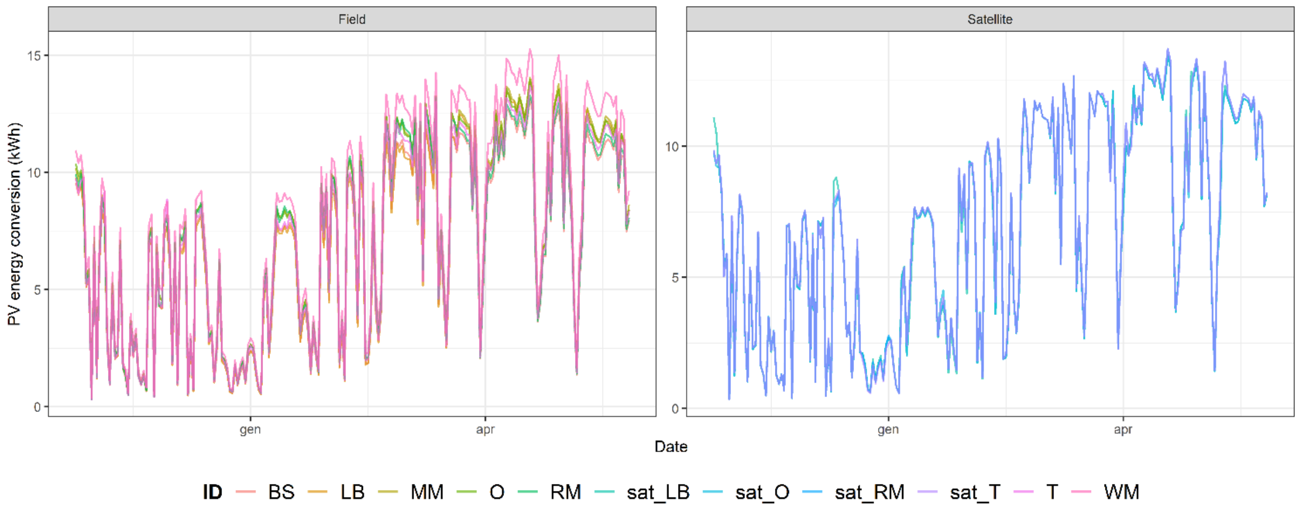


Figure 14 *Energy conversion Vertical system using albedo field-data and satellite-derived data from October 2021 to May 2022. BS= bare soil, LB= lemon balm, MM= Miscanthus mulching, O= oregano, RM= rosemary, WM= White mulching, sat= satellite-derived data*

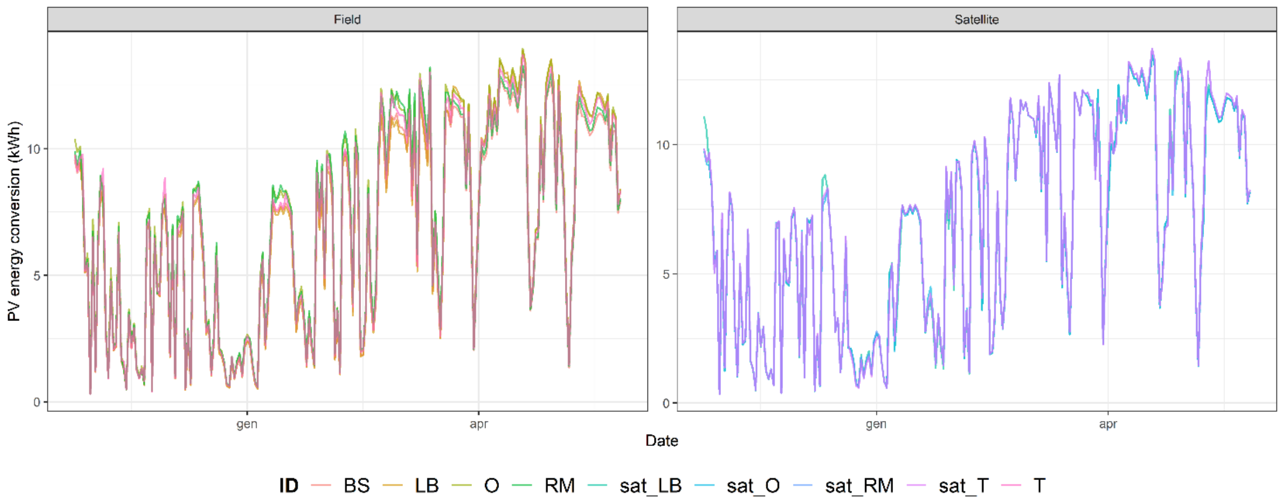


Figure 15 *Energy conversion Vertical system using only crop albedo field-data and satellite-derived data from October 2021 to May 2022. BS= bare soil, LB= lemon balm, O= oregano, RM= rosemary, sat= satellite-derived data*

