



MICROCLIMATIC AND ENERGETIC FEASIBILITY OF AGRIVOLTAIC SYSTEMS: STATE OF THE ART

Author(s):

I. Khele^{1,2}*, M. Szabó²

Affiliation:

¹ Doctoral School of Mechanical Engineering, Hungarian University of Agriculture and Life Sciences, Páter K. u. 1, Gödöllő, H-2100, Hungary.

² Department of Building Engineering and Energetics, Hungarian University of Agriculture and Life Sciences, Páter K. u. 1, Gödöllő, H-2100, Hungary.

* Corresponding author

Email address:

Issam.Khele@phd.uni-mate.hu ; Szabo.Marta@uni-mate.hu

Abstract: Agrivoltaic systems have been proposed as the most prominent synergetic application of agricultural and energetic sectors. Integrating solar power generating with agricultural activities is relatively new; however, it has started with implementing the PV panels into the greenhouses. Comparatively, open-field agrivoltaics systems are still growing and under-development in many locations around the world. The urge to explore innovative solutions for the increasing demand for electricity and food has been the main motivation for the research centers, researchers, and governments to escalate agrivoltaics development globally. In this paper, the current and most recent projects and studies of open-field agrivoltaic systems are presented, compared, and analyzed in order to anticipate the potential and path of development for agrivoltaics in the near future. Several pieces of research from different countries globally were included to illustrate the main features and performance indicators of agrivoltaic systems. The paper concludes that the agrivoltaics system has the potential to grow to big-scale projects in different climatic regions because it provides benefits either by increasing the Land Equivalent Ratio (LER), protecting the plants from severe ambient weather, and diversifying the income for farmers. New technologies and methods have been integrated with the agrivoltaics systems in different projects to optimize the model; however, many aspects of development could be introduced in the near future.

Keywords: Agrivoltaics, Agrophotovoltaics, dual-use land, crop production

1. Introduction

The increasing need for energy worldwide has been accompanied with increasing demand for food due to the constant population explosions. That elaborated a (food vs. energy) dilemma, especially in countries with scarce arable lands [1]. Moreover, since renewable energy sources onshore (mainly solar and wind energy) require huge areas of land for the infrastructure in order to generate a sufficient amount of electricity, the dilemma of exploiting the arable lands for energy-generating purposes has been debatable, especially in the last decade. Therefore, sustainable solutions have to be proposed to allow the dual use of land, especially in countries with no arid or semi-arid lands (like most European countries), which can be exploited mainly for solar energy harnessing.

Agrivoltaic systems (APV) have emerged to provide a synergetic solution for both energetic and agricultural sectors, allowing for the dual-use of the land leading to maximizing the benefit and diversifying the income. Agrivoltaics could simultaneously meet the growing demands on energy and food and reduce fossil fuel emissions. [2][3][4] Therefore, the installed capacity has increased exponentially from 5 megawatts (MW_p) peak in 2012 to at least 2.8 gigawatts peak (GW_p) in 2020. [5]

On the other hand, the key feature of agrivoltaic systems, which is the synergy that can be created between agricultural and energetic sectors, is what causes the complexity of optimizing the system. (APV) evaluation

is not just impacted by the performance of the photovoltaic modules, the tilt angle, or the losses factor. Many aspects shall be considered since the agricultural performance is as essential as the energetic performance, and in some cases, it may be prioritized.

In this paper, the current state of the art of the agrivoltaic systems is presented and discussed to assess the current barriers and challenges, explore the new technologies and methods, and the potential technologies to be used in the field.

The article is organized as follows. Section 2 presents the research method and the keywords used for the literature review. In section 3, a brief definition and background were provided to illustrate the context of agrivoltaics development. Section 4 is dedicated to expressing and discussing the current state of the art of agrivoltaic systems. Finally, the main conclusions are discussed in section 5.

2. Materials and Methods

To collect relevant research publications, a review process was conducted, and the following keywords were used in (Google Scholar), (Web of Science), and (Scopus): (Agrivoltaics, Agrophotovoltaics, dual-use land, Solar sharing).

It should be noted that the chosen papers and scientific papers of research focused on the open-field agrivoltaic systems. The papers that only focus on the greenhouses integrated with photovoltaics were excluded from the review.

3. Background of Agrivoltaics

No universal definition can be found in the standards for agrivoltaic systems; however, Fraunhofer ISE Institute defined the agrivoltaic systems as "Agrivoltaics allows the simultaneous use of land for both agriculture and photovoltaic power generation. Food crops and electricity can be harvested on the same plot of land." [5]

Table 1. Different terms used worldwide for agrivoltaics

Term	Region	Reference
Agrivoltaics - Agrophotovoltaics	Germany- France- US	[7][8][9]
Colocated systems		[10] [11]
Horticulture PV		[12]
Agrovoltaico	Italy	[13]
Solar sharing	Japan	[14] [15]

Figures (1,2) are respectively illustrating the two most spreaded types of open-field agrivoltaic. The first (Figure 1) is for Fraunhofer ISE research plant at Lake Constance, which is horizontal-tilted and stilted PV panels above the crops, and one of the main advantages of this structure is the ability to use machinery under the panels for higher accessibility. The second (Figure 2) is the vertical PV panels agrivoltaic implemented in Donaueschingen-Germany and mainly use bifacial modules [6]. The vertical-mounting structure is cost-effective since it does not need to be 3-4 meters in height. Moreover, it would benefit from mitigating the wind effect on the crops; however, this structure has fewer light-management options than the stilt-mounted agrivoltaics.[5]

The term used for referring to agrivoltaic systems is different based on the country or region. In the following table, we included the most used terms for this method of integration between agriculture and solar power.

Agrivoltaic systems can be classified based on multiple aspects regarding function, mobility, structure, or farming type. Figure (3) shows the classification proposed by Fraunhofer ISE for the agrivoltaic systems.

Generally, two main structures of agrivoltaic systems can be found in the studies currently, interspace PV (either vertical or horizontal PV panels), which is more focused on providing sufficient space between the PV rows to be used. The other is overhead PV, in which the PV panels are mounted on 2-4 m of height. Also, tracking systems are essential in the case of agrivoltaics. The function and the number of tracking axis systems could characterize the system. Moreover, the microclimate underneath is a crucial variable since it directly affects the crop yield.



