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Review

Solar Photovoltaic Architecture and Agronomic Management in Agrivoltaic System: A Review

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Abstract: Agrivoltaic systems (AVS) offer a symbiotic strategy for co-location sustainable renewable energy and agricultural production. This is particularly important in densely populated developing and developed countries, where renewable energy development is becoming more important; however, profitable farmland must be preserved. As emphasized in the Food-Energy-Water (FEW) nexus, AVS advancements should not only focus on energy management, but also agronomic management (crop and water management). Thus, we critically review the important factors that influence the decision of energy management (solar PV architecture) and agronomic management in AV systems. The outcomes show that solar PV architecture and agronomic management advancements are reliant on (1) solar radiation qualities in term of light intensity and photosynthetically activate radiation (PAR), (2) AVS categories such as energy-centric, agricultural-centric, and agricultural-energy-centric, and (3) shareholder perspective (especially farmers). Next, several adjustments for crop selection and management are needed due to light limitation, microclimate condition beneath the solar structure, and solar structure constraints. More importantly, a systematic irrigation system is required to prevent damage to the solar panel structure. To summarize, AVS advancements should be carefully planned to ensure the goals of reducing reliance on non-renewable sources, mitigating global warming effects, and meeting the FEW initiatives.

Keywords: agrivoltaic system; solar photovoltaics; agronomic management; crop production; Food-Energy-Water nexus; sustainable integration

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1. Introduction

The concept of integrating solar PV with agricultural produce, known as agrivoltaic system (AVS), was originally proposed by [1] back in 1982; however, this concept was rarely discussed until the beginning of the new millennium. This agrivoltaism approach is derived from the intercropping method applied in the agricultural sector to increase the land equivalent ratio and total revenue [2–6]. AVS technology is gaining popularity due to its dependability in variable-scale applications. The development of commercial and research facilities around the world demonstrates the potential of this technology [5,7,8]. The concept of the system utilizes the generation of electrical energy and the production of agricultural products in the same area of production [6,9–12]. In other words, beneficial interaction, or symbiosis between these two productions in the same area, is created in this way [2,3,8,13–16]. Solar production could also offset global energy demand if less than 1% of cropland were converted to an AV system [17]. The integration of both productions in the same area may reduce the efficiency of either solar energy generation, agricultural production, or both productions; however, the total revenue may be increased [7,15,18–21] as illustrated in Figure 1. Additionally, crop production consumes less than 1% of the total energy generated by AVS [10].

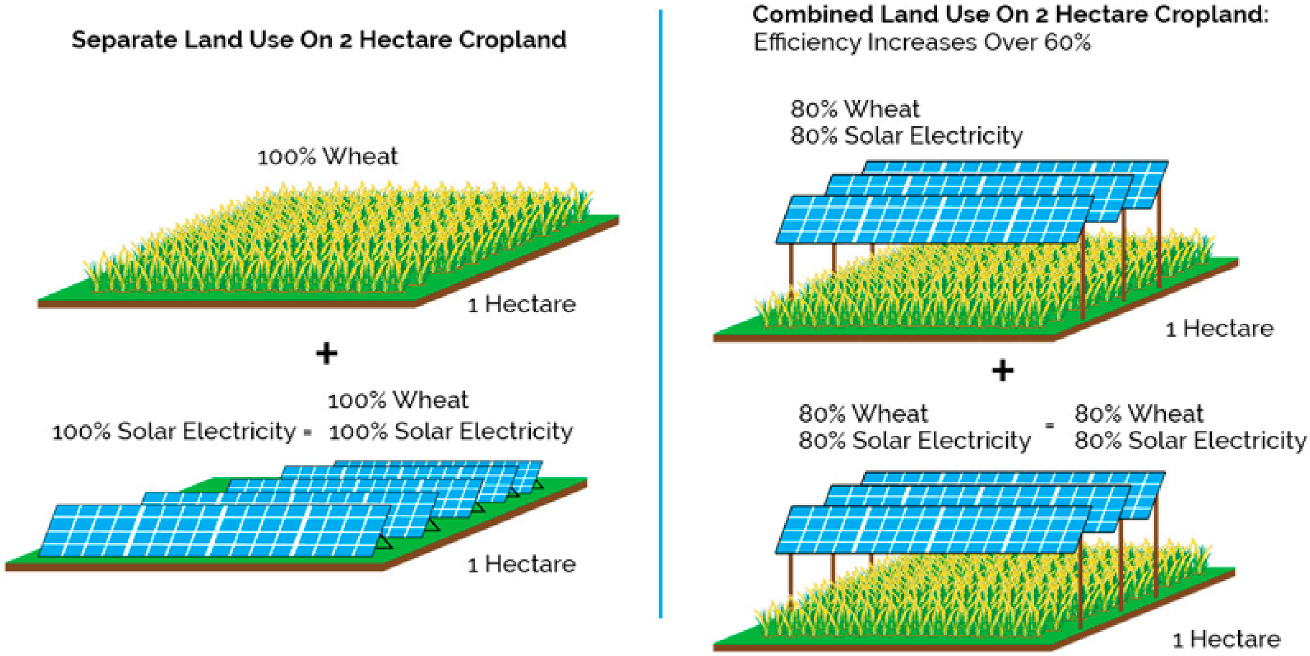


Figure 1. Comparison of efficiency traditional farming versus AVS. (Source: [22]).

1.1. Motivation for the Development of Agrivoltaic System

There is a connection between sustainability and resilience, and COVID-19 has illustrated how rapidly life can change. The work of [23] demonstrates that the deployment of new infrastructure lowers land-use availability, and this element must be managed properly. Despite the profound upheaval and uncertainty produced by the Covid-19 epidemic in the energy industry, which has forced global energy consumption to decline by 5% by 2020, renewables continue to play a critical part in all of our circumstances, with solar taking center stage [24]. The rapid development of solar farms raises a new threat and friction in terms of land-use for electricity production whilst satisfying increasing food demand. The amount of land required to establish large-scale solar farms has become a source of concern [8,13,25–27].

Current studies also show that the environmental factors that may influence the efficiency of photovoltaic (PV) panels are sometimes ignored [12,17,28–31]; however, for AVS, these factors are very crucial [32,33]. For example, gravel underlay for solar PV sites may contribute to a heat island effect that increases the ambient temperature below the PV structure. This situation potentially reduces the efficiency and life span of the solar panel [3,10,11,34,35]. Simultaneously, agricultural lands are shrinking due to land reuse for new industry production, homes, and urban areas [8,10,36–39]. The summary report of World Agriculture: Towards 2015/2030, released by [40], has stated that the global demand for an agricultural product will keep on increasing every year. Developed countries will suffer from a high dependency on agricultural imports, and food insecurity in developing countries will persist without a significant increase in local production. These conflicts are compounded by the fact that the amount of arable land available per capita decreased by 48 percent between 1961 and 2016, owing to the global population increase [41]. Thus, it is believed that the solution of AVS technologies enables the possibility of resolving the competing interest between the two sectors' requirements while meeting the demand [14,21,42–44].

1.2. Benefits of Agrivoltaic System

There are a variety of fascinating details about AVS technology derived from previous studies such as: (1) increase in total revenue [7,15,19–21,45,46]; (2) crops cultivated beneath the solar structure help reduce the ambient air temperature by creating a cooler microclimate [7,11,47–49]; hence, indirectly reducing the solar panel temperature up to 1–2 °C and increasing the solar PV efficiency [21,50]; (3) solar PV panels must be washed regularly to maintain their solar radiation efficiency. The water used to clean them can be reused to irrigate the agriculture beneath the solar panel, resulting in increased water efficiency [2,13,21,26,34,51]; (4) emissions due to CO_2 are also uptaken by crops, while low CO_2 is produced by solar energy compared to fossil fuel-based power generation [2,20,43]; (5) solar PV provides a good shading effect on some plants that do not like direct sunlight [30,39,52–55]; (6) providing new jobs [12,21,27,51,56]; (7) raising taxes [20] and (8) the expansion of cleaner and renewable energies are necessary to reduce the fossil fuel dependency and global warming [9,28,29,41,46,57–59]. Furthermore, efforts to reduce CO_2 emissions and promote sustainable energy are always gaining international support [60]. Thus, these AVS initiatives are highly in line with Food-Energy-Water (FEW) nexus [9,13,14,34,61] and Sustainable Development Goals (SDGs) [28,32,56,62–64].