The results of the simulations to estimate the irradiance received by the rear face of the photovoltaic modules showed an increase in the energy conversion of the rear face compared to the BS (6392 kWh) of 9.3 % for O (6985 kWh), 5,8 % for RM (6764 kWh), for 5.2% for T (6724 kWh), 3.8% for LB (6637 kWh), 23.3% for WM (7880 kWh) and 13.4% for MM (7249 kWh) (Figure 16).

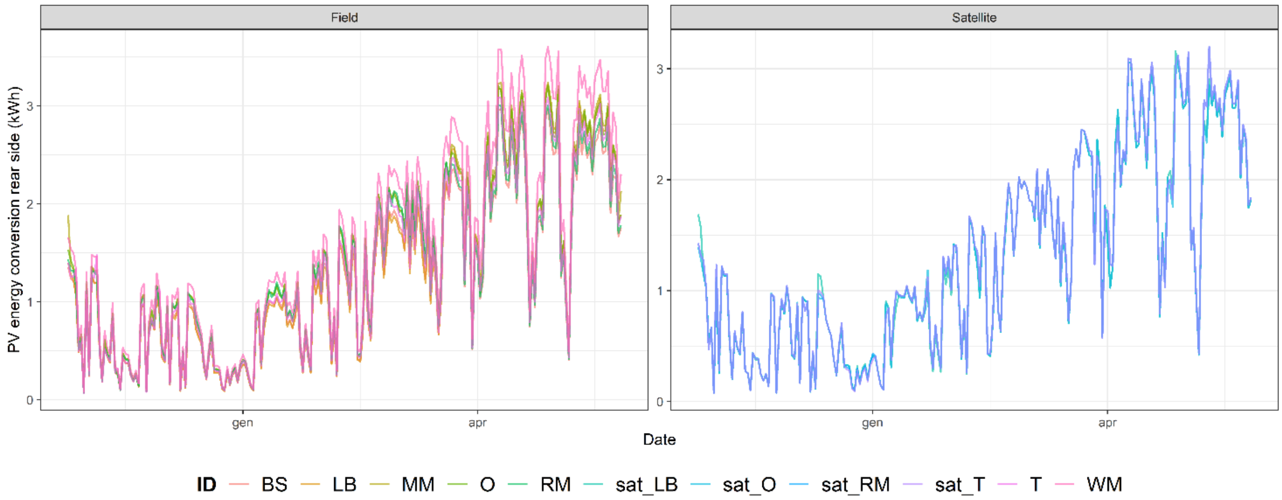


Figure 16 *Rear side energy conversion of Vertical system for 7 months. BS= bare soil, LB= lemon balm, MM= Miscanthus mulching, O= oregano, RM= rosemary, WM= White mulching, sat= satellite-derived data*

Energy conversion: Biaxial system

The total energy conversion obtained with albedo values of BS was 36584 kWh for the seven-month period considered. The increase in total energy conversion compared to bare soil was 4.7% for O (38296 kWh), 3.1% for RM (37727 kWh), 2.8% for T (37609) and 1.7% for LB (37205 kWh) (Figure 17 and 18).

Using satellite-derived albedo data the increase in total energy conversion compared to the albedo of bare soil measured in the field was 2.9% for RM and T, which recorded the same value (37655 kWh), 2.3% for LB (37440 kWh) and 2.2% for O (37395 kWh) (Figure 17 and 18).

The results obtained using satellite-derived albedo underestimated the total energy conversion in the O of -2.4% and -0.2% for RM compared to the results obtained from field albedo. For LB and T there was an overestimation of 0.6% and 0.1%, respectively, when compared to albedo field data (Figure 17).

O was the crop that showed the greatest increase in energy conversion using the field albedo data during the simulations of the AV biaxial system. The albedo of the same crop, however, when extracted from satellite images, showed such a reduction that it resulted in a lower energy conversion than all other crops. Similarly to the results obtained for the vertical system, RM and T were the crops whose albedo led to a higher energy conversion when measured by satellite.

The total energy conversion for the MM was 38518 kWh and 40650 kWh for the WM for the seven-month considered. These value, when compared to the energy output of BS (36584 kWh), marks a conversion increase of 5.3% and 11.1% for MM and WM, respectively (Figure 17).