Figure 1. The Fraunhofer ISE agrivoltaic research plant at Lake Constance. @Fraunhofer ISE



Figure 2. Bifacial modules installed vertically, Donaueschingen-Germany. @Next2Sun GmbH

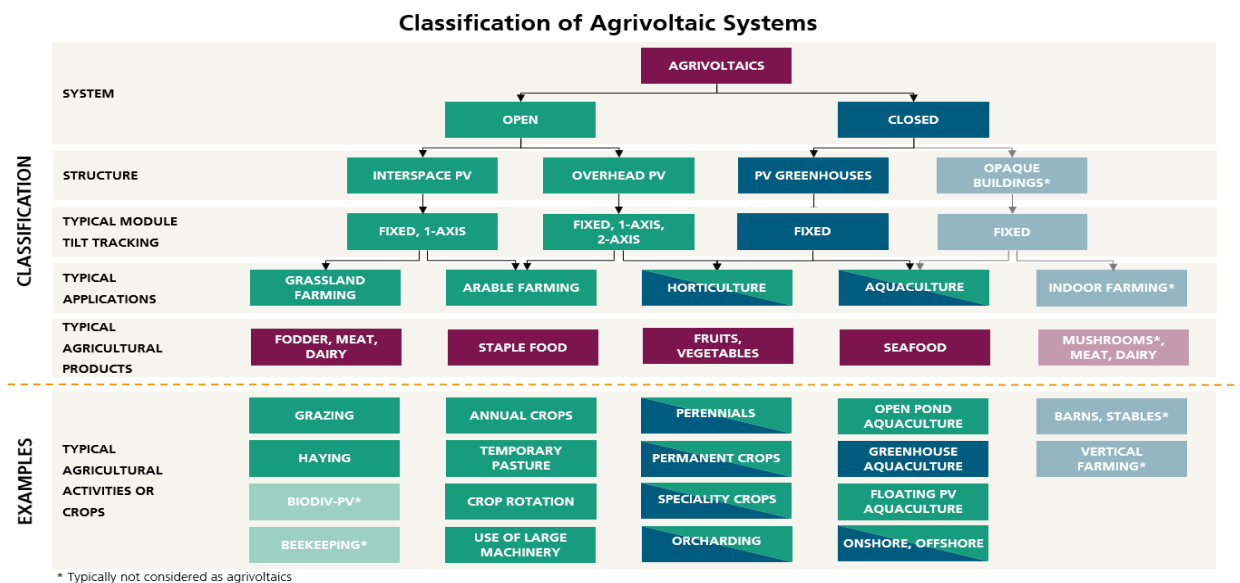


Figure 3. Classification of agrivoltaic systems. proposed by Fraunhofer ISE. @Fraunhofer ISE

Figure (4) shows a more simplified classification proposed by [16]. The objective-based classification has been added to this classification since it is important, especially in the planning phase, to determine the objective of the planned agrivoltaic system if it is energy or agriculture centric or integrated centric. [17]

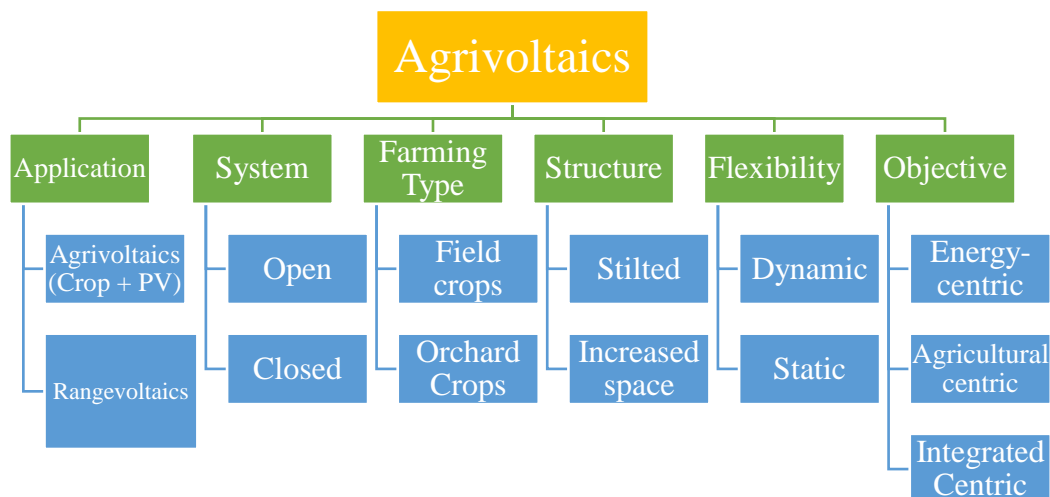


Figure 4. Classification of agrivoltaic systems proposed by [16]

that the energy used in crop production is less than 1% of the total energy generated using agrivoltaic systems. It is observed that 50% of the agricultural land would make up for the sale price of the land within two years with agrivoltaic systems.

Also, in the USA, [19] performed their research on the applicability of agrivoltaic systems in California at SunPower research center (Figure 6). A variety of crops used in this study included: Kale, Swiss chard, broccoli, bell peppers, tomato, and smooth leaf spinach.

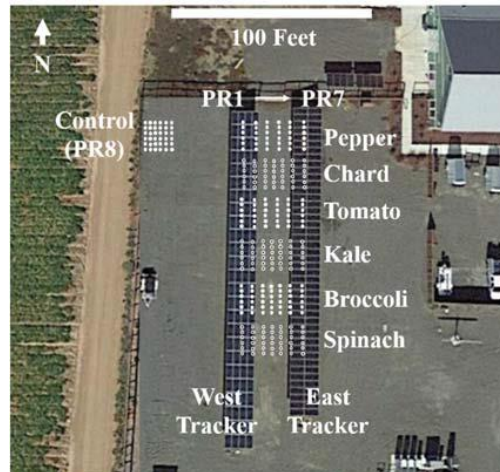


Figure 6. Layout of the shade treatments among the PV at the SunPower Research center in Davis, California. Circles show individual, container-grown plants of the indicated crops. Image source[19]

It was found that Kale produced the same amount within all PAR levels between (55-85%) of FS (Full Sun). Chard yield was the same in PAR levels of 85% and greater. Also, Tomatoes produced the same yield in all PAR levels greater than 55% of FS.

The research suggested that crops like Kale, chard, and tomatoes can be planted throughout the solar array with only a limited yield penalty as long as light levels are at least 55% of full-sun irradiance. Other crops like spinach are not advisable among solar panel arrays due to their strong dependence on high irradiance for best crop yields.

