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Review

Agrivoltaic, a Synergistic Co-Location of Agricultural and Energy Production in Perpetual Mutation: A Comprehensive Review

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Abstract: Agrivoltaic systems, which consist of the combination of energy production by means of photovoltaic systems and agricultural production in the same area, have emerged as a promising solution to the constraints related to the reduction in cultivated areas due to solar panels used in agricultural production systems. They also enable optimization of land use and reduction in conflicts over land access, in order to meet the increasing demand for agricultural products and energy resulting from rapid population growth. However, the selected installation configurations, such as elevation, spacing, tilt, and choice of panel technology used, can have a negative impact on agricultural and/or energy production. Thus, this paper addresses the need for a review that provides a clear explanation of agrivoltaics, including the factors that impact agricultural and energy production in agrivoltaic systems, types of panel configurations and technologies to optimize these systems, and a synthesis of modelling studies which have already been conducted in this area. Several studies have been carried out in this field to find the appropriate mounting height and spacing of the solar panels that optimize crop yields, as this later can be reduced by the shade created with the solar panels on the plants. It was reported that yields have been reduced by 62% to 3% for more than 80% of the tested crops. To this end, an optimization model can be developed to determine the optimal elevation, spacing, and tilt angle of the solar panels. This model would take into account factors that influence crop growth and yield, as well as factors that affect the performance of the photovoltaic system, with the goal of maximizing both crop yield and energy production.

Keywords: energy-water-agriculture nexus; agrivoltaics; combined model; optimization; arrangement; yields

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1. Introduction

Of all natural resources, water, energy, and food are the most essential to sustain life on earth [1,2]. Water, energy, and food share common challenges of limited accessibility, increasing global demand, and sustainability constraints [3]. Moreover, these essential resources are expected to face a significant surge in demand due to rapid population growth, in order to meet the basic needs of the population [4]. Indeed, according to UN projections, the world's population will increase from 8.5 billion in 2030 to 9.7 billion in 2050 and reach about 10.4 billion in the 2080s [5]. Moreover, according to the FAO [6], agricultural production will have to be doubled to meet demand in developing countries, while these countries will have to face constraints related to increased competition for access to water and energy and the impacts of climate change. To this end, it has been predicted that production needs to be increased by 60% [7] or even doubled to meet the population's needs in the face of population growth and changing diets [8]. The major constraints to agricultural development are related to access to water and energy for irrigation. Irrigation is the controlled delivery of water for agriculture through artificial systems to meet water needs not met by rainfall for crop growth and development [9]. Sophisticated and water-efficient irrigation techniques have significantly increased energy requirements. The energy cost required to operate these systems compromises the viability of many irrigation networks [10]. To this end, new perspectives have emerged, namely the use of renewable energy in irrigation systems as an alternative to pumping systems powered by fossil fuels [11,12], bearing in mind that the high cost of fuels and the lack of electricity, especially in rural areas, are factors that negatively affect the functioning of irrigation systems [13]. Solar PV panels are utilized due to their environmental benefits, cost-effectiveness, and ability to address issues of fossil fuel scarcity and unavailability in certain regions. The energy sector has seen significant and accelerated progress in terms of innovations observed with the use of renewable energy. A total of 20% of global energy consumption in the world comes from renewables, and about 30% of investment in renewables is in wind power and 60% in solar power [14].

Solar photovoltaic energy has emerged as an environmentally friendly and economically viable alternative with lower energy costs [9,13]. In addition, photovoltaic panels are among the leading renewable energy technologies in the world and have seen continuous decrease in costs over the years. It is predicted that 25% of the electricity needed in 2050 will come from solar PV, with a reduction of 4.9 Gt of CO_2 corresponding to a 21% decrease in emissions in the energy sector [15].

Nevertheless, using solar panels to pump water for irrigation can significantly reduce cultivated areas due to the space occupied by the solar panels [16]. One solution to this problem is, therefore, the adoption of agrivoltaic systems. These dual-use systems involve raising the PV panels to use the space under the panels for agricultural purposes [17]. Thus, this system reduces the issue of conflicts regarding land access [18,19]. Agrivoltaics can also significantly reduce the constraints on access to electricity for populations. According to Jamil et al. [20], agrivoltaic practices on only 1% of cultivated land can satisfy the energy demands of at least one-quarter of the population in Canada. However, solar panels installed in an area can impact microclimate, temperature, and solar radiation distribution, water, biodiversity, air quality, and ecosystem-energy balances [21,22]. Given the impact of solar panels on crops, several studies have investigated the optimal panel layout to maximize crop production in the presence of the panels. These studies have mainly focused on determining the height and spacing of the panels to create a suitable environment for crops under the panels. However, these arrangements were determined through studies that primarily focused on the irradiation received under the PV array and the resulting shading on the crops, with specific arrangements being tested [23–25]. Other studies have examined panel orientation through field experiments [26]. Kim et al. [27] worked on modeling the hybrid performance of an agrivoltaic system in South Korea. Their model focused on the variation of the amount of electricity generated and the crop yield obtained based on the incident radiation, as well as the impact of atmospheric conditions on the radiation. Three different shading ratios were tested to compare the levels of shading (21.3%, 25.6%, and 32%), with the shading ratio calculated as the panel area divided by the system area. A height of 5.42 m was used for all three tests and the shading rate was based on the density of the modules. However, there is still limited research and decision-making tools to determine the appropriate configuration for the crop being grown. Thus, modeling studies to determine the optimal height, spacing, and inclination of the panels to maximize growth and development for a given crop and the performance of the panels would help users to find the right configuration.