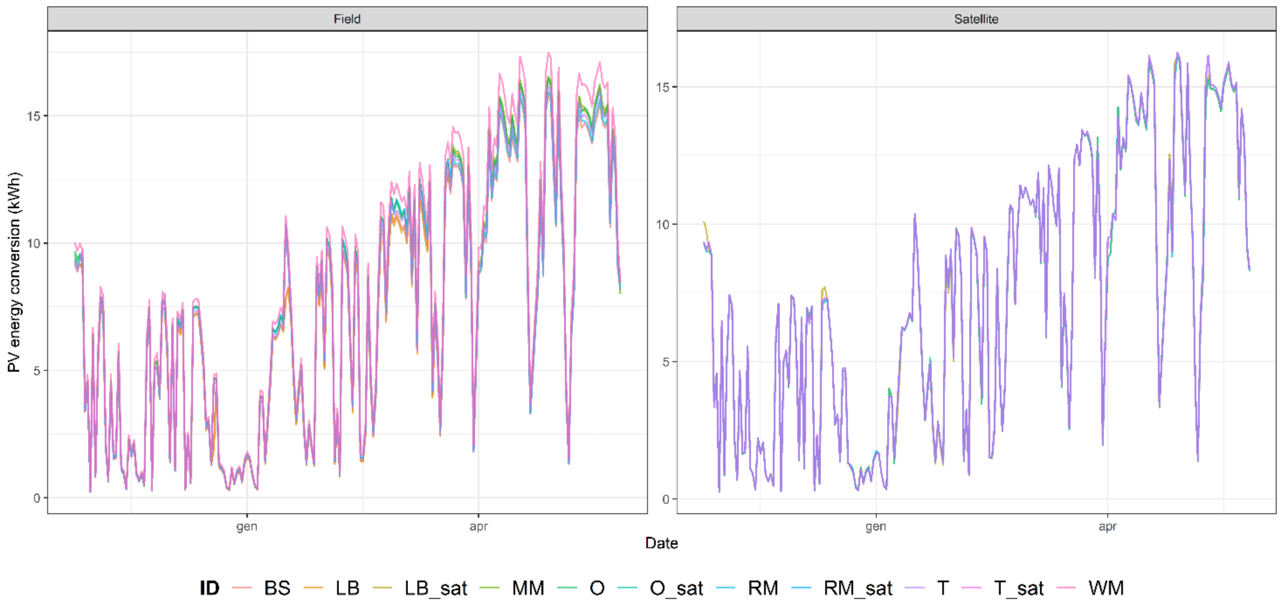


Figure 17 *Energy conversion biaxial system using albedo field-data and satellite-derived data from October 2021 to May 2022. BS= bare soil, LB= lemon balm, MM= Miscanthus mulching, O= oregano, RM= rosemary, WM= White mulching, sat= satellite-derived data*