4.2. Design parameters, performance indicators, and their impact

Usually, the tilted PV panels can optimize the tilt angle based on the annual local solar irradiation [12] [20]. Also, the possibility of deriving the tilt angle of the optimal situation in the critical growth stage for the crop was mentioned by (Elborg 2017) in the manually controlled tracking system cases. Moreover, in addition to the operation temperature, which is determined by the ambient temperature, wind speed, and solar irradiation, the dust caused by the agricultural activities can impact the power generated. The amount of dust collected on the PV panels has an inverse relationship with the tilt angle. [21] [3].

Crop-Sim, a Decision Support System (DSS), is an interesting method used to anticipate and optimize crop status and energy yield under a dynamic agrivoltaic system to achieve the highest possible energy yield without impacting the crop (Chopard et al., 2021). This (DSS) defines a plant's well-recognized three abiotic indicators associated with crop development under panels. 1-the predawn water potential (leaf water potential measured just before dawn) 2-the canopy temperature, and 3-the amount of carbon produced through photosynthesis. And these indicators would allow anticipating the plant's performance throughout the year. The function of Crop-Sim is to simulate the soil, the plant, the atmosphere, and the interactions between them.

In order to conduct the first study on agrivoltaics under organic field management conditions. [22] [23] in Germany investigated how celeriac would be affected by cultivating under agrivoltaics system and the impact of solar panels on the microclimate underneath. Cultivating celeriac was part of a four-year crop rotation consisting of Celeriac, Potato, winter wheat, and grass-clover as in Figure 7.

The research stated that PAR was reduced by 29.5% on average under agrivoltaics, while irradiance reduction was between 12-60% depending on the agrivoltaics setup. Despite the differences in some variables, the crop yields were not significantly reduced, and the research stated that celeriac could be considered a suitable crop under agrivoltaics.

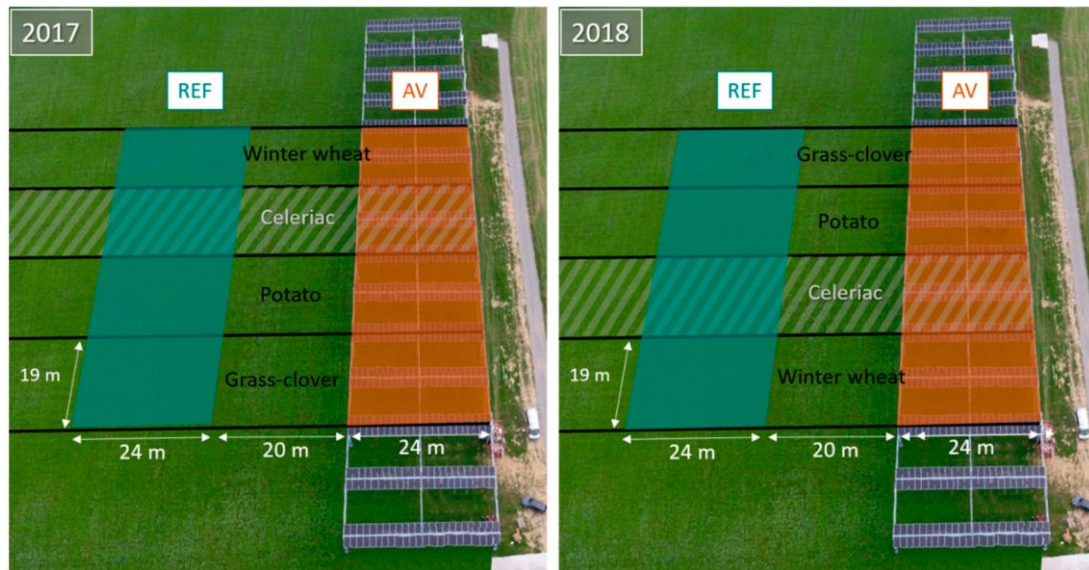


Figure 7. Setup of the field experiment in 2017 and 2018 with the location of celeriac within the crop rotation. The source [22]

Considering the viability of a crop such as rice, especially in Asia, the yield should not fall below 80% of crops grown under normal conditions in the surrounding area [14] [24]. To assess the applicability of agrivoltaics systems over rice crops, [25] carried out a comprehensive study in four different farms in Japan with different ratios of projected shade under solar panels to the total surface area and to optimize agrivoltaics in the case of rice yield. Also, [24], in an MSc thesis, conducted simulation and experimental assessment to estimate rice yield integrated with energy yield under an agrivoltaic system. The research reported experimental data to refer to a reduction in the grain yield by 22.6% under partial shading compared to full sun condition; even delaying the harvest didn't change the reduction percentage. The model has been performed accurately, and the experimental results validated it.

4.3. Innovative solutions and applications

Not only stationary PV panels were investigated in the agrivoltaics systems, but also mobile PV panels were proposed by [26]. The study conducted a comparative assessment of the performance of stationary and mobile agrivoltaics systems over lettuce in the aspect of energy production and yield biomass using (LER). The sun-tracking solar panels were installed beside the typical stationary panels in the field with the flexibility to control the microclimate under the agrivoltaic system. Physiological traits should be measured in a crop as the projected area, leaf number, specific leaf area, leaf shape. Two types of lettuce were cultivated under the panels (Kiribati, Madelona). The experiment was well prepared by dividing the field into three main areas: 1-Mobile Panels with solar tracking (ST) 2- Mobile Panels with controlled tracking (CT) 3- Stationary panels area which contains Half Density (HD) and Full Density (FD) areas. Also, full sun condition (FS) was placed in the south of the agrivoltaic system as a control for the crop yield. Three experiments in spring, summer, and autumn were carried out.

Interestingly, all of the cases studied in that experiment achieved an (LER) bigger than 1, which indicates that in all the cases, the agrivoltaic system reduced the required area to produce the same amount of electricity and yield biomass. Notably, both types of mobile agrivoltaics achieved higher (LER) than the stationary system due to the significantly increased power generated and slightly increased biomass. Even though ST mobile systems achieved better electricity generation than CT systems, the latter provided a crop yield at levels close to the control FS systems yield, introducing it as a solution for different crops that may be more shading intolerant.

A patented agrivoltaic solar tracking system named (Agrovoltico) (Figure 8) was investigated using simulation with a maize crop by [27] in northern Italy. One of the unique traits of this system is the tensile structure of the stilts which minimize the use of land.



Figure 8. The tensile structures of the Agrovoltaico systems. The source[13]a

The study used Generic Crop Growth Simulator (GECROS) with coupled radiation and shading models. A simulation model was used in this study in (Scilab) software platform, and the crop model was prepared using (GECROS). The simulation provides results for the years (1976-2014).

After a comprehensive analysis, the grain yield was higher and more stable under Agrovoltaico than full sun conditions under the drought stress, while it is slightly lower when water is not limited. Using (LER) method, always Agrovoltaico achieved more than 1.