1.3. Land Equivalent Ratio

Land equivalent ratio (LER) is a method used for measuring the efficiency of land utilization for the simultaneous production of crops and electricity [11,18,53,55,65,66]. A similar technique is used in agroforestry systems, which integrate trees and food crops [4,41,66,67]. The *LER* can be extended to include the mixing of any two (or more) production systems in the same area. Numerous previous studies have also used this method to identify the possibility of integrating agriculture production with a solar farm. In general, *LER* is the ratio of the *AVS* installation's area to the total of the areas required to meet the *AVS* installation's agricultural and electric production [18]:

$$LER = \frac{FM_{AVS}}{FM_{CP}} + \frac{E_{AVS}}{E_{PV}} \quad (1)$$

where FM_{AVS} and FM_{CP} denote fresh biomass in the *AVS* installation and on the *CP* control plot (agricultural mono-production), while E_{AVS} and E_{PV} denote the *AVS* installation's and PV installation's electric production, respectively. *LER* values greater than one indicate that combining agriculture and solar *PV* is more efficient than doing so separately [11,37,68]. To be noted, the efficiency of *AVS* technology is highly dependent on the solar PV architecture [4,6,21,28,51,53,69,70] and agronomic management [6,25,31,53,54,56]. Numerous methods are constantly being developed to improve the effectiveness of this technology. However, *AVS* applications are still in their early stages, therefore there is plenty of room for technological advancements and expanded application fields [14,34,61,62,71–73]. Thus, this paper is written to discuss the consideration of *AVS* architecture with design criteria for solar photovoltaic systems and agronomic managements to improve the *AVS* outputs.

2. Design Consideration for Agrivoltaic System

2.1. The Importance of Solar Radiation for Energy Generation and Crop Cultivation

Solar radiation is an important factor in photosynthesis, which is the process by which plants and other autotrophic organisms convert light energy from the sun into chemical energy that can be used to synthesize carbohydrates and power the organisms' activities [28,34,55,73–75]. At the same time, solar radiation can also be converted to electricity using solar power systems. Solar systems are classified into two types: photovoltaic (PV) systems that convert sunlight directly to electricity using semiconductor materials [36,76–79] and concentrated solar power (CSP) systems that convert sunlight to heat before using the heat to produce electricity [30,41,46,51,80]. Despite the fact that both processes need solar radiation to occur, the photosynthesis process is concerned more with the Photosynthesis Active Radiation (PAR) range [47,52,68,81–83] while electrical energy generation is dependent on solar irradiance or light intensity [8,15,35,84,85].

2.1.1. Photosynthetically Active Radiation

Photosynthesis is a light-dependent process that occurs best in the visible light spectrum. As shown in Figure 2, visible light has a wavelength range of 400–700 nm. Ultraviolet cannot be used for photosynthesis because it has too much energy which can disrupt molecular bonding, and destroy DNA and other important organismal structures. On the other end of the spectrum, infrared light does not contain enough energy to sufficiently excite electrons in molecules for photosynthesis [86]. The range of light wavelengths that is most suitable for photosynthesis is called Photosynthetically Active Radiation (PAR) [87]. Since photosynthesis is a quantum process, PAR is expressed in terms of Photosynthetic Photon Flux Density (PPFD, $mol \cdot m^{-2} \cdot s^{-1}$), or in terms of Photosynthetic Radiation Flux Density, Q_p (PAR irradiance, $W \cdot m^{-2}$), which is more relevant to energy balance studies [47,81,83].

2.1.2. Light Intensity

In contrast, the intensity with which radiation enters the atmosphere is the solar irradiation, R_s [28,77]. It is the amount of radiant flux incident on a surface and is expressed in watts per square meter ($W \cdot m^{-2}$). The R_s parameter is frequently integrated over time to determine the radiant energy emitted into the surrounding environment (joules per square meter, $J \cdot m^{-2}$) during that period [88,89]. This total solar irradiance is referred to as solar irradiation. The amount and intensity of R_s that the earth's surface receives depends on a variety of factors such as cloud cover [81,90–93], latitude [6,73,80,94], altitude [77,78,90,95], season [73,93,96–98], weather [19,38,40,99,100], and daytime [34,46,48,76,101]. In addition, the distance that radiation has to travel is dependent on the angle of the sun [88,93]. The greater the angle, the lower the solar intensity, which is why the R_s parameter is less intense in the morning and evening than at noon [89,101]. Furthermore, the annual net Rs is higher at the equator than at the northern and southern poles [28,102]. Also, as a hemisphere is tilted away from the sun, the R_s value decreases [68,96,103,104].

2.1.3. Correlation between Photosynthetically Active Radiation and Light Intensity

Though R_s and Q_p are correlated, photosynthetic and photovoltaic systems have distinctive requirements in solar radiation quality and quantity [74]. The quality of solar radiation absorbed by PV panels can be tailored to capture a specific solar spectrum or the entire solar spectrum (Figure 2A). In contrast, the absorption spectra of plants are determined by their photosynthetic pigments (Figure 2B). The amount of solar radiation absorbed and used to create products further distinguishes plants and solar panels. The electrical output of solar panels is usually linearly proportional to the intensity of incident light. While plants require radiation energy to generate biomass, this does not correlate linearly above a certain intensity because the rate is limited by numerous linked, complex metabolic steps [97]. Next, owing to the lack of ground measurements of the Q_p parameter, the improvement of plant-growth models also necessitates precise estimations of the Q_p values, which are also indirectly determined based on their interaction with the R_s parameter [105]. Acting to balance the needs of solar radiation between PV panels and crops may be able to further improve the efficiency of electricity generation and agriculture yield production in AV systems. Thus, the AVS design should pay attention to how to maximize the exposure of high quality solar irradiation to the PV panels and the exposure of optimal PAR flux to the crop underneath the panel structures [8,21,87].