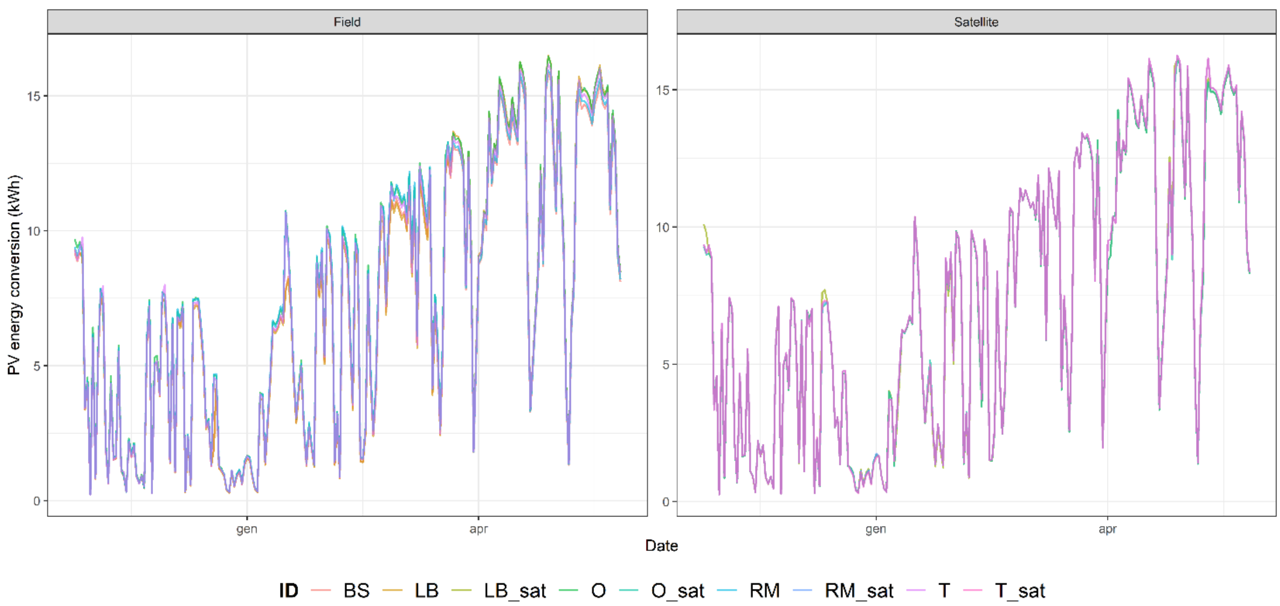


Figure 18 *Energy conversion biaxial system using only crop albedo field-data and satellite-derived data from October 2021 to May 2022. BS= bare soil, LB= lemon balm, O= oregano, RM= rosemary, sat= satellite-derived data*

The estimated rear side energy conversion for BS was 4282 kWh, over the seven months of the study. The crop that reported the highest energy conversion was O (5880 kWh) by increasing the energy conversion compared to BS by 37.3%. The increase in energy conversion compared to the BS for the other crops was 23.4% for RM (5284 kWh), 20,9% for T (5179 kWh) and 15.2% for LB (4932 kWh) (Figure 19). The WM reported an energy conversion value for the rear side of the PV modules of 8303 kWh, marking a 93.9% increase over bare soil, while the MM increased the conversion by 42.8%, producing 6117 kWh (Figure 19).

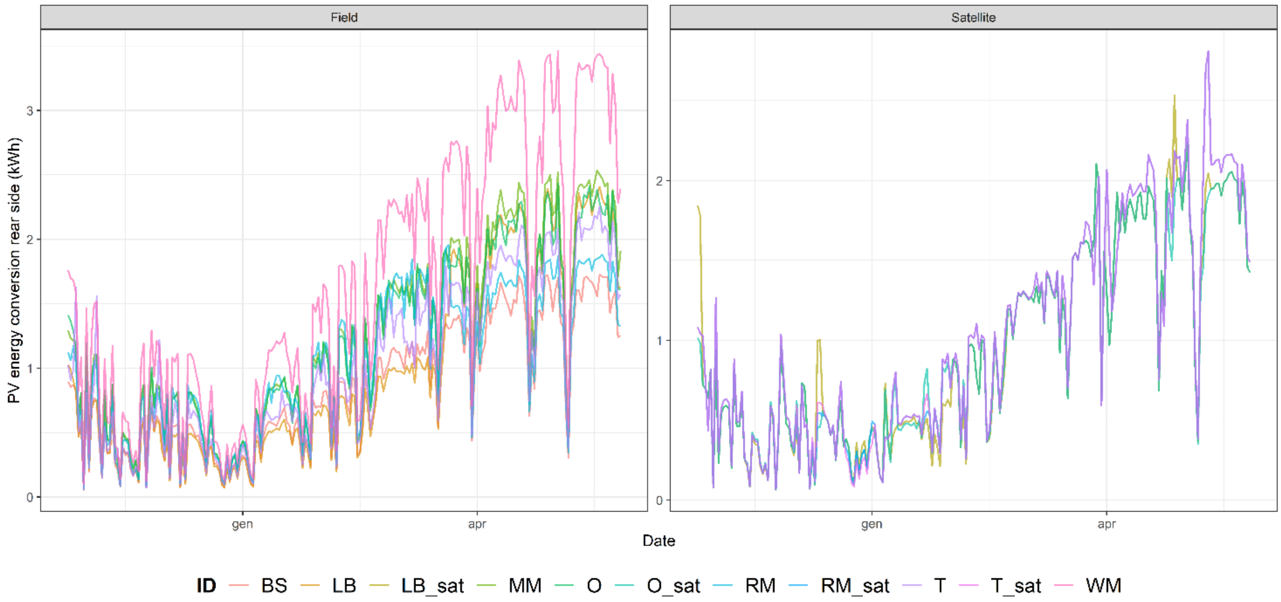


Figure 19 *Rear side energy conversion of biaxial system for 7 months. BS= bare soil, LB= lemon balm, MM= Miscanthus mulching, O= oregano, RM= rosemary, WM= White mulching, sat= satellite-derived data*

Discussion

Effect of crop morphological traits on albedo

Crop albedo is affected by LAI and crop height (Oguntunde et al., 2004; 2007), it depends on crop morphological and physiological traits (Genesio et al., 2021; Hollinger et al., 2010; Singarayer & Davies-Barnard, 2012) on climate and soil characteristics (Bonan, 2015; Bright et al., 2015; Sieber et al., 2019) and on the crop development (Richardson et al., 2013). In this study, the crop morphological traits such as crop height and LAI influenced the crop albedo by increasing, decreasing or maintaining it stable throughout the crop cycle.