Arid and semi-arid lands are a suitable location for conventional PV farms because of the high potential yield and because it is usually far from the centers of human activity. In the arid and semi-arid lands in Northeastern India, [10] investigated an agrivoltaic system as a compromise between the conventional installation of solar panels and cultivation (Aloe vera) as shown in Figure 9, which is xerophytic and doesn't require special requirements of solar infrastructure. (Aloe vera) has a short growth stature and low maintenance.



Figure 9. (a) Colocation of solar PV and vegetation in Colorado, USA. (b) Aloe vera cultivation in Rajasthan, India. Source[10]

The research investigated the aspects of energy inputs/outputs, water use, greenhouse gas emissions, and the solar installation system's economics compared to aloe vera cultivation, another widely promoted and economically important land use in these systems. The life cycle analysis showed that agrivoltaics are economically beneficial in rural areas and could create better rural economic growth opportunities. The water inputs for cleaning solar panels are similar to the amounts required for annual aloe vera productivity. The authors recommended integrating the two systems to maximize land and water use efficiency. A life cycle analysis of a hypothetical colocation indicated higher returns per m^3 of water used than either system alone.

Choosing the appropriate module and technology for the solar panels is still under study, and the emergence of bifacial modules opened the door for comparison between them and monofacial modules. The comprehensive analysis of agrivoltaics in Paras, Maharashtra, India [12] recommended using bifacial solar panels after the practical measurements. The bifacial modules produced 6.4% of electric yield, more than the monofacial modules.

[28] in their research investigated the performance of vertical East-West oriented bifacial modules computationally compared to the conventional tilted North-South oriented monofacial modules (Figure 10).

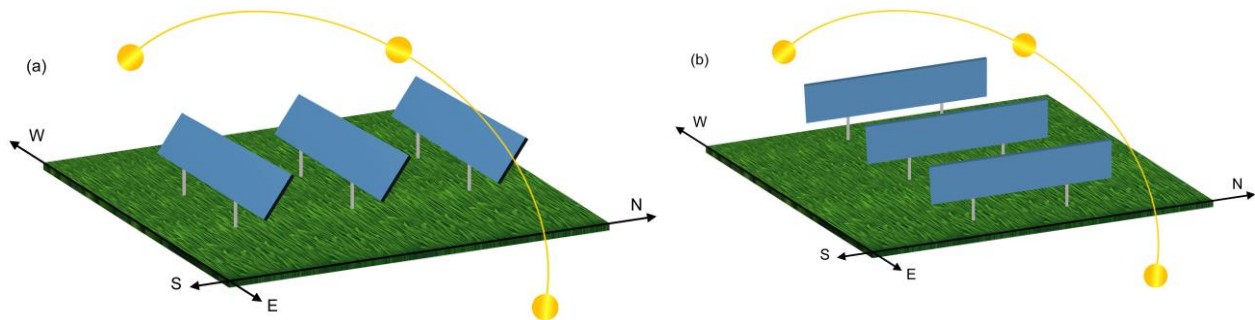


Figure 10. (a) Tilted monofacial south-facing (mono-N/S), and (b) vertical bifacial east-west facing (bi-E/W) solar modules. The source [28]

In some areas, power loss due to soiling can reach 10% per day for lightly soiled panels and 40% for heavily soiled panels. This effect could be mitigated by shifting the tilt from horizontal to vertical [29]. The potential of vertical bifacial solar is high because it can mitigate soiling losses, making it important to assess its performance, especially in arid areas.

[28] in their research, stated that the performance of the bifacial panels is affected by the density of solar rows. When the farm is half-density, the vertical panels produce the same energy as the tilted conventional one. Also, the combined PAR/Energy yields for the vertical bifacial farm is not always superior, and the study suggested that it could still be an attractive choice for agrivoltaics due to its distinct traits such as minimizing the land coverage, more flexibility to the farm machinery, ability to mitigate soiling losses, in addition to the cost advantages due to potentially reduced elevation, in the cases when the elevation is not a requirement for the system.

Interesting experimental research was conducted to use tinted semi-transparent solar panels in agrivoltaics systems [30], as presented in Figure 11, where spinach and basil were the crops under the solar panels. Physiological/metabolic variations of the crops were analyzed, and the relative content of lipid, carbohydrates and protein from plants under agrivoltaics compared to control plants. The main trait of tinted semi-transparent panels was the selectivity of the electromagnetic spectrum so the photovoltaic system and the plant can harness different parts of the spectrum. The sum of experimental data showed that agrivoltaics could provide an overall financial gain of +2.5% for Basil and +35% for spinach. Also, the amount of protein extracted from both plants increased despite the loss of marketable biomass for basil and spinach plants.

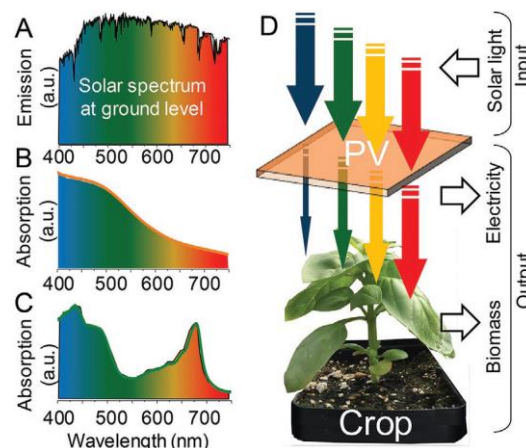


Figure 11. Agrivoltaics for food and energy double-generation implemented with tinted semi-transparent solar panel. A) Solar radiation spectrum in the visible range at the ground level. B) Absorption spectrum for the tinted semi-transparent solar PV panel (a-Si single-junction) used in this study. C) Absorption spectrum for a basil plant leaf. D) Schematic representation of the input (solar energy) and the two contextual outputs of agrivoltaics (i.e., electricity and biomass). The source [30]

The possibility of cultivating grape as a shade-intolerant crop under agrivoltaics in Nashik, Maharashtra, India, was assessed using simulation [31]. The ground coverage ratio was about 0.26, to decrease the effect of shade as much as possible. The research estimated an increase in the revenue of 15 times when using agrivoltaics system on the grape lands than in the case of conventional grape farming. However, actual experiments are needed to verify and validate the model to check the effect of shade on crop yield performance.