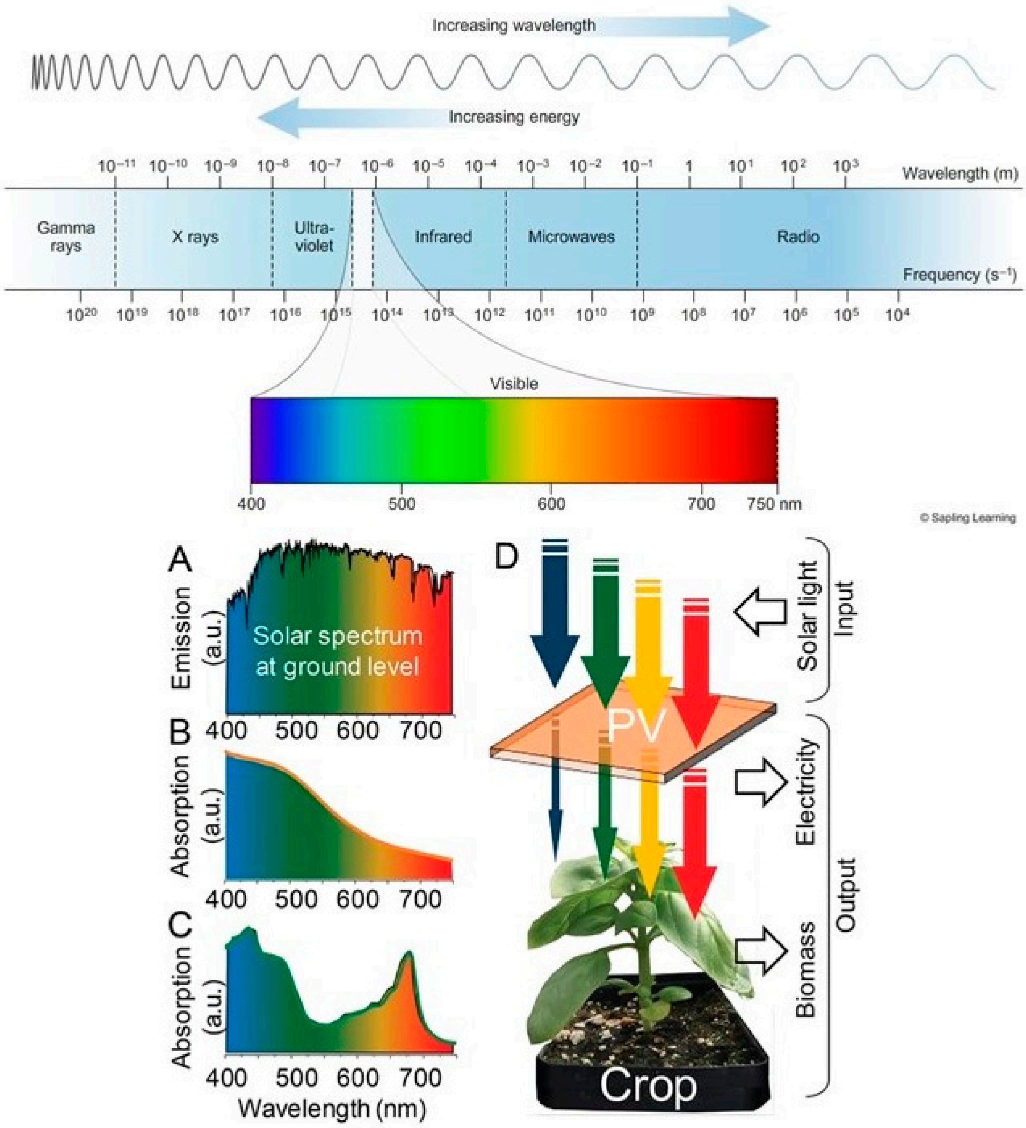


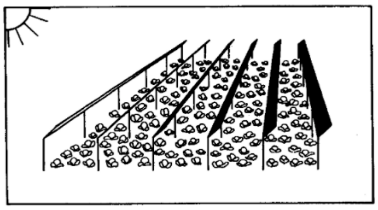
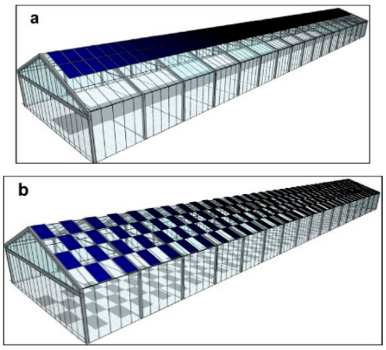
Figure 2. Electromagnetic spectrum. (**A**) Solar radiation spectrum in the visible range at the ground level. (**B**) Absorption spectrum for PV panel. (**C**) Absorption spectrum for a crop. (**D**) Schematic representation of the input (solar light) and the two contextual outputs of AVS (i.e., electricity and biomass). (Modified from original. The electromagnetic spectrum, source: [106]; The absorption spectrum, source: [97]).

2.2. Integration of Solar Energy and Agriculture

The integration of large-scale solar power and agriculture has the capacity to ensure efficient energy generation and to sustain agricultural production with minimal environmental impacts [33,92,95]. This act to co-locate is characterized as the intentional development of agriculture and energy in the same location [17,34,63]. Agriculture growth could occur beneath or near energy infrastructure [6,9,16]. There are three types of co-location opportunities and approaches: energy-centric, agricultural-centric, and integrated agricultural-energy-centric [44,107]. Energy-centric approaches to the co-location of solar energy developments and agriculture are marked by behaviours that optimize solar energy production while minimizing changes to solar construction best practices and fostering agriculture growth under and around the solar installation. Energy-centric methods could be better suited to areas with large amounts of land earmarked for solar energy production or areas where solar development has already taken place [107]. For example, when [1] first introduced the concept of agrivoltaic in 1982, the proposed design was focused on energy production. A minimal modification of the PV structure has been made to allow light to reach the ground at the gap between the rows of solar panels, allowing crops to be planted there. Next, Tenaga Nasional Berhad (TNB) has developed a 50 MW solar farm in Selangor, Malaysia, as part of the Large-Scale Solar (LSS) initiative led by the Malaysian government. The project was created to generate renewable energy [108], and the AVS concept was used indirectly in these solar farms by planting grass to help maintain soil stability.

Agricultural-centric approaches to the co-location of solar energy and agriculture are defined as actions that serve to optimize biomass production activities and mitigate alterations to current plant management activities, while still integrating solar energy production activities. In areas with limited land or that are already established agricultural areas, agriculture-centric methods could be a good fit [44,107]. For example, as illustrated in Table 1, Ref. [54] has conducted a study to assess the integration of different PV module arrangements (i.e., (a) straight pattern and (b) checkboard pattern) with different orientations (E-W orientation and N-S orientation) for greenhouse production in Decimomannu (Sardinia, Italy). The study reveals fundamental assumptions, stating that the agricultural efficiency of the land being used is not sacrificed for the sake of solar generation. Ideally, optimizing solar energy generation does not significantly alter standard agronomic management and has an insignificant impact on agriculture yields. Meanwhile, [63] highly recommends the model AVS of the Junagadh Agriculture University (JAU) to the farmer's community in India. The model is said to be self-sufficient in terms of energy for agricultural and other operations. The crop production has been recorded as 15% higher under this type of system than under open field conditions. The farmer can also make additional money by generating electricity revenue.

Table 1. Approaches of agrivoltaic system.

Energy-Centric	Agricultural-Centric	Agricultural-Energy Centric
 [1]  [108]	 [54]  [63]	 [53]  [61]

Next, there are hybrid methods that aim to combine both energy performance and agriculture production targets, in addition to agriculture-centric and energy-centric approaches to the co-location of solar energy technologies and agriculture. Known as agricultural-energy-centric, these methods could result in lower agriculture and energy production; however, other advantages make co-location preferable, including additional revenue streams [107]. These methods are differentiated by the integration of both agriculture and energy priorities into system designs. Incorporating agriculture and energy into the same area of production could be suitable: (1) on an existing solar farm or farmland, and (2) on underdeveloped land [109]. However, hybrid approaches to entail alterations for both agriculture and solar energy production methods can range from major structural changes to minor tweaks [107]. Several prior experiments focused on these methods have been carried out. There are modifications to be made to the solar energy system, such as altering the solar panel's structure [6,53] and using a specific algorithm for agricultural growth [4,53], but also in terms of using agronomic practices [33,59] to maximize the output [6,8,47,56]. Table 1 shows several previous studies based on different approaches to the agrivoltaic system.

Based on the description of AVS approaches, the developers, energy providers, and farmers need to decide which AVS approach is the best suited to their interest. It is important to note that, although investing in AVS may be of benefit to them in the long-term, at the moment it is still an open debate as to whether the high capital cost in the installation of solar panel would be prudently compensated when farmers have a diverse financial profile and risk adversity [41,44].

2.3. Agricultural Sector Perspective on Agrivoltaic System

Policymakers should conduct sector-wide social impact scoping (SSIS) for renewable energy technology (RET) to elicit diverse perspectives from previously reclusive stakeholders, and to gradually increase the positive impact and mitigate the negative impact of RET [110]. For agrivoltaic system technology (AVS), the fundamental focus in order to be successful is the farmers' perception of the application, challenges, and opportunities of this dual land-use system [12,44]. Experts in the agriculture sector believe that AVS installation seemed to be able to produce a positive impact for themselves, with several defining constraints to the acceptance of AV technology. Among the constraints are (1) the need for long-term land productivity. Farmers, for example, are concerned about the longevity of permanent solar panel systems and the limitation of agricultural maintenance due to the permanence of all solar panels and the scale of the plot [109–111]; (2) farmers are concerned about demand insecurity as a result of the many unknown procedures associated with this dual land-use technology [2,9,44,46]; (3) farmers are looking for compensation if a portion of their property is taken for the installation of solar panel structures [38,44,52,112]; (4) built-in versatility to accommodate different sizes and types of activities, as well as evolving farming practices [54,109]; (5) the implementation of specific AVS approaches that have both positive economic and no non-negative environmental effects [62,110,113]; (6) in some cases, design of PV infrastructure should prioritize potential reversibility [3]; (7) proactive awareness-building events for AVS promotion [10,11,15,110].

Despite these constraints, there was a significant gap in the social impacts perceived by farmers who had already implemented AVS technology and those who had not [110]. Most farm operators who had already implemented AVS thought that the ultimate effect had been more positive than negative, including the positive impact of stable income and sustaining stable agricultural productivity as a result of electricity sales [21]. A considerable number of these interviewees were motivated by the increased revenue from selling AVS-generated energy to keep their farms rather than to farm [14,110]. Income from electricity production was sufficient to pay for strenuous farming work and provided additional gratification due to the possibility of conserving farmlands. To their minds, this dual-land technology was not a hindrance to growth; instead, they considered it an additional resource to work with [110]. However, in a case study in China, the act of agrivoltaism with an innovative business model shows a promising economic performance for both productions. The Annual Return on Investment (AROI) increased by about 9% to 20%, with a discounted payback period ranging from four to eight years depending on the crops produced in this integration scheme. According to the study, sensitivity and uncertainty analyses indicate that the most sensitive aspect is crop price. The significance of the electricity feed-in tariff is somewhat less than we expected [20]. In this case, the AVS firms are advised to prioritize crop planting [20] without neglecting energy production [44]. At the same time, policymakers should be more flexible in terms of solar energy and agricultural incentives [3,20], depending on AVS approaches [107].

Following that, based on the level of growth of the AVS industry, various government officials may be tasked with setting specific quantity targets, ranging from prototype installations to widespread adoption [2,34]. Either an AVS price control system could be used to grant an add-on to an already commissioned solely ground-mounted photovoltaic (PV-GM) development program, compensating for the cost of technology adaptation, or a separate AVS funding mechanism could be established [41]. Governments will be asked to legally identify AVS, adopting a nationwide AVS standard that will guarantee high-quality AVS execution, in order to prevent windfall gains [2,41], improve social recognition, and resolve land rivalry between solar PV and agriculture [44]. In comparison to PV-GM, AVS technology is still in its infancy, with a high learning curve but the scope for even more techno-environmental synergies. The dual role of AVS, which protects agricultural yields while also producing solar electricity [7,27,51,54], boosts economic production per square meter [13,46] and strengthens farmers' resistance to the effects of global warming by securing and diversifying their sources of income [14,59]. The implementation of financial support schemes to conserve cropland, diversify farmers' income sources, and counteract rural exodus in some countries was the driving political goal behind the introduction of AVS diffusion regulations [38,41,114]. With proper implementation, this technology is expected to accelerate development and lead to farmer yield increases, as well as environmental sustainability [2,19,115].