The presence of aromatic crops, compared to bare soil, resulted in an average albedo increase of 43% for oregano, 29% for rosemary, 19% for thyme and 5% for lemon balm (table 1S, supplementary material) over the 7 months of experimentation.

The greatest change in height was observed for oregano and lemon balm. The increase in albedo was measured in autumn and winter for oregano due to a lower canopy development and a higher exposure of white plastic film to pyranometer. For oregano the increase in LAI and height led to a decrease in albedo values, this result, as reported by Lombardozzi et al., (2018) was influenced by the coverage of the white surface (in this study white mulching film, snow in the study previously mentioned) underneath.

Regarding lemon balm, the vegetative growth in spring led to an increase in height (up to 45 cm) and LAI. The situation reported for lemon balm is opposite to that presented for oregano in that, oregano during the 7 months always presented leaves on the stems, unlike lemon balm lost its leaves from November to March. As already reported previously, crop phenology, crop morphology and leaves characteristics influence the albedo by increasing or decreasing it (Oguntunde et al., 2004; Song, 1999; Doughty et al., 2011, Genesio et al., 2021; Hollinger et al., 2010; Singarayer & Davies-Barnard, 2012) and for lemon balm the albedo tends to decrease with reduced canopy in fact. This result confirms the correlation between LAI, height, and albedo reported by Oguntunde et al. (2004).

Throughout the campaign of measurements, thyme albedo ranged between 0.24 and 0.25. For thyme, both LAI and height values did not influence the albedo value despite their changes during the seasons (Figure 10).

In rosemary plant height showed very limited variability going from 30 to 33 cm, while a larger variation was measured for LAI, which decreased from 2.7 to 1.53 during spring season. The correlation of the crop albedo with LAI (Oguntunde et al., 2004) is confirmed because LAI decreased due to winter frost and rosemary showed a lower albedo value in spring (0.21) compared to those measured in fall and winter (0.29 and 0.32, respectively).

Comparing albedo satellite-derived data and field albedo data

The average albedo values obtained from the satellite data were lower than those measured in the field for thyme, rosemary, oregano and bare soil, while for lemon balm the value was overestimated. Satellite albedo data were not able to perfectly distinguish the crops in the field due to the presence of several rows of crops in the same field. The variability of the data obtained for satellite albedo values compared to those measured in the field is due to the different surface area measured in field or throughout satellite in fact, the albedo satellite-derived is not homogeneous in the pixel (Robledo et al., 2021).

The satellite-derived data also influenced the energy conversion of the two agrivoltaic systems compared to the data obtained by field measurement. The simulated PV energy converted for the vertical system compared to that of the field albedo measurement was reduced by 3.5% for oregano and 0.3% for rosemary while a slight increase of 0.2% for the PV energy converted was estimated for thyme and lemon balm. By considering the biaxial system the PV energy conversion result reduced for O by 3.4% and for rosemary by 0.7% compared to that reported for the field measurements. For thyme and lemon balm, the simulated PV energy conversion was slightly overestimated by 0.1% and 0.5% respectively, compared to the results obtained with field data. It is possible to conclude that the albedo should be measured at the site to decrease uncertainties caused by the surroundings (Hutchins, 2020; Marion,2021).

Impact of mulching techniques on albedo and on energy conversion

In this study among the two mulching techniques chosen the average albedo increase over the 7 months considered was 47% for Miscanthus mulch and 114% for white mulching plastic film (without crops) (Table 1s, supplementary material).

Mulching techniques can influence the surface albedo and thereby also the surface energy budget. Fan et al. (2014) showed that grassland albedo was increased by 23.5% and 33.9% on clear and cloudy days, respectively, when it was covered by agricultural white plastic film. Therefore, combining the use of a white mulch to avoid weed infestation and in conjunction having crops growing, and not bare soil, can be a strategy to increase albedo, and consequently energy conversion from PV panels. In turn, bifacial panels can improve the availability of sunlight for crops by multiplying the reflection of incoming light to the ground.