Agrivoltaic systems are developing rapidly, researchers all over the world are reporting advancements on agrivoltaics performance. A new configuration of agrivoltaic system was proposed lately by [32] named the Even-Lighting Agrivoltaic System (EAS) against what so-called Conventional Agrivoltaic System (CAS) in both Fuyang city and Hefei City, Anhui province, China (Figure 12). The essential concept in this system is to reduce 1/3 of the solar panel and replace it with a grooved glass plate, and this plate is designed to distribute the light evenly over the shadowed cultivated area by scattering the incident light into three parts by refraction.

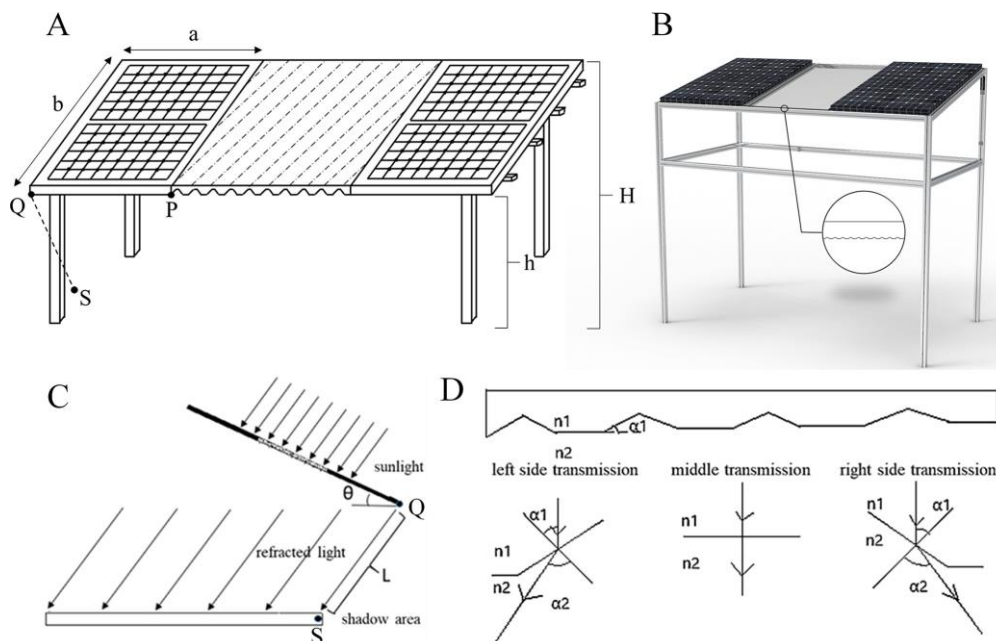


Figure 12. The structure of the EAS (A). The rendered output diagram of EAS structure (B). The side view of the EAS (C). The structure of the grooved glass plate. The source [32]

The crop cultivated under solar panels is lettuce for the small-scale facility, and broccoli, shallot, garlic sprouts, garlic, rape, broad bean, and Jerusalem artichoke in the large-scale facility. The research stated that using EAS is most similar to the control land in the aspect of crop yield. The yield of crops fell by 5% except for broccoli and rape, while Jerusalem artichoke yield was 23% higher. EAS improved the irradiation for the crops by 47.38% compared to CAS, Land Equivalent Ratio (LER) for the crops range between (1.55-1.9) under EAS. An interesting enhancement was combining supplementary LED lamps with the EAS, which increased the soluble sugar content of lettuce by 72.14% and decreased nitrate content by 21.51%.

4.4. Environmental and economic centric studies

To provide a holistic approach over (Agrovoltaico) system, the environmental and economic performance of the system was modeled by [13] to provide a Life Cycle Assessment for the system and investigate the implementing costs' details compared to other PV applications or sources of electricity can be found in the Italian market.

It was found that in the aspects of climate change, ecosystem quality, air quality, and resources depletion, the agrivoltaico systems have a similar performance to the ground or roof-mounted PV due to the tensile construction, although the first release of (Agrivoltaico) systems with the huge concrete basements and large poles made the environmental performance of these proposed systems worse than the conventional ground or roof-mounted PV applications and even than coal electricity.

The environmental impact of agrivoltaic systems is another important aspect to consider. [33] assessed the environmental impacts and viability of energy production efficiency of agrivoltaic systems compared to other forms of energy production, by comparing three different solar array designs as shown in Figure 13; the first emphasizes maximizing the crop yield per area unit by providing the optimal conditions for it, the second emphasizes maximizing the energy production per area unit, and the third was developed to be balanced between crop and solar production. The panels were ground mounted with 0.61 m height above the ground. The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) was used to analyze the environmental performance of the agrivoltaic system by considering ten different impact categories. The research stated that even though agrivoltaic systems have a higher Global Warming Potential (GWP) than traditional PV, this difference is insignificant compared to the amount of space that agrivoltaics saved by co-existing solar panels and agriculture. Also, agrivoltaics was recommended for maximizing land-use efficiency.

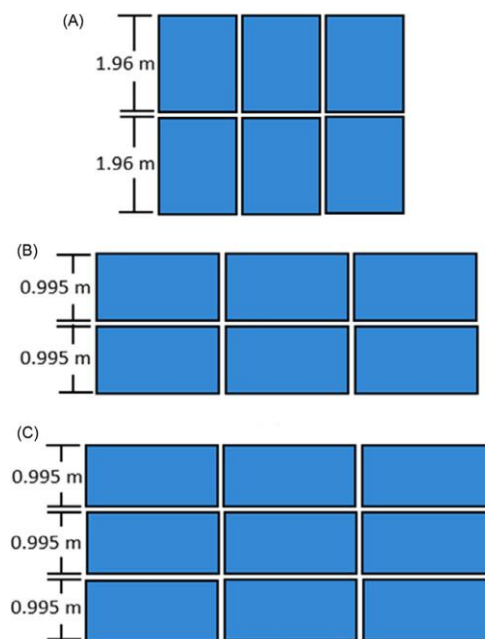


Figure 13. Front views of PV array system design 1 (A), 2 (B), and 3 (C). The source [33]

4.5. Microclimate under the panels

To emphasize the importance of assessing the patterns of shade and availability of PPFD and DLI within the agrivoltaic system, [34] quantified the spatial and temporal availability variability of PPFD and DLI under the Agrivoltaic system in Jodhpur, India. Three blocks of PV modules were installed on an area of 32*32m and 35 KW_p for each (Figure 14).