In order to achieve our purpose, this review focuses on a clear explanation of agrivoltaic systems and the functioning of its different components, as well as the factors that affect each of them. We believe that a large literature review will allow us to identify the most important parameters to consider for the design of the optimization model. The present paper will also summarize the studies carried out on the possible configurations of agrivoltaic systems, as well as the overall successes and failures of the arrangements and orientation.

2. Definition and Terminology

An agrivoltaic practice is a concept that originated in 1980 [23]. It is defined as a land-use concept that directly integrates solar energy production and agricultural activities, which are practiced under the photovoltaic field installation, both of which are highly dependent on sunlight [28]. Agrivoltaics has several names that vary according to region and application, such as "dual-use", "co-location", "agri-PV", "agri-solar", "solar sharing", "pollinator-friendly solar", etc. [29]. Indeed, it is a symbiotic relationship in which both activities interact directly and benefit from this co-location [30]. This practice leads to synergies by optimizing the potential offered by both production systems [31], especially in agroforestry systems [32].

Agrivoltaic practices can be carried out in different ways depending on the activities carried out by the population in a given area (Figure 1). Agrivoltaic applications represent the combination of energy production with (i) agricultural production in the field or (ii) agricultural production in greenhouses or livestock rearing, or (iii) provision of ecosystem services through vegetation management or (iv) different agricultural practices combined [29].