3. Solar Photovoltaic Architecture in Agrivoltaic System

3.1. Alteration and Modification of Solar Photovoltaic

A solar photovoltaic (PV) system is a power generation unit made up of an electrically integrated assembly of a PV array, inverter, and other components. PV panels (also called PV modules) are composed of several photovoltaic cells that convert sunlight energy to electricity. The solar PV modules are wired together in series to form PV strings, which are then linked together in parallel to form a PV array (MS IEC 61836:2010) [116]. The process is simple as it is a direct conversion of sunlight to electricity without any complicated mechanical movement or release of waste to the surrounding environment [52,78,92]. The solar PV cells can absorb up to 80% of the incident solar radiation received from the solar band, but only a small amount of this absorbed energy is transformed into electricity, with the rest increasing the temperature of the cells [89,117,118]. Next, grid-connected and stand-alone solar systems are the two types of solar energy systems. These two systems are intended to offer a direct current or alternating current source for use with the utility grid, an independent storage system, or other electrical/electronic equipment [77,93,119,120]. Even though much of the photovoltaic system demand can be matched with aggressive building-integrated PV (BIPV) and rooftop PV [79,87,95,102], both systems cannot provide all the energy necessary, especially for regions with high population densities compared to land-based solar farms [8,95]. A solar farm is designed to generate enough energy [37] to power thousands of homes and business [9,121]. They are much like the solar panels you place on your roof to power your specific requirements [28]. Most energy generated by solar farms is sold to the grid. However, to sell power to the grid first you need approval from your country's power provider and authorities [32,122].

The AVS idea is mainly based on photovoltaic technology being adapted for agricultural use, considering space and wiring restrictions [30,38,117,123,124]. However, AVS is configured differently from typical ground-mounted photovoltaic systems (PV-GM), which are more prevalent because of their cheaper installation costs and higher panel density, which improve energy production [3,25,36,62]. The systems in traditional ground-mounted solar installations are immobile [2,36,93]. For this solar installation, the PV panels are around 1.6 feet (0.5 m) from the ground, and space between rows is kept to a minimum to avoid shade. Also, panel clusters do not have spacings since they abut [125]. Certain modifications of the solar PV structure to suit the agricultural production requirements are needed to allow optimum solar radiation to reach the ground under the solar PV structure. Among the modifications are: (1) elevation of solar PV structure [25,28,65,94,112]; (2) optimizing the distance between solar PV structure [15,25,68,95]; (3) configuring of the density of solar panels in one solar structure [4,6,49,87]; (4) optimization of the sloping angle of the solar panel [4,6,113,115]. Nevertheless, AVS developers should keep in mind that all modifications and alterations to solar photovoltaic structures would adhere to AVS approaches [91,107,109], geographical regions [19,65], crop selection [33,65,69], and agronomic management [18,19,33].

Several studies have been conducted at Montpellier Experimental Agrivoltaic Station since 2010 by [4,6,18,69] to determine the characteristics of the photovoltaic structure to be integrated into the AV system. Full-density (FD) and Half-density (HD) AV systems have been developed and tested in this facility for almost 10 years. FD structure is designed for optimal solar energy production, thus only allowing around 50% of solar radiation to the crop below the panel. While HD structure is designed to balance between electric generation and agriculture production, thus allowing up to 70% of solar radiation to reach the crop level. The percentage of light transmission was determined under the FD and HD experimental panels. To obtain the percentage of targeted solar radiation, the FD and HD structures were designed at 5.0 ft (1.6 m) and 10.0 ft (3.2 m) in the panel row spacing, respectively. Moreover, both panels were mounted 13.0 ft (4.0 m) above the ground and tilted at an angle of 25 degrees. The elevated PV panels make the spatial distribution of radiation increase because light can penetrate underneath the panels from the sides, thus creating conditions where crops are able to grow below the panels [53]. In another study conducted at UMass Crop Research Farm (Massachusetts), the AVS structure without concrete bases was constructed with a height of 7.5 ft (2.3 m) from the ground to allow nearly 70% of solar radiation to reach the crop below the panel. The study found that 4.0 ft (1.2 m) and 5.0 ft (1.5 m) distances are optimal for the AVS plots for biomass production [125]. These conclude that the modification of panel rows spacing, the height of mounted panels, configuration of the density of the solar panel, and the tilting angle are variable and dependent on the specific geographic location. In addition, the growing season also contributed to AVS adjustment [18,25,45].

In addition to the modification of the tilted monofacial PV structure, a vertical bifacial PV structure could be an alternative to AVS infrastructure [5,7,47,65]. According to [65], vertical bifacial PV provides several advantages, including less land coverage, less interference with agricultural machinery and rains, natural resilience to PV soiling, faster cleaning, and cost savings owing to a possible lower elevation. However, the combined PAR/energy yields for this type of arrangement may not always be superior [65]. Still, the trade-off between a higher capital expense and a low cost for frequent cleaning should be carefully considered when calculating the relative Levelized Cost of Energy (LCOE) [41,62,65].

Next, instead of modifying the PV structure and use of opaque photovoltaic (OPV) as modules, there is also a study conducted to determine the potential of using semi-transparent photovoltaic (STPV) modules in AV system [76,91,126]. The idea is to turn the agrivoltaic principle from just solar sharing to the selective use of various light wavelengths [97,126]. The solar sharing concept is a common concept in conventional AVS that uses OPV modules and creates a shade to the portion of farm fields, throwing a shadow on the underlying plants [97,127,128]. However, The STPV's eclipsing frequency was 9.7 percent, and the cell shadow never completely covers the plants while the gap between the module and the crop is greater than 1 m [126]. Next, as illustrated in Figure 2, since the electrical energy generation capacity also varies depending on the light spectrum [55,78,117,129], special attention should be paid to identify suitable types of crops that are able to carry out the photosynthesis process with the limitation of certain PAR wavelengths [28,47,69] to be integrated with SPTV modules in agrivoltaic system [97,126]. In addition, Table 2 summarizes some of the studies that have been conducted worldwide to improve AVS technology.

Table 2. Overview of Existing Agrivoltaic System Research Project.

Location	Electricity Yield ($kWha^{-1}$)	Capacity (kWp)	Solar Tracking	PV Specification	Cultivated Crops	Sub-Treatment	Highlights	Source
Oregon State University, USA	unknown	1435	No	Polycrystalline, east-west oriented strips, 1.65 m wide and inclined southward with a tilt angle of 18°, 1.1 m above ground (at lowest point) and distance between panel is 6 m	semi-arid pasture	SFO, SPO, SFC	Extreme heterogeneity and spatial gradients in biomass production and soil moisture were observed as a result of the heterogeneous shade pattern of the PV array.	[5,44]
Po Valley, Northern Italy	1,890,000	1461	Yes (2-axis)	Polycrystalline panel, height 4.5 m above ground, spacing between rows of panels is added to decrease the density of panels, the fixed panels were set at 30 degrees whereas sun-tracking had differing angles throughout the day.	Maize (*Zea mays* L.)	Single density (panel area/land area ratio) of 0.135 and double density of 0.36	Yield under AVS is slightly lower when water is non-limiting, it is higher in conditions of drought stress	[53]
Sardinia, Italy	E-W 1547 N-S 1330 (100% Mono-pitched roof), E-W 1562 N-S 1290 (60% Venlo-type), E-W 1553 N-S 1317 (50% Gable roof), E-W 1523 N-S 1292 (25% Gable roof)	71 (100% Mono-pitched roof), 47 (60% Venlo-type), 35 (50% Gable roof), 20 (25% Gable roof)	No	Multicrystalline and Monocrystalline, PV greenhouse (mono-pitched, venlo-type, gable roof). East-west and north-south orientations. PV cover ratios ranging from 25% to 100%	Unknown	unknown	(1) Both the checkerboard pattern and the N-S orientation allowed to improve the uniformity of light distribution. (2) A valid design criterion to improve the agronomic sustainability of next-generation PV greenhouses	[54]
Japan	unknown	Unknown	No	Installing semi-transparent PV module (STM) on the greenhouse roof	Unknown	unknown	(1) The conversion efficiency of the semi-transparent module (STM) was stable at around 0.2% and was not affected by the slope angle, because of the isotropic photoreception of the spherical microcells. (2) The eclipsing level of the STM was 9.7% and the cell shadow never covers the plants entirely when the distance between the module and the crop is greater than 1 m	[126]