Both the mulching techniques analysed increase the total energy conversion and the energy conversion of the rear side of the PV modules. Miscanthus mulch increases the total energy production of 4% in vertical system and in 5.3% the biaxial system (if compared to the energy conversion of the bare soil albedo). For the rear side of the panel the energy conversion ranged is between 13.4% and 42.8% respectively for the vertical and the biaxial system. The biaxial system using the albedo of white mulching plastic film increase the total energy conversion by 16.8% in the vertical system and 11.1% in the biaxial system. The gain in energy conversion was also obtained for the rear side of the panel, in the vertical system 23.3% and a 93.9% in the biaxial compared to the energy conversion derived by bare soil albedo.

Crop albedo impact on energy conversion

Results of this study showed an increase in the total energy conversion for the two AV systems modelled and by using crops and mulching albedo. The increase in total energy conversion was only considering crops compared to bare soil between 2.8% and 6.7% in the vertical system and between 1.7% and 4.7% in the biaxial system. In particular, the rear side of the PV panels tends to increase the energy conversion compared to bare soil conditions from 15% to 37.3% in the biaxial system and from 3.8% to 9.3% in the vertical system. A similar result on the increase in energy conversion was already reported in a bifacial AV system by Schindele et al. (2020) that reported a gain in electricity generation of 8% for bifacial panels in an AV system with potato, wheat or celeriac crops in the first year of operation.

Conclusions

In this study, albedo for four species, for bare soil and for miscanthus mulching was measured while albedo for white mulching film was derived from literature. These data were used to simulate the energy conversion for two bifacial agrivoltaic system: one vertical and one biaxial.

The crop albedo influenced the energy conversion of the bifacial agrivoltaic systems simulated by increasing the energy conversion of the rear side and the total energy conversion if compared to bare soil albedo. The energy conversion of the bifacial PV panels was also influenced by agronomic management in particular by the white mulching plastic film and the Mischantus mulching technique to prevent weed formation.

At field level within the seven-months considered albedo differed mainly depending on crop type, height and LAI. The albedo values of the three crops examined (oregano, rosemary and thyme) was greater than bare soil. For lemon balm, the highest albedo was found in spring with the development of leaf organs, during the autumn and winter months the albedo was less than or equal to bare soil. The albedo of Miscanthus mulch and white mulch were higher than bare soil due to greater reflectance influenced by the light colour of the mulching techniques used.

The simulated total energy conversion and that of the rear face of the panel for the seven months considered has increased with the crops and the mulching technique, thus demonstrating the synergy that is generated between the cultivation of crops and photovoltaic systems in the same field.

Comparing different albedo values (crops and mulching techniques) shows that the hourly albedo had a better accuracy than the satellite-derived albedo or fixed albedo (white plastic film). The satellite-derived data tend to under or overestimate the real value of the albedo collected in the field and this influenced the difference in energy conversion obtained from the albedo field data. However, the field measurements were not carried out in summer, this season might have affected the result because of the high availability of radiation and due to a seasonal change during the summer expected for crop canopy and surrounding environment. The satellite-derived albedo provided an albedo value covering a much larger area than the crops row selected, and it might lead to the provided albedo every 3 days depending on the surrounding crops and soil.

The satellite-derived albedo can be retrieved faster and easily however higher availability and applicability are not correlated with more accurate simulations (as demonstrated by field-data albedo) of the irradiance on the rear side for biaxial tracker due to the high share of ground-reflected irradiance. Using field albedo data has led to greater precision for crop albedo, but considering the costs involved in measuring albedo throughout the crop cycle, satellite-derived data is more cost-efficient and faster compared to albedo field measurement and, the maximum reduction of simulated energy conversion obtained for this study was 3%.

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Supplementary material

Table 1S. Percentage of increase or decrease of albedo value during the three season and over the 7 months of experimental trial compared to bare soil value (0.21)

Crop|Mulching technique	**Albedo variation in Autumn**	**Albedo variation in Winter**	**Albedo variation in Spring**	**Average increase in albedo over 7 months**
Oregano	+ 52%	+38%	+33%	+43%
Rosemary	+38%	+52%	0%	+29%
Thyme	+14%	+19%	+19%	+19%
Lemon Balm	0%	-31%	+38%	+5%
Mischanthus Mulching				+47%
White mulching plastic film				+114%

Main results of the thesis

The main objective of this thesis was to study the eco-physiological response and productivity of crops under agrivoltaic systems and how the albedo of crops can affect energy conversion of photovoltaic panels. The studies on crops response and energy conversion were carried out throughout field activity and model simulations. In the following section all the research questions outlined in the Introduction (Section 1.3 "Thesis outline", Table 1 on pag. 9) will be addressed:

1. What are the main aspects to be considered when developing an agrivoltaic system to enhance synergies between crop and energy production

In Chapter 1 the state of the art of research on AV systems was reviewed. In particular, it was highlighted: how AV system can contribute to the achievement of global environmental goals and what are the main AV features both for the PV system and crops traits (e.g., PV system design characteristics, crop physiological and morphological traits, modelling simulation) that should be adjusted to co-optimise electricity and food production.