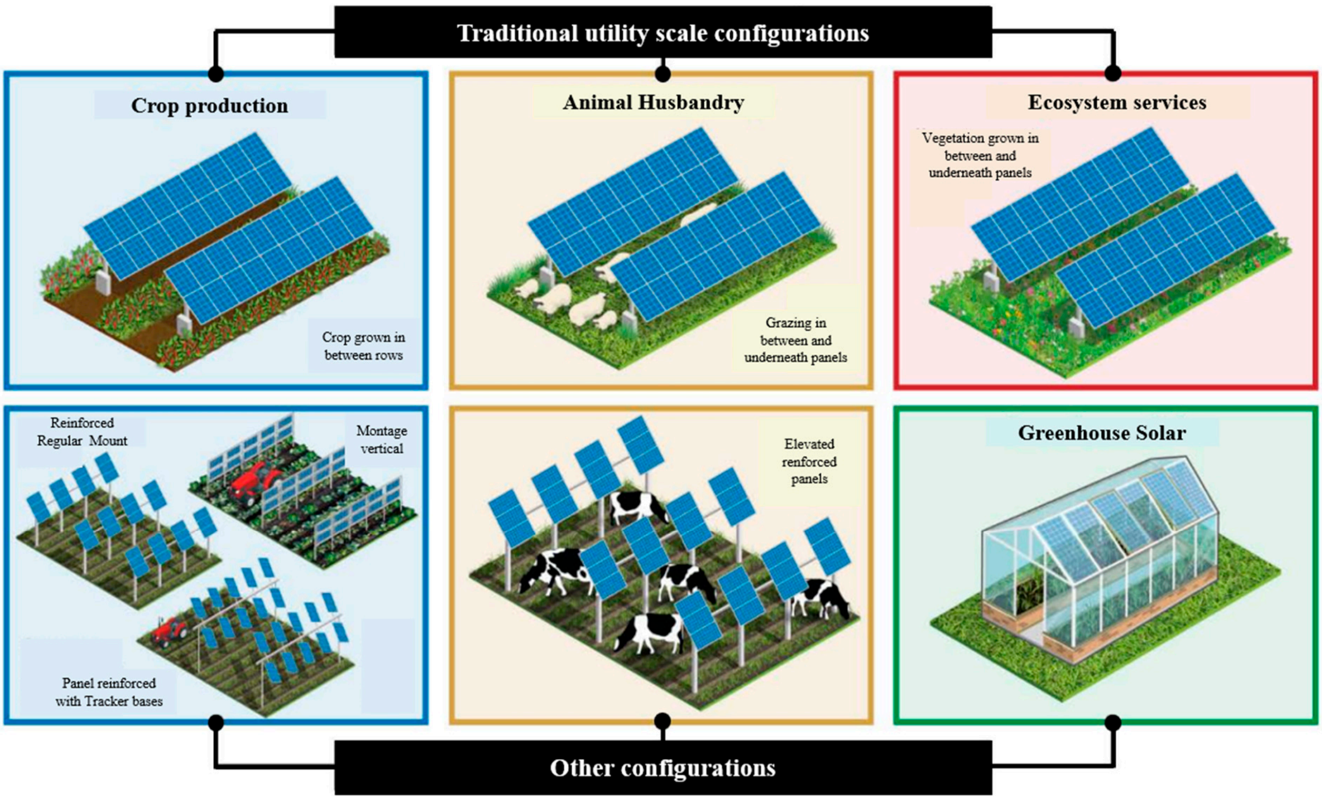

Figure 1. The different agrivoltaic systems [29].

Agrivoltaic technology has an important role in strengthening the water–energy–food relationship [33], given the increasing future need for energy and food production in the face of population demand [34]. Indeed, one of the constraints on the development of PV systems is the increased competition for land due to high population growth and rising food demand [35]. Although land resources are limited, the need for energy and food is increasing, leading to increased competition for land between the two sectors. In response to this growing competition, agrivoltaics was conceived to keep the two activities in balance [36]. Due to their dual use, agrivoltaics would mitigate competition for space and offers the possibility to install large PV systems, while keeping the land accessible for food production [37]. Thus, agrivoltaics system reduces land constraints concerning the placement of solar PV plants for electricity generation [38]. Moreover, this system has proven to be a particularly effective way to increase land use efficiency [32]. Land use efficiency is determined by the so-called parameter Land Equivalence Ratio (LER). The method of measuring land use in integrated agricultural and electricity production systems was originally derived from the intercropping method applied in the farming sector to increase land yield and total income [39]. The LER is a function of the area of the PV system and the total area needed to meet the agricultural and electricity production of the system [40]. Agrivoltaic systems can increase overall land productivity by 35–73%, thus they avoid using land solely for energy production at the expense of agricultural production [41]. According to Lee et al. [42] and Weselek et al. [31], agrivoltaics can increase land productivity by 60–70%, and for Dinesh and Pearce [38], it can increase the economic value of land by more than 30% by minimizing yield losses due to shading effects through appropriate crop selection. According to Trommsdorff et al. [43], land use efficiency varies depending on time and climate. In 2017, the Land Equivalence Ratio (LER) in Germany indicated an increase in land productivity from 56% to 70%, and this value reached 90% during the dry and hot summer of 2018. Abidin et al. [39] reported that applying agrivoltaics to less than 1% of the world's cultivated land could offset the global energy demand. Although agrivoltaics may reduce the efficiency of electricity generation or agriculture when viewed in isolation, studies have shown that the synergy between the two activities can lead to increased overall efficiency. For example, the combination of two hectares of land (1 ha of crops and 1 ha of solar panels each considered individually) corresponds to 100% of crops and 100% of solar energy. However, the use of agrivoltaics in two hectares of land corresponds to 160% cultivation and 160% energy (i.e., 80% of crop and 80% of energy in only 1 ha of land) [39].

As reported by Trommsdorff et al. [43], Formula 1 is used to calculate LER. However, Formula (2) can be used to take into account the high land loss due to the surface occupied by the mounting structure of the solar PV panels.

$$LER = \frac{Yeild_x(dual)}{Yeild_x(mono)} + \frac{Yeild_y(dual)}{Yeild_y(mono)} \tag{1}$$

$$LER = \frac{Yeild_x(dual)}{Yeild_x(mono)} + \frac{Yeild_y(dual)}{Yeild_y(mono)} - 8.3\% \tag{2}$$

x is the cultivated crop and y is the electricity.

3. Solar Panel Installation Techniques to Optimize Agrivoltaic Systems

3.1. Classification of the Different Agrivoltaic Installations

The module configurations in agrivoltaic systems can be categorized into elevated and inter-row systems. The modules are installed above the crop at more than 1.8 m in elevated systems. Growing crops under elevated solar panel installations typically leads to a decrease in the amount of solar radiation they receive, which can cause shading and reduced exposure to sunlight. The main crops used in this type of agrivoltaic system are grapes, small fruit trees, and delicate vegetables. In contrast, inter-row PV systems are systems in which agricultural production is usually carried out in the space between the rows of panels. The distance between two consecutive rows of the panels can be considerable in this type of installation to facilitate the passage of large agricultural machinery. The most common crops in inter-row solar systems are grasses, hardy vegetables, and higher-value horticultural crops [29]. The different configurations are established to compare their impact on the level of shading created by the panels and their consequences on crop yields to determine the optimal density for an agrivoltaic installation [44]. Another way to increase the efficiency of a PV system is to install double-sided PV panels [45]. Figure 2 summaries the different configurations.