Table 2. *Cont.*

Location	Electricity Yield (kWha^{-1})	Capacity (kWp)	Solar Tracking	PV Specification	Cultivated Crops	Sub-Treatment	Highlights	Source
Montpellier Experimental Agrivoltaic Station, France	Unknown	Unknown	No	Monocrystalline, panels were mounted 13 ft (4 m) above the ground, 14 degree aspect angle orientation of the panels towards East, tilted at an angle of 25 degrees, space every 1.64 m (distance between panel structure)	lettuces (short cycle crop), cucumbers (short cycle crop), and durum wheat (long cycle crop)	FD (50% light allowable) 1.6 m panel spacing, HD (70% light allowable) 3.2 m panel spacing	(1) The study found that although the FD plot had higher LER's than the HD plot because of higher energy production, the HD plot significantly limited crop yield losses while also maintaining an LER over 1. (2) AV system should be designed to allow about 70% radiation to the crop to prevent significant restrictions in yields. (3) Different varieties of certain crops that can be chosen for AV systems due to their adaptability to shaded conditions. (4) Shading in the AV systems saved between 14–29% water depending on the level of shade (FD or HD).	[4,21,22,45]
			Yes (single-axis)	Controlled-tracking (CT) system (Distance from the ground: 16.5 ft (5 m), Panel rotation: 50 degrees E and 50 degrees W), Sun-tracking (ST) system (Distance from the ground: 16.5 ft (5 m), Panel rotation: 50 degree E and 50 degrees W)		FD, HD, ST and CT	(1) ST AVS is the most effective design to optimise AV outputs (LER 1.5), while Fixed HD AVS and CT were the most efficient in producing biomass.	[2,6,13]
Renewable Energy Research Office (RERO), Malaysia	unknown	10	No	Monocrystalline	Java Tea	FD	(1) Strong justifications of sustainable herbal plant growth, profitable margin with short returns of the initial investment is the backbone of this work. (2) It is observed that high humidity level due to water evaporation process with PV shading features provides a good attraction for pests which increases the risk of attack to crop.	[14,17,33]

Table 2. *Cont.*

Location	Electricity Yield ($kWha^{-1}$)	Capacity (kWp)	Solar Tracking	PV Specification	Cultivated Crops	Sub-Treatment	Highlights	Source
Demeter-certified farm community Heggelbach, Germany	unknown	194.4	No	Duo bi-facial PV, clearance height: 5 m, overall height: 7.8 m, Unit width: 19 m	Potato, winter wheat	unknown	(1) The maximum sunlight reduction due to shading from the PV panels on any square foot of land under the dual-use system may be no more than 50%. (2) Beneficial price-performance ratio of 0.85 for potato production and a nonbeneficial price-performance ratio of 4.62 for winter wheat	[41]
Zhangjiakou, China	unknown	1500–1700	Yes (single-axis)	Oblique PV, East-west oriented and faces towards the south, PV height: 2.5 m from ground, tilt angle 39 degree	unknown	unknown	(1) By studying the tracking law of oblique single-axis AV system, it can be found that in the higher latitude, variations in rotation angle are approximately similar during every day of the growth period of plants. (2) Light adaption point (LAP) and required solar radiation time length of crops can be regarded as two indexes to select the right crop	[101]
India	unknown	200–250	No	Ground clearance: 0.5 m, structure width: 2.95 m, structure heigh: 1.94 m, row distance: 6 m	*	SFO, SPC	Suitable crops for AVS suggested here is applicable for arid western India and for other regions different crops need to be identified as per prevailing rainfall and weather conditions	[25]

* Discuss in sub-Section 4.1.

3.2. Solar Tracker for Agrivoltaic System

Solar monitoring is a technique for increasing the amount of energy obtained by keeping a solar collector, either PV or photothermal, in an optimal location perpendicular to the sun during daylight hours [7,76,77]. A solar tracker aims to ensure that the panels achieve the greatest amount of solar irradiation possible during the day [54,85,96,130]. Solar tracking began in 1962 when Finster launched the world's first fully mechanical tracker. The following year, Saavedra demonstrated an electronic-controlled system for orienting an Eppleypyrheliometer [131]. Since then, the techniques of solar tracking were improved with the main purpose being to increase the total amount of irradiance to the maximum possible [35,78,80]. Despite that fixed solar PV configuration is preferable to be integrated with AV systems [1,6,54] because fixed solar PV intercepts less solar radiation compared to single-axis and dual-axis solar trackers, there is an effort towards the integration of solar trackers into AV systems [8,30,53,101,127].

Refs. [4,18] have developed an AV solar tracking system at Montpellier Experimental Agrivoltaic Station in their trials to increase the electricity generation without having detrimental effects on agricultural production. There are five plots set up in their experiments. The first plot is a fixed structure with full-density (FD) AVS and the second plot is a fixed plot with half-density (HD) and has the same specifications as the original AV systems developed by [6]. The two types of AV solar tracker system used in their studies are controlled-tracking (CT) system and sun-tracking (ST) system. Both systems were specifically designed by: (1) altering the density of the PV panel and height of the solar PV from the ground; (2) developing a specific solar tracking algorithm with the inclusion of the parameters for agricultural growth. The LER values obtained were more than one in all AV plots, indicating that the AV system is more efficient than the monosystem production. With LER values of 1.5 and above, the ST plot has proven to be the most successful method for optimizing AV outputs; the ST plot's high LER value is mostly due to electricity generation. It is critical to highlight that the CT layout was the most efficient in terms of agricultural production. Furthermore, the LER values for either the CT or ST plots were greater than the LER values for the HD plot.

In another study by [53], at Po Valley (Northern Italy), a new platform was developed and introduced to conduct simulations aimed at optimizing agrivoltaic systems, which combine the output of electrical energy and arable crops. There are four configurations of AVS set up in this study: (1) dual-axis, sun-tracking system equipped with 5 secondary axes and 10 solar panels (ST1); (2) dual-axis, sun-tracking system equipped with 4 secondary axes and 32 solar panels (ST2); (3) still unit equipped with 5 secondary axes and 10 solar panels (F1); (4) still unit equipped with 4 secondary axes and 32 solar panels (F2). All the AV systems were constructed by raising the panels and fixed to a rotating axis before being coupled with Agrovoltaico software. A radiation model was integrated with the Agrovoltaico programme (based on the shading conditions determined from the AVS structure set-up). A crop model known as GECROS was used to input AVS's modelled radiation and a 40-year temperature and environmental dataset from the site. Then, the software is used to measures radiation mitigation and its effect on simulated crop yields in aggregate. Based on the simulation, the highest electricity generation came from ST2, followed by F2, ST1, and F1. While, for biomass, even though F2 has the highest yield, the yield in all treatments ranges from 2202–2091 gm^{-3} only. Surprisingly, ST1 and ST2 have higher biomass yields compared to stand-alone agriculture production. Other summaries of studies that utilize solar trackers are mentioned in Table 2.

To the best of the understanding of the authors, there is a potential to integrate the solar tracking system into the agrivoltaic system [4,5,30,53]. According to [77,88,130], a solar tracker system can be classified based on the techniques used to control the movement of the PV panels. The tracker system can be a passive, active [78,89], or chronological tracker system [77]. The operation, advantages, and disadvantages of each type of solar tracking system technology are summarized in Table 3 [77]. Even though an active solar tracker (also known as a dynamic solar tracker) is required, despite extra power consumption and not being very accurate under a cloudy day, the use of this type of solar tracking system contributed to the higher energy generation efficiency compared to a passive and chronological system [77,132]. For this reason, previous studies by [4,18,53,101] also used this type of solar tracking system. The active solar tracker uses sensors and motors [77,88] to control the rotational angle of the PV axis and allows them to follow the sun's trajectory directly [4,78,101,132], or based on a tracking algorithm [27,49,53,78,133]. For AVS conditions, the integration of a solar tracker in the AVS is focused on creating an ingenious partnership between both parties to optimize the productions of electricity and agriculture [28,30,61,87,110]. A specific and improvised tracking algorithm can be developed to optimize light penetration beneath the solar structure to suit selected crops while balancing the energy production [47,53,101].

Table 3. Passive, Active, and Chronological Solar Tracking System.

Technology	Descriptions	Advantages	Disadvantages	AVS Preference
Passive	- thermal expansion of the tracker's material or an imbalance in pressure between two spots at the tracker's ends	- operate independently of motors or actuators. - quick and simple to set up. - minimal maintenance cost.	- a high level of weather dependency. - low precision.	-
Active	- design systems that employ sensors and motors.	- more accurate. - efficient at tracking the sun's location.	- requires additional electricity usage. - not very precise on an overcast day.	Single-axis: [4] * ST and ** CT, [18] * ST and ** CT, and [101] * ST Dual-axis: [53] * ST
Chronological	- rotate at a specific rate of degrees each hour.	- low energy losses. - minimal tracking error.	- continuous rotation is more energy-intensive. - irrational work on an overcast day.	-

* ST = Sun-tracking system, ** CT = Controlled-tracking system.