The measurements were carried out around the winter solstice because in this period, the day length is the minimum, and the magnitude of shade is greatest in the northern hemisphere. A major obstacle reported in this study was the absence of (DLI) and (PPFD) standards for the field crops, while in the literature, the greenhouse crops standards can be found. Also, in the case of high stilted panels (5 m, for example), the issue of cleaning the panels from the dust in such a dry region in India was encountered. The research results proved that in the region of Jodhpur, the availability of PPFD was not a constraint in order to meet the photosynthesis requirements. The shaded area in the interspace during the winter solstice varied from 18 to 58% of the total interspace area. The proportion of shaded area was greater in the single row PV array design than in the double row PV array and triple row PV array designs of the AVS. It was suggested that standardizing the required amount of (DLI) and (PPFD) and mapping spatial and temporal distribution of these parameters to optimize the crop yield and choose the optimal crop.

Generally, under agrivoltaic systems, there is shade and light fluctuation during the day [35] because of the sun's position. Due to that, the stomatal conductance process that indicates plant water status will be affected. [36] focused in their research on modeling the water budget and crop growth of irrigated lettuce under an agrivoltaic system, concerning stomatal conductance as a variable that considers the short-term alternation of sunlight and shade in the intersections between panels. Four devices were considered in the

study compared to the control plot, Full Density (FD), Half Density (HD), Solar Tracking (ST), and Control Tracking (CT). By averaging all the tested cases in this study, it was found that the (LER) of the proposed agrivoltaic system value is 1.21. The mean overall effects of the tested artificial shading conditions were a reduction of plant water demands by -20%, a delay in maturity of about 5–7 days in the agrivoltaic installation concerning the control plot, or a decrease of agricultural yield by -15% to -25%.

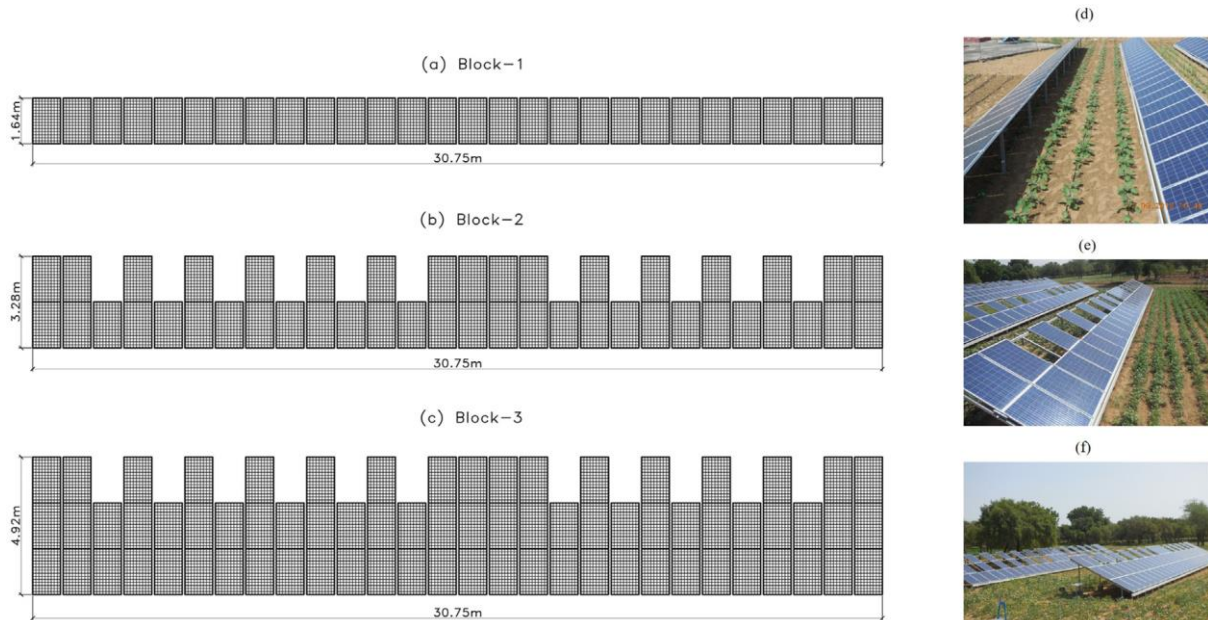


Figure 14. Agrivoltaic system (AVS) at ICAR-CAZRI, Jodhpur; (a-c) design of PV array in three field blocks of the AVS and (d-f) field photographs of the installed AVS in block 1, block 2, and block 3, respectively.
Source[34]

As mentioned previously, using agrivoltaics as a shelter from severe environmental conditions is popular. In Ongjin-Gun, the Republic of Korea [15] installed an agrivoltaic system over the grape crop to protect the crops from heavy rain. Acryl panels were added to the structure mounted on its top for that purpose. And the shading rate was controlled to be 30% of the total roof area. The experiment consisted of three sections with three different module technologies, 1-conventional opaque monofacial solar panels, 2- bifacial solar panels, and 3- transparent solar panels with three relevant control sites to compare the results of each type. Experimental data of the microclimate under agrivoltaics were collected (Carbon dioxide, Illuminance, and soil temperature), in addition to the germination process monitoring and the sugar content of the grape fruit. These variables were monitored to investigate each technology performance of agrivoltaics system compared to control conventional cultivation. The research stated that the coloring and growth of the test-site grapes were delayed compared to the control site due to the solar irradiance reduction and temperature change under the panels. However, by delaying the second harvest time by ten days after the first, the researchers reported a grape yield quality in the agrivoltaic site as equal to the quality under the control site at the first harvest time.

Coupling agrivoltaics with shade-intolerant crops was addressed by [37] to assess the performance of corn as a shade-intolerant crop under stilted mounted PV panels as presented in Figure 15. The experiment was carried out on a farm in Ichihara city, Chiba prefecture, Japan. The farm contains three sub-configurations: low module density, high module density, control area (no modules).

The study stated that high-density agrivoltaic land revenue could be 8.3 times larger than the control one, while the low density was 4.7 times larger. Speaking in detail, the biomass of corn stover under a high-density system was 96.9% of the control biomass, while the biomass under a low-density system was interestingly larger than under control by 4.9%. The authors proposed that light saturation point is the key to understanding these results, so when the plant is photosynthetically saturated, no more light is required to boost photosynthesis. In addition, to the shelter provided by solar panels from too much light, and increasing the water efficiency.