AV is a promising technology that can maximize synergies along food, energy, and environmental security and that helps to increase land productivity (Dupraz et al., 2011; Hernandez et al., 2019; Al Mamun et al., 2022). Furthermore, AV can improve land-use, water use, and energy generation and it was demonstrated to be a win-win strategy for the dual land uses, and it can benefit various ecosystem services, biodiversity conservation, carbon sequestration and erosion control (Semeraro et al., 2018; Walston et al., 2018, 2021; Siegner et al., 2019; Randle-Boggis et al., 2020, Barron-Gafford et al., 2019; Hernandez et al., 2019; Proctor et al., 2021).

Future research should expand our knowledge on the feasibility and cost implications of large-scale AV system and on the ecophysiologial response of crop cultivated under AV systems. To date research on crop production in AV systems has shown the possibility of cultivating some shade-tolerant crops such as lettuces, tomatoes, kale, and peppers under the shading conditions of PV modules (Marrou et al., 2013; Barron-Gafford et al., 2019; Weselek et al., 2019; Hudelson and Lieth, 2021; Al Mamun et al., 2022). Field data should be gathered both to provide direct evidence of the potential of a range of agricultural species under AV but also to validate crop models, which can thereafter be used to optimise AV system design and to enhance the synergies between agricultural activity and energy conversion.

2. **What are the main physiological and morphological parameters affected under agrivoltaic conditions?**
3. **How is crop production affected under PV panels?**

Agrivoltaics are systems where both agricultural crops and PV panel infrastructure share the same land (and sun), these may result in i) lower crop yields due to the shading conditions and due to a reduction in the land that can be used for cultivation or ii) lower energy conversion per unit of land due to an higher pitch compared to the ground mounted PV system that means a lower panel density to maintain a cropping systems (Walston et al., 2022).

The ecophysiological and production parameters analysed in Chapter 2 and 3 for soybean and tomato can be beneficial in the identification of crops to be cultivated in an AV environment, especially when considering the development of large-scale AV system. The main parameters influenced were Specific Leaf Area (SLA), height, Leaf area Index (LAI), net photosynthetic rate (PN), yield (number of fruits and quantity produced). The parameters that wer not statistically influenced by AV conditions were chlorophyll content (SPAD) and fruit quality.

In Chapter 2 it was demonstrated that height of crops can change with shading conditions as shade-tolerance traits, but this response need to be considered in the design of an AV system to better forecast how a crop can change its morphological traits and so, to use this information to develop a well-designed AV system. In fact, one of the main constraints in the design of PV systems is the height of crop, especially for the PV tracking system where the height of the PV modules is relatively low (for example < 2.5 m) (Walston et al., 2022 e.g., depending on the inclination angle higher than ±30° of the PV module and related also to the dimension of the PV panel the crop can be close to the PV surface, and this can cause some implication in the crop agronomical management and growth). Crop height can limit the plants that can be cultivated under AV system and further research is needed to evaluate different crop species (e.g., tall crop such as maise, fruit tree or crops that require high radiation C4 species, cereals). Furthermore, it is necessary to consider that the design modifications of the PV panel height to accommodate AV crops can result in additional costs for the solar system (CAPEX) and it will influence the price of electricity (Schindele et al., 2020).

In this thesis in the Chapters 2 and 3, it was highlighted the importance of two main physiological parameters linked to the leaf area surface: LAI and SLA. These parameters are of fundamental importance both for evaluating crops to be cultivated under AV environment and to use them in crop growth models (Heuvelink, 1999; Bruer 2003; e.g., to estimate total leaf area or dry weight Reddy et al., 1989, or by simulating the production and distribution of the assimilates to the plant organs Danalatos et al., 2010) in order to validate the outputs of the model used under the simulated shading conditions. SLA as well as LAI (evaluated in Chapter 2 for soybean) entail those physiological adaptation mechanisms that the plant implements to capture more light (Franklin, 2008). SLA attested the plasticity of the two crops to adapt to photosynthesis-limiting conditions (Gratani et al., 2014). In the AV system this trait was analised only in few studies (Valle et al., 2017; Stallknecht et al., 2022; Jiang et al., 2022; Potenza et al., 2022) and if physiological data are not available for crops to be used in the AV environment these can be obtained from similar research such as in intercropping systems. In fact, SLA together with LAI is often analysed in intercropping crops (Liu et al., 2017; Chimonyo et al., 2018; Kishore et al., 2021; Zhang et al., 2021) to understand how the two crops can coexist in the same land notwithstanding one for example shadows the other (e.g., soybean-corn, Liu et al., 2017).