4. Agronomic Management for Agrivoltaic System

4.1. Crop Selection

The microclimate aspect under the solar PV structure should be taken into account in the selection of suitable crops to be cultivated in solar farms [5,46,103,126]. A setup by Refs. [42,134] in particular divided the area beneath the solar panel into three sub-treatments: (1) sky fully open area between panels (SFO); (2) Solar partially open between panels (SPO); (3) solar fully covered area under panels (SFC) as illustrated in Figure 3A. SFO zones are located between the edges of mounted photovoltaic panels and areas that have received full light [28]. No shade covers the SFO zone, according to the shadow length estimate [132], while SPO areas are situated in the penumbra and have been subjected to episodic shade [104]. SFC areas are located immediately under the photovoltaic panels and receive complete shade [73]. However, the division of the sub-treatments are subjective and subjected to the solar photovoltaic design [5,19,38,91]. For example, the AVS design at Montpellier Experimental Agrivoltaic Station by [4,6,18,69] (as described on page 9) is high in length, and is thus less suitable to be divided into SFO, SPO, and SFC. Previous researchers at that station classified the area beneath the solar panel as FD and HD. The average proportion of daily radiation emitted below the solar panel (FD and HD treatments) relative to the FS treatment varies with the growing season. In general, AVS is not recommended in crop rotation systems [41]. However, crop rotation could increase the production of agriculture in AVS farms [69], especially in regions that experience different seasons throughout the year [128]. Furthermore, when used in conjunction with permanent cultures—such as berries, bananas, or wine grapes—the cost of these types of applications is smaller, thus delivering increased efficiency through the optimization of techno-ecological synergies [41].

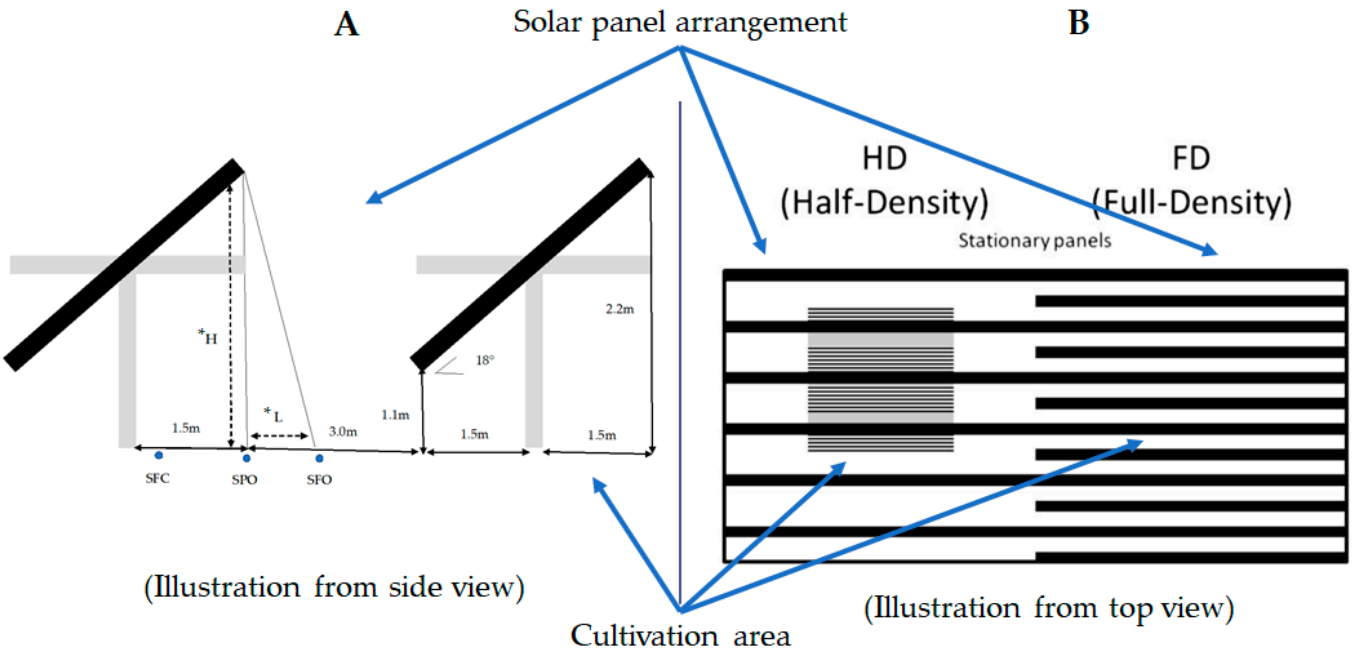


Figure 3. Schematic Drawing of Shade Zones. (**A**) SFO, SPO and SFC. (**B**) FD and HD. (Modified Figure 3A), source: [32]; The illustration 3(B), source: [4]). *H is object height and L is shadow length.

Next, the heat or thermal energy dissipated under the photovoltaic array is also a critical factor to consider in relation to the continuous development of the crops beneath [19,54,111,123]. In this case, the open field AVS is better than the closed greenhouse AVS [82], as its key characteristics are the mean daily reduction in light access for plants [28,38] without major changes in other microclimate parameters such as relative humidity, wind speed and direction, and soil moisture [26,84,132] at the level of the canopy [69,127]. If the AVS design were able to regulate adequate air circulation below the open structure, the air temperature, VPD [69], mean relative humidity, and wind speed [132] might be insignificantly different [98], or optimized [11], compared to the ambient surrounding; however, it depends on the structural design [21,54,62] and regions [10,103,115]. Enclosed structures, on the other hand, offer the advantage of being able to regulate the temperature inside the structure to meet the demands of the crop [91,103,126]. Furthermore, in a study conducted by [31], it was found that reduced light is not often harmful to crop quality, as improved Radiation Interception Efficiency (RIE) has been shown in the shade; however, a specific arrangement of the solar panel is needed to compromise between agriculture production and electricity generation in a way that can improve the production of both. However, solar management is not amenable to all types of crops, and there is a need for further research before an economically viable approachable system using PV technology can be designed [7,12,26,132,135].

There are several factors suggested by the author, based on reviews, to facilitate the crop selection for AVS: (1) the design of solar PV structure [8,54,62,63]; (2) the location of sub-treatments [6,69,132]; (3) the approaches of AVS [44,107]. For the first factor, types of design considered for solar PV structure have been described in Section 3. In case the introduction of agriculture production is on the existing solar farms or an unaltered solar panel structure, the approach used by [50] could be the sustainable solution to combine both productions. They suggested the planting of high-value herbal crops in solar farms with zero or minimal modification of the solar PV structure. The authenticity of growing herbal crops under solar photovoltaic arrays is justified by the sustainability and morphological aspect of the arrangement as a way of using unused land. For example, the maximum height of the Java Tea Plant (high-value herbal crops), which is less than three feet (from the ground) and grows in a regulated manner, is considered suitable and will not interfere with the PV panel electricity generation operation. The chosen plant is also classified as a shade-loving herb, and the temperature beneath the solar PV structure measured is within an acceptable range for ornamental herbal plants. The solar farm project's maintenance requirements are met by field arrangements of herbal polybags and a manual irrigation solution [59].

For the location of sub-treatments which are SFO, SPO and SFC [42,132], or FD and HD [4,6,18,69], a wide range of crops can be selected to be planted based on their physiological and morphological traits [4,28,71]. Besides that, the selection of suitable crops for AVS should also be identified based on local climate and weather conditions [5,12,21,28]. In general, shade-loving plants are best suited for planting in less sunlit areas, while sun-loving plants are better suited to seeding in sunlight areas [64,107,112]. For the arid region, such spices may be successfully grown between two rows of solar PV, as these are short in nature, for example: *Trigonella foenum-graecum* Linn. ('methi'), *Plantago ovata Forsk*. ('isabgol'), Coriandrum sativum Linn. (coriander or 'dhania'), etc [25]. The following vegetable crops may also be grown: *Brassica oleracea* var. botrytis (cauliflower), *Brassica oleracea* var. capitate (cabbage), *Allium cepa* Linn. (onion), *Allium sativum* (garlic), *Capsicum annum* Linn. (chilli), etc. [25]. The land area beneath photovoltaic panels can also be used to grow vegetable crops of the Cucurbitaceae family, such as *Cucurbita pepo* Linn. ('kakri'), *Lagenaria siceraria* ('lauki'), *Citrullus fistulosus* Stock ('tinda'), etc. [25]. Cultivating crops in areas below the photovoltaic panel has the added benefit of reducing the heat load on the bottom surface of the photovoltaic panel by modifying the microclimate and thus assisting in generating the maximum amount of electricity [21,50]. Additionally, [59] also proposed that herbs could be planted in tropic areas using AVS applications with minor modification of the solar panel structures. Herbal plants such as *Orthosiphon stamnieus* is suitable in the tropical region [50], while *Cassia angustifolia* (senna), Aloe vera ('gwarpatha'), and others may also be considered as potential crops if the PV structure is in rocky scrubs or degraded lands, depending on the region [25]. Next, some studies performed in various regions of the world indicate different kinds of crops, such as semi-arid pasture (Oregon, USA; [132]), Maize (Po Valley, Northern Italy; [53]), lettuce (short cycle crop), cucumbers (short cycle crop), durum wheat (long cycle crop) cultivated at Montpellier Experimental Agrivoltaic Station, France [6,31], and potato and wheat (Demeter-certified farm community Heggelbach, Germany; [41]). In addition, [5] stated that, in some regions, certain crops such as fruit trees (i.e., kiwi, apple, pear, cherry), berries (i.e., raspberries, blackberries), tomatoes, sweet peppers, coffee, and ginseng, are among the crops that are also able to cope with a reduction of more than 50% in the light source. Based on these findings, it is possible to conclude that the selection of suitable crops for integration into the AV system is subjective, depending on local weather and the architecture of the PV structure [8,28,33,87,103,136].