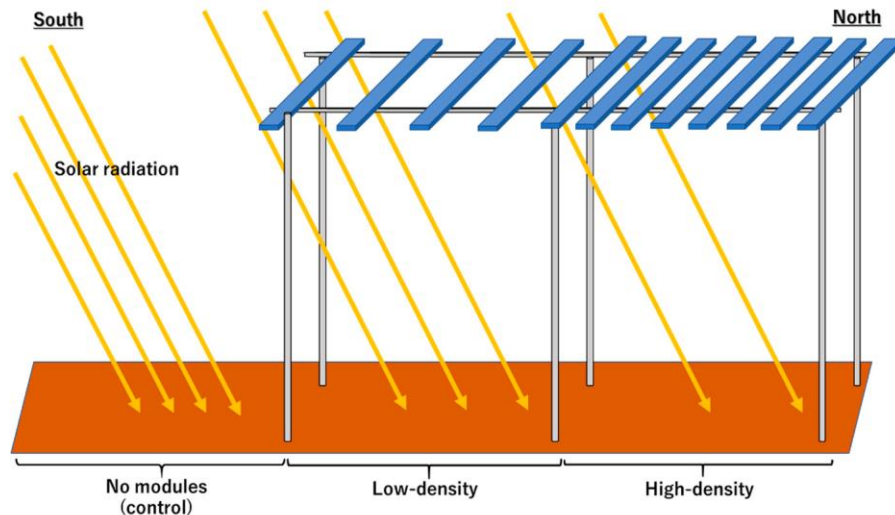


Figure 15. PV module configurations at the agrivoltaic experimental farm in [37]

5. Conclusion

Agrivoltaics systems are one of the most promising synergetic technologies that allow the dual-use of land, which is more significant for countries with a scarcity of land. Moreover, many studies reported the efficiency of using agrivoltaic systems in the arid and semi-arid areas where different crops would benefit from the effect of solar panels' existence on the microclimate underneath, as it mitigates the ambient impact, which could harm the yield.[37][34][38] Along with the attractive trait of diversifying the farmers' income and providing more rural services. [39]

The aspects of developing agrivoltaics systems are diverged into the technology by using Semi-Transparent PV [30] and tracking systems [26][36]. Innovative structure optimizing methods like using acrylic-panels to protect the crops from heavy rain [15], or dynamic system which can be moved along the land [40].

The publicity of agrivoltaics systems is expected to increase and be promoted more by the governments. More researchers, institutions, and research centers are working on the optimization process of the system, which can not be an easy task due to the high number of variables and the complexity of modeling the crops to anticipate the output of the project during the planning stage.

References

- [1] **D. Ketzer, P. Schlyter, N. Weinberger, and C. Rösch** (2020) "Driving and restraining forces for the implementation of the Agrophotovoltaics system technology – A system dynamics analysis," *J. Environ. Manage.*, vol. 270, no. May, 2020, doi: 10.1016/j.jenvman.2020.110864.
- [2] **A. S. Pascaris, C. Schelly, and J. M. Pearce** (2020) "A first investigation of agriculture sector perspectives on the opportunities and barriers for agrivoltaics," *Agronomy*, vol. 10, no. 12, 2020, doi: 10.3390/agronomy10121885.
- [3] **H. Dinesh and J. M. Pearce** (2016) "The potential of agrivoltaic systems," *Renew. Sustain. Energy Rev.*, vol. 54, pp. 299–308, 2016, doi: 10.1016/j.rser.2015.10.024.
- [4] **C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, and Y. Ferard** (2011) "Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes," *Renew. Energy*, vol. 36, no. 10, pp. 2725–2732, 2011, doi: 10.1016/j.renene.2011.03.005.
- [5] **Fraunhofer ISE** (2020) *Agrivoltaics: Opportunities for agriculture and the energy transition - A guideline for Germany*, no. October. 2020.
- [6] "Homepage - next2sun." <https://www.next2sun.de/en/homepage/> (accessed Mar. 05, 2022).
- [7] **M. Trommsdorff et al.** (2021) "Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany," *Renew. Sustain. Energy Rev.*, vol. 140, no. January, 2021, doi: 10.1016/j.rser.2020.110694.
- [8] **H. Marrou, J. Wery, L. Dufour, and C. Dupraz** (2013) "Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels," *Eur. J. Agron.*, vol. 44, pp. 54–66, 2013, doi: 10.1016/j.eja.2012.08.003.