Future research under AV system needs to be carried out on the physiological and morphological aspects of plants not only for SLA, LAI or for example chlorophyll content as was evaluated in this thesis but also other parameters should be considered to analyse the crop response under shading conditions, such as Radiation Use Efficiency (RUE), crop growth rate (CGR, plants tends to cover more area by expanding its canopy and so tends to increase the crop cover rate to use the available radiation under AV system, Marrou et al., 2013a), net photosynthetic rate (PN to evaluate the allocation of assimilates under shading conditions).

Chlorophyll fluorescence parameters (Fv/Fm, PI, PN, gs) under AV environment can help in understanding how crops photosynthetic systems is affected by shading conditions. Monitoring crop photosynthetic parameter can help in understanding the carboidrate accumulation and consequently how the crop yield can change compared to open field conditions (Peoples et al., 1980, Hashemi-Dezfouli & Herbert, 1992; Bellasio & Griffiths, 2014). Furthermore, the microclimate conditions under an AV system due to shade can change the diffusion of CO_2 from the atmosphere to the leaves (Wu et al., 2018, Yang et al., 2020) and evaluate this parameter together with other microclimatic conditions such as temperature, wind speed, diffuse radiation can be used to understanting the crop response in shading conditions.

Finally, with the study carried out on tomato and soybean, it was demonstated that yield is reduced with higher shading values for example for soybeans at 27% shade depth and for tomatoes under shading nets with 90%, but the fruit quality was not affected despite the shading conditions. Quality of the final product can be valuable in the sales of products obtained in an AV system to show that quality standards can be maintained for the chosen products. Yield parameter can be used to forecast an AV system design that is not too limiting especially for those crops that require more radiation (e.g., wheat, corn) by setting a lower panel density (lower Ground Cover Ratio, GCR) depending on the AV design concept that company used according to different crops (for example, in the Japanese AV guidelines, the GCR varies according to the crop that is underneath the panels in order to be able to provide the right amount of radiation and thus be able to encourage agricultural production, Japanese Guidelines 2021). Yield is a relevant parameter that farmers (and more broadly society) take into account when deciding whether to install an AV system. In fact, among the parameters set for assessing the economic viability of an AV system the "allowable yield reduction" (e.g., in the case of the DIN standard in Germany not more than 34% and for Afnor certification in France not more than 10% compared to standard growing conditions) is of great importace, in Italy this parameter can be used to evaluate the gross saleable production (PLV, guidelines Mase, 2022).

4. **What are the main morphological and physiological traits that affect crop albedo?**

5. **Can agricultural management influence the energy conversion of bifacial PV modules?**
6. **How the crop albedo affects the energy conversion of the AV systems?**

Chapter 4 assessed the impact of the measured crop albedo from different crops on the energy conversion of two AV systems with bifacial PV modules (vertical and 2-axis tracking).

The main morphological and physiological traits that affect crop albedo were height and LAI. Highest height and highest LAI value influenced the albedo of the crop and in particular, for linear leaves (e.g., oregano) the albedo tends to decrease as these two values increase instead, for ovate leaves (lemon balm) the albedo tends to increase. These results suggest that the crop canopy influence the scattered and reflected light and this response need to be investigated to understand which crop can fit better in a bifacial PV system especially in low radiation environment where, a specific choice of the crops can increase the energy conversion in low radiation months.

The agricultural management (mulching film) influenced the light reflection by increasing the albedo value for crops that during the winter season did not have a developed canopy. This result demonstrated that different agricultural management can improve the energy conversion of the bifacial PV panels during the low radiation months (autumn and winter seasons) and it is a technique that can increase the sustainability of the AV system not only for the renewable energy production but also to avoid weed infestation. In fact, by using a mulching technique the reduction in the pesticide use can cause a lower damage on the PV panels due to the chemical compounds release on the PV panel surface.

Finally, the results showed that the albedo of the crops in AV system plays a key role in increasing the energy conversion of the PV system. For both the total energy conversion and the energy conversion obtained from the rear side of the panel, crops increased energy conversion. This result, considering the expansion of the bifacial panel market, can favour the use of these technology on an AV system, justifying the costs incurred to use bifacial PV panels compared to monofacial PV panels when referring to the CAPEX of an AV system.

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