However, a suggestion from [107], as shown in the table below, to include the AVS approaches may be able to further facilitate the selection of suitable crops. The table illustrates how solar farms and crops can be combined according on the land-use type and AVS strategies. Next, several modifications of the solar PV structure and types of the crop cultivated will be recommended. For example, the suggestions for short crop planting area with agriculture centric approach are as follows: (1) plant mix of sun-loving and shade-tolerant crops, (2) raised solar PV structures, and (3) space solar PV structures. Other options are covered in Table 4.

Table 4. Opportunities for Solar PV and Agricultural Integration by Land-Use Type. (Source: [107]).

	Energy Centric	Agriculture Centric	Integrated Agriculture-Energy Centric
Grazing/ un-used/scrub/ desert land	• Leave native vegetation intact • Plant short shade-tolerant crops	• Leave native vegetation intact • Plant mix of sun-loving and shade-tolerant crops • Elevate solar PV structure • Space out solar PV structure • Continue/initiate grazing activities	• Leave native vegetation intact • Plant short shade-tolerant crops • Elevate solar PV structure • Continue/initiate grazing activities
Agriculture (short crop)	• Plant short shade-tolerant crops beneath and around solar PV structure	• Plant mix of sun-loving and shade-tolerant crops • Elevate solar PV structure • Space-out solar PV structure	• Plant mix of sun-loving and shade-tolerant crops • Elevate solar PV structure
Agriculture (tall crop)	• Limited options	• Plant mix of sun-loving and shade-tolerant crops • Elevate solar PV structure • Space out solar PV structure	• Place solar PV structure in non-utilized parts of agricultural land • Elevate solar PV structure

4.2. Agronomic Practices

Solar energy is the most plentiful and readily available source of energy [25,28,47,98]. The use of AVS technologies in areas where a solar farm and agriculture coexist [51,75,109] could have synergistic effects that aid in the production of ecosystem services such as crop production [9,20,38], local climate regulation [34,115,137], water conservation [13,18,56], and renewable energy production [21,87,138]; and it also aligns with food-energy-water (FEW) nexus [34,63,137].

Thus, the integration should potentially influence the microclimate and soil moisture [21,51,103]; hence, it may provide suitable environmental conditions [18,34,43] and increase the water-use efficiency for agricultural production [3,82,97] while maintaining the renewable energy production [41,44]. As mentioned in 2.1, the photosynthesis process requires light, carbon dioxide, and water to produce glucose as the source of energy for plants. If the sources of light and carbon dioxide are not limited, an optimum amount of irrigation water is needed to enhance the photosynthesis rate. Thus, regions with insufficient water resources are most likely to benefit as solar management decreases potential evapotranspiration (PET) and water demand [26,51,132,137]. The reducing amount of irrigation water needed without compromising crop-water requirements can make a significant contribution to reducing agricultural production costs, making the industry more competitive and sustainable [18,21,65]. However, a systematic or proper irrigation schedule is a must in AVS sites [82,139] to minimize the environmental impacts caused by excess water and leaching of subsequent agrichemicals [140] that might affect the structure of solar PV. Water-use efficiency can be improved [3,8,82] by understanding the concept of evaporation, evapotranspiration (ET), and irrigation water requirements [141]. ET is the mechanism by which water originates from a wide range of sources such as soil compartment and/or layer of vegetation and is transferred to the atmosphere [100]. Also, ET involves evaporation from bodies of surface water, surface of land, sublimation of snow and ice, plant transpiration, and intercepted canopy water [82]. Besides that, the evaporation process that happens also significantly reduces the percentage of soil moisture content [19,41,137]. On the other hand, irrigation water requirements are defined as the quantity of water necessary for crop growth [141,142]. In addition, the loss of electrical output due to dust accumulation on the panel surface as a result of agricultural management, such as tillage and harvesting, is also a source of concern [5,7,10,21]. In regions with low precipitation or long stretches of dry weather (e.g., monsoon climates), periodic cleaning of the module surface should be considered to prevent decreasing electricity yields due to dust accumulation [87]. This could be done by combining irrigation systems and PV cleaning to reduce increased water use [51]; however, without a small water distributor under the panels, it may result in inconsistent watering of crops [111]. Hence, proper assessment of evapotranspiration [139], soil moisture content [140], and PV cleaning processes [10,111] are needed before designing the irrigation system for agricultural production in AVS.

Another aspect is that extreme heterogeneity and spatial gradients in biomass production [5] and soil moisture [45,82] were observed as a result of the heterogeneous shade pattern of the PV array [132]. In the studies conducted at Montpellier Experimental Agrivoltaic Station by [4,6,18,69], the shadow effect of the PV array can be seen from the agricultural yield, where the HD structure produces more yield than the FD structure. The results show that, with the improvement of PV panel arrangement, LER may potentially exceed 1 [38,87]. Next, a solar tracker controller developed by [53] found that maize grown under the AVS plots tended to have more stabilized and higher yields in drought stressors and rainfed conditions. Besides that, crop selection can also reduce the effect of the heterogeneous shade pattern of the PV array [11,25,28]. This can be seen in the experiment conducted by [61] using Java Plant Tea in Malaysia. The result obtained shows a good agreement between the selected crop and the PV panels above them that act as their artificial shading. To sum up, acts to reduce the extreme heterogeneity and spatial gradients in agricultural production are: (1) optimize PV array placement to create a spatially uniform shadow pattern [4,10,75]; (2) improve the solar tracker controller that considers the need for solar radiation for both productions (electricity and agriculture) [53,91,101]; (3) select a suitable crop to be planted with a minimal light source (due to shading effect of solar PV structure) [25,54,87]. Besides that, as suggested by [5,112], the PV structure can be raised to reduce the heterogeneity effect, while allowing the conventional agricultural machines to pass [4,28,38], and reducing the back pain [68] while doing agricultural work due to low PV structure [95]. The gap between the pillars also needs to be suitable for planting distances and working widths of the machinery to avoid the loss of utilizable land [5,41]. Careful planning is essential, since the space required for the machine to pass might restrict the amount of land available for solar panels [19,68]. Also, ram protection should be installed to avoid collisions between agricultural machines and the solar PV pillars [68].

Other than that, the agronomic practices for agricultural production at AVS, likely similar to standard and common agronomic practices [62,126], include the steps listed in Figure 4. More information on standard practices can be found in documents such as the ones written by [143], which specifically address cropping systems and agronomic management. However, precision agriculture methods such as site-specific crop management (SSCM), for which decisions on resource application and agronomic procedures are being improvised, can be developed to better meet crop requirements based on soil heterogeneity in the field [33].

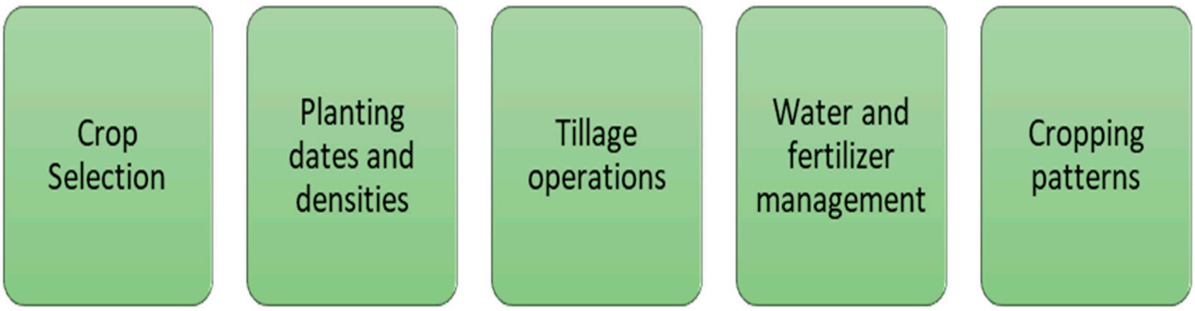


Figure 4. Common Agronomic Practices.