- [9] **D. Majumdar and M. J. Pasqualetti** (2017) "Dual use of agricultural land: Introducing' agrivoltaics' in Phoenix Metropolitan Statistical Area, USA," *Landsc. Urban Plan.*, vol. 170, no. May 2017, pp. 150–168, 2018, doi: 10.1016/j.landurbplan.2017.10.011.
- [10] **S. Ravi et al.** (2016) "Colocation opportunities for large solar infrastructures and agriculture in drylands," *Appl. Energy*, vol. 165, pp. 383–392, 2016, doi: 10.1016/j.apenergy.2015.12.078.
- [11] **J. Macknick, B. Beatty, and G. Hill** (2014) "Overview of opportunities for colocation of solar energy technologies and vegetation," *Sol. Energy Sites Considerations Areas Veg. or Contam. Disturb. Lands*, no. December, pp. 1–21, 2014.
- [12] **M. Trommsdorff et al.** (2019) "Feasibility and Economic Viability of Horticulture Photovoltaics," no. July 2021. 2019, [Online]. Available: https://www.eupvsec-planner.com/presentations/c49900/a_standardized_classification_and_performance_indicators_of_agrivoltaic_systems.htm.
- [13] **A. Agostini, M. Colauzzi, and S. Amaducci** (2020) "Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment," *Appl. Energy*, vol. 281, no. June 2020, p. 116102, 2021, doi: 10.1016/j.apenergy.2020.116102.
- [14] **M. Elborg** (2017) "Reducing Land Competition for Agriculture and Photovoltaic Energy Generation - A Comparison of Two Agro-Photovoltaic Plants in Japan," *Int. J. Sci. Res.*, vol. 6, no. 9, pp. 1–5, 2017, doi: 10.21275/1081704.
- [15] **J. Cho, S. M. Park, A. Reum Park, O. C. Lee, G. Nam, and I. H. Ra** (2020) "Application of photovoltaic systems for agriculture: A study on the relationship between power generation and farming for the improvement of photovoltaic applications in agriculture," *Energies*, vol. 13, no. 18, pp. 1–18, 2020, doi: 10.3390/en13184815.
- [16] **B. Willockx, B. Uytterhaegen, B. Ronsijn, B. Herteleer, and J. Cappelle** (2020) "A Standardized Classification and Performance Indicators of Agrivoltaic Systems," *Eu Pvsec 2020*, pp. 1–4, 2020, [Online]. Available: https://www.eupvsec-planner.com/presentations/c49900/a_standardized_classification_and_performance_indicators_of_agrivoltaic_systems.htm.
- [17] **A. Scognamiglio and C. Toledo** (2021) "Agrivoltaic systems design and assessment: A critical review, and a descriptive model towards a sustainable landscape vision (three-dimensional agrivoltaic patterns)," *Sustain.*, vol. 13, no. 12, 2021, doi: 10.3390/su13126871.
- [18] **H. Marrou, L. Guillioni, L. Dufour, C. Dupraz, and J. Wery** (2013) "Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels?," *Agric. For. Meteorol.*, vol. 177, pp. 117–132, 2013, doi: 10.1016/j.agrformet.2013.04.012.
- [19] **T. Hudelson and J. H. Lieth** (2021) "Crop production in partial shade of solar photovoltaic panels on trackers," *AIP Conf. Proc.*, vol. 2361, no. June, 2021, doi: 10.1063/5.0055174.
- [20] **E. D. Mehleri, P. L. Zervas, H. Sarimveis, J. A. Palyvos, and N. C. Markatos** (2010) "Determination of the optimal tilt angle and orientation for solar photovoltaic arrays," *Renew. Energy*, vol. 35, no. 11, pp. 2468–2475, 2010, doi: 10.1016/j.renene.2010.03.006.
- [21] **G. Talbot, S. Roux, A. Graves, C. Dupraz, H. Marrou, and J. Wery** (2014) "Relative yield decomposition: A method for understanding the behaviour of complex crop models," *Environ. Model. Softw.*, vol. 51, pp. 136–148, 2014, doi: 10.1016/j.envsoft.2013.09.017.
- [22] **A. Weselek, A. Bauerle, S. Zikeli, I. Lewandowski, and P. Högy** (2021) "Effects on crop development, yields and chemical composition of celeriac (*Apium graveolens* L. var. *rapaceum*) cultivated underneath an agrivoltaic system," *Agronomy*, vol. 11, no. 4, 2021, doi: 10.3390/agronomy11040733.
- [23] **A. Weselek, A. Bauerle, J. Hartung, S. Zikeli, I. Lewandowski, and P. Högy** (2021) "Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate," *Agron. Sustain. Dev.*, vol. 41, no. 5, 2021, doi: 10.1007/s13593-021-00714-y.
- [24] **T. C. Hau** (2019) "Simulation Approach to Estimate Rice Yield and Energy Generation under Agrivoltaic System," The University of Tokyo, 2019.
- [25] **R. A. Gonocruz et al.** (2021) "Analysis of the rice yield under an agrivoltaic system: A case study in Japan," *Environ. - MDPI*, vol. 8, no. 7, pp. 1–18, 2021, doi: 10.3390/environments8070065.
- [26] **B. Valle et al.** (2016) "Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops," *Appl. Energy*, vol. 206, no. July, pp. 1495–1507, 2017, doi: 10.1016/j.apenergy.2017.09.113.
- [27] **S. Amaducci, X. Yin, and M. Colauzzi** (2018) "Agrivoltaic systems to optimise land use for electric

- energy production," *Appl. Energy*, vol. 220, no. February, pp. 545–561, 2018, doi: 10.1016/j.apenergy.2018.03.081.
- [28] **M. H. Riaz, R. Younas, H. Imran, M. A. Alam, and N. Z. Butt** (2019) "Module Technology for Agrivoltaics: Vertical Bifacial vs. Tilted Monofacial Farms," pp. 1–8, 2019, [Online]. Available: <http://arxiv.org/abs/1910.01076>.
- [29] **A. Ullah, H. Imran, Z. Maqsood, and N. Z. Butt** (2019) "Investigation of optimal tilt angles and effects of soiling on PV energy production in Pakistan," *Renew. Energy*, vol. 139, pp. 830–843, 2019, doi: 10.1016/j.renene.2019.02.114.
- [30] **E. P. Thompson et al.** (2020) "Tinted Semi-Transparent Solar Panels Allow Concurrent Production of Crops and Electricity on the Same Cropland," *Adv. Energy Mater.*, vol. 10, no. 35, pp. 1–9, 2020, doi: 10.1002/aenm.202001189.
- [31] **J. M. Pearce, P. R. Malu, and U. S. Sharma** (2017) "Agrivoltaic potential on grape farms in India," *Sustain. Energy Technol. Assessments*, vol. 23, no. April, pp. 104–110, 2017, doi: 10.1016/j.seta.2017.08.004.
- [32] **J. Zheng et al.** (2021) "Increasing the comprehensive economic benefits of farmland with even-lighting agrivoltaic systems," *PLoS One*, vol. 16, no. 7 July, 2021, doi: 10.1371/journal.pone.0254482.
- [33] **E. M. Ott, C. A. Kabus, B. D. Baxter, B. Hannon, and I. Celik** (2020) *Environmental Analysis of Agrivoltaic Systems*, 2nd ed., no. 1982. Elsevier Inc., 2020.
- [34] **P. Santra, H. M. Meena, and O. P. Yadav** (2021) "Spatial and temporal variation of photosynthetic photon flux density within agrivoltaic system in hot arid region of India," *Biosyst. Eng.*, vol. 209, pp. 74–93, 2021, doi: 10.1016/j.biosystemseng.2021.06.017.
- [35] **G. Roccaforte** (2021) "Eclipse: A new photovoltaic panel designed for greenhouses and croplands," *AIP Conf. Proc.*, vol. 2361, no. June, 2021, doi: 10.1063/5.0054544.
- [36] **Y. Elamri, B. Chevion, J. M. Lopez, C. Dejean, and G. Belaud** (2017) "Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces," *Agric. Water Manag.*, vol. 208, no. October 2017, pp. 440–453, 2018, doi: 10.1016/j.agwat.2018.07.001.
- [37] **T. Sekiyama and A. Nagashima** (2019) "Solar sharing for both food and clean energy production: Performance of agrivoltaic systems for corn, a typical shade-intolerant crop," *Environ. - MDPI*, vol. 6, no. 6, 2019, doi: 10.3390/environments6060065.
- [38] **S. Ates, A. C. Andrew, C. W. Higgins, M. Bionaz, and M. A. Smallman** (2021) "Pasture production and lamb growth in agrivoltaic system," *AIP Conf. Proc.*, vol. 2361, no. June, 2021, doi: 10.1063/5.0055889.
- [39] **R. Mahto, D. Sharma, R. John, and C. Putcha** (2021) "Agrivoltaics: A Climate-Smart Agriculture Approach for Indian Farmers," *Land*, vol. 10, no. 11, 2021, doi: 10.3390/LAND10111277.
- [40] **N. Loots** (2018) "Technologic, Biological and Economic analysis of a dynamic agrivoltaic system in the Dutch agriculture sector," 2018.