5. Outlook and Future Improvement

AV systems are still in their infancy, and there is plenty of room for technical advancements and expanded application fields [7,95]. This paper is focused more on technical improvements that can be made to the solar PV architecture and agronomic management to improve the AVS outputs. As already described in Section 2.1 to Section 2.3, there are several factors such as (1) competition against solar radiation between solar PV and crop; (2) AVS approaches; (3) public's acceptance of AVS applications (especially farmers). The issues related to the first factor can be minimized by properly designing the PV structure [6,31,54,62] and by efficiently managing the agricultural production [33,64,87]. In many cases, some alterations to PV architecture are required to balance the amount of solar radiation received by PV panels with the amount of light allowed to reach the crop beneath the solar structure [5,6,28,87]. Most importantly, future research should not overlook the fact that the photosynthesis process is primarily concerned with the Photosynthesis Active Radiation (PAR) range [49,83,128,129], whereas electrical energy is dependent on solar irradiance or light intensity [65,80,96]. Therefore, as a future study for AV system technology, we suggest some areas that are deemed intriguing to be investigated.

5.1. Guidelines for PV Architecture of Agrivoltaic System

Solar farms and agricultural production can be integrated in a variety of ways, with small to large impacts on solar energy and vegetation best practices [44,107]. Solar PV structure installations, at one extreme, can incorporate low-lying crops beneath the installation to mitigate environmental impacts without modifying existing site preparation activities [50]. On the other end of the spectrum, certain agricultural areas can incorporate solar PV technologies in ways that preserve crop production or harvesting techniques while also providing an additional source of electricity [54]. Between these two extremes, solar farm developers and agricultural producers have a variety of options for modifying system designs to allow for greater levels of integration [2,4,6]. The preliminary AVS studies suggested that solar farming and agricultural productions integration is only feasible when a fixed solar structure is used [6]. Numerous alterations and modifications can be made to optimize the AVS integration, including optimizing the spacing between panel rows, adjusting the height of mounted panels, configuring the solar panel density, and adjusting the tilt angle; however, all the works are subjected to the type of AVS developed [44,107], geographical condition, and crop growing season [25,45]. As no comprehensive guidelines and regulations exist for PV structure alterations for different climates at the moment, this allows for more research and testing on AVS technologies to take place [5].

5.2. Solar Tracker Improvement for Agrivoltaic System

Research conducted more recently has shown that solar trackers can also be sustainably used in AVS applications [4,18,53,101]. Based on the techniques used to control the movement of the PV panels, solar tracker systems are divided into passive, active [78,89], and chronological tracker systems [77]. However, previous studies indicate that the use of active solar trackers, as opposed to passive and chronological tracker systems, is gaining more traction either in mono PV systems [77,80,88,93] or in AV systems [5,8,30,53,101]. The integration of direct sun-tracking (ST) with agricultural production in previous studies conducted by [4,18] recorded an LER value of 1.5 and above, hence proving that the combinations effectively optimize the AV productions. The high LERs are mostly contributed by the PV production compared to agriculture production. Meanwhile, the use of a controlled-tracking (CT) system based on a tracking algorithm has been seen to be more reliable in creating an ingenious partnership between both parties in optimizing the productions of electricity and agriculture. The algorithm-based solar tracker pairing with a single-axis system [4,18,101] or dual-axis system [53] is acceptable in the AV system. The most important thing is that a customized and adaptable tracking algorithm should be developed to optimize light penetration beneath the solar structure for specific crops while maintaining a balance in energy production [53,101].

5.3. Guidelines for Agronomic Management of Agrivoltaic System

Generally, crops that can withstand a reduction in solar radiation should be chosen to be planted using the AV system [65,87,94]; however, previous studies show some reduction in agriculture yields depending on light penetration, crop growing season, and climate [5,28,87]. Even for shade-loving plants, the allowable light penetration should not be less than 50%; otherwise, the qualities of crop production could be significantly dampened [5]. In addition, according to [41], crop rotation systems are not recommended in AVS unless in conjunction with permanent cultures, due to cost efficiency. However, this recommendation should be validated because crop selection in some regions is different depending on crop growing season and climates. Moreover, efficient solar management has great potential to significantly improve land-use efficiency economically [17]. For the time being, there is not enough data on crop recommendation provided by the previous studies. Most of these studies evaluated the potential of the AV system by utilizing only one or a few crops in their research. Furthermore, fewer studies focus on water management [18,132], even though water management is one of three critical components of AVS [34,137]. The agronomic practices for AV systems are generally similar to common agronomic practices [62,126]; however, precision agricultural methods such as site-specific crop management (SSCM) may be created to better match crop requirements in the field depending on soil heterogeneity [33]. Also, a systematic or proper irrigation schedule is critical in AVS sites to minimize environmental impacts caused by excess water and subsequent agrichemical leaching [140] that could affect the solar PV structure. To summarize, the discussions above provide opportunities for additional in-depth research to: (1) create more comprehensive crop recommendation guidelines [28,31]; (2) improvise existing crop management that can be used in various AVS circumstances [33]; (3) develop a systematic irrigation system for AVS systems [18,25].

5.4. Farmer's Perspectives on Agrivoltaic System Design

The adoption of AVS technology is likely to face some challenges [14,28]. There is always a certain amount of public controversy accompanying the introduction of new technologies, and this should not be underestimated in AV systems [5]. The barriers to agrivoltaic adoption include the following: (1) a demand for long-term production to be guaranteed [109–111]; (2) market potential [2,9,44,46]; (3) fair compensation [38,44,52,112]; (4) a need for predesigned system flexibility to suit varied sizes, types of activities, and evolving agricultural methods [54,109]; (5) the identification of AVS approaches that are both economically beneficial and have no adverse environmental consequences to them [62,110,113]; (6) the design of photovoltaic infrastructure should promote reversibility [3]; (7) less promotional activities aimed at increasing public knowledge about AVS [10,11,15,110]. All these obstacles can be overcome with ongoing public education and strong political will on the part of the authorities to ensure the effective implementation of AVS projects [41]. These AVS technology acceptance factors may be less relevant to technical improvements of AV systems; however, farmers' perspectives and acceptance must also be considered before any improvements are made, because they are the end-users of this technology [44].

5.5. Food-Energy-Water Nexus in Agrovoltaic System

Based on the FEW nexus concepts, improvement of the AV system should account for food (agriculture), energy, and water management as interdependent aspects of the integration system [9,14,34,63]. As agricultural and water management are parts of agronomic management, future studies should emphasize the importance of both managements in a balanced manner [33,132,142]. Also, to advance our understanding of complex interactions between food (agriculture), energy, and water in the AVS system, we require a mathematical framework that can adjust in response to new data and incorporates a wide range of interactions, including natural processes and anthropogenic inputs to sustain resources for future generations [137].

6. Conclusions

The deployment of agrivoltaic systems provides a variety of benefits that vary according to geographic and climatic conditions. The real added advantage of the AVS approach is that it is applicable to agriculture and sustainable energy production, allowing a unique combination of short-synergic results to sustain resources and give economic benefit to the farmers. This is especially relevant in heavily populated developing and developed countries, where renewable energy development is becoming increasingly necessary; however, profitable farmland must be maintained. The performance of the AV system is determined using LER, and if the value exceeds 1, the system is said to be optimal. A good deal of care and attention needs to be paid to the architecture of the solar PV structure and agronomic management for AVS to succeed. For instance, relevant parties such as AVS developers, researchers, government officials, etc., should consider and understand the energy and agricultural production systems' reliance on light sources, the approaches of AVS production combinations, and the public' acceptance towards the system. Once these three factors are grasped, the additional features of the solar panel structure and agronomic management become apparent. However, it is important to periodically review the AVS application's capability and employ dynamic actions to further improve its effectiveness. For instance, structural alterations to solar panels used to be primarily focused on fixed structural design; however, now the advancements include the use of vertical bifacial photovoltaic (PV) technology, semi-transparent photovoltaic (SPTV), and solar tracking systems. The goal is to keep competition for solar radiation between solar PV and agriculture to a minimum while maximizing energy generation and agricultural production. As addressed in the FEW nexus concepts, the advancements of AVS technologies should not only focus on energy management, but also food (agriculture) and water management, as these three factors are nexus domains. Since the management of agriculture (crop) and water are parts of agronomic management, future enhancements should emphasize the importance of balancing the two. The agronomic management in AV systems that requires improvement includes crop selection recommendations, improved crop management guidelines, and a systematic irrigation system that minimizes environmental impacts caused by excess water and subsequent agrichemical leaching that could affect the solar PV structure. In conclusion, the advancements of AVS technology are expected to reduce reliance on non-renewable fuel sources and mitigate the effects of global warming, as well as addressing the food-energy-water nexus's demands.

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