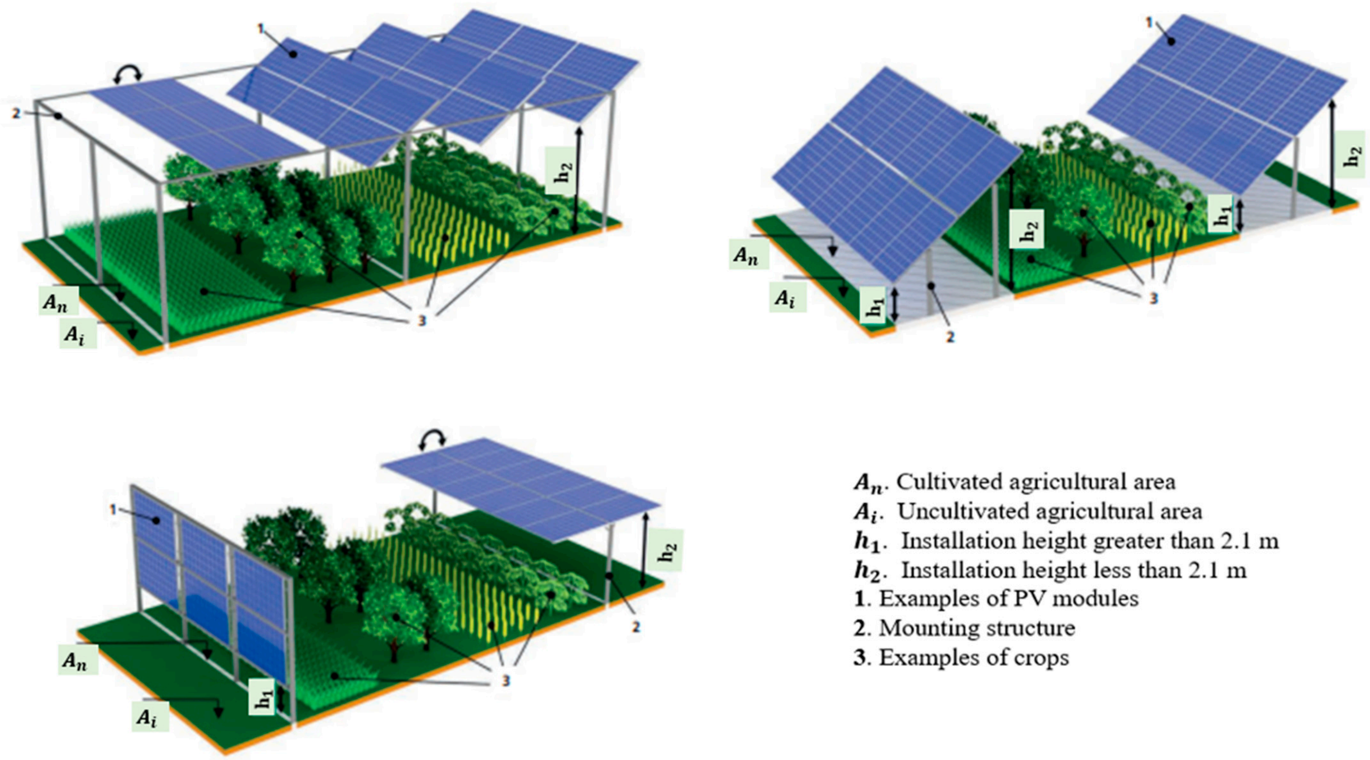

Figure 2. Overview of different configurations of agrivoltaic installations [44].

Several configurations and technologies have been developed and tested to optimize production in agrivoltaic systems. Therefore, the installation must meet the requirements of both the crop and the photovoltaic panels, which can be achieved by using optimal panel spacing and installation height that also allows the passage of agricultural machinery and appropriate panel technology [44]. Macknick et al. [46] have identified three types of approaches for the implementation of agrivoltaic systems: (i) the energy production approach, which focuses on optimizing the solar energy produced (thus minimizing changes in standard solar development practices), while cultivating between and/or under the panels, (ii) the agricultural production approach which focuses on optimizing biomass production (minimizing changes in existing vegetation management activities), while taking energy production into account, and (iii) the integrated agricultural and energy production approach (incorporating vegetation and energy priorities into system design).

These approaches are based on implementing one of the two installation techniques: open agrivoltaic systems, in which the PV module are installed at the ground level via support, and closed agrivoltaic systems, in which the modules are installed on greenhouses, thus serving as a cover [44]. However, only open agrivoltaic systems are considered in this paper. For this purpose, a general classification of the different agrivoltaic systems is proposed in Figure 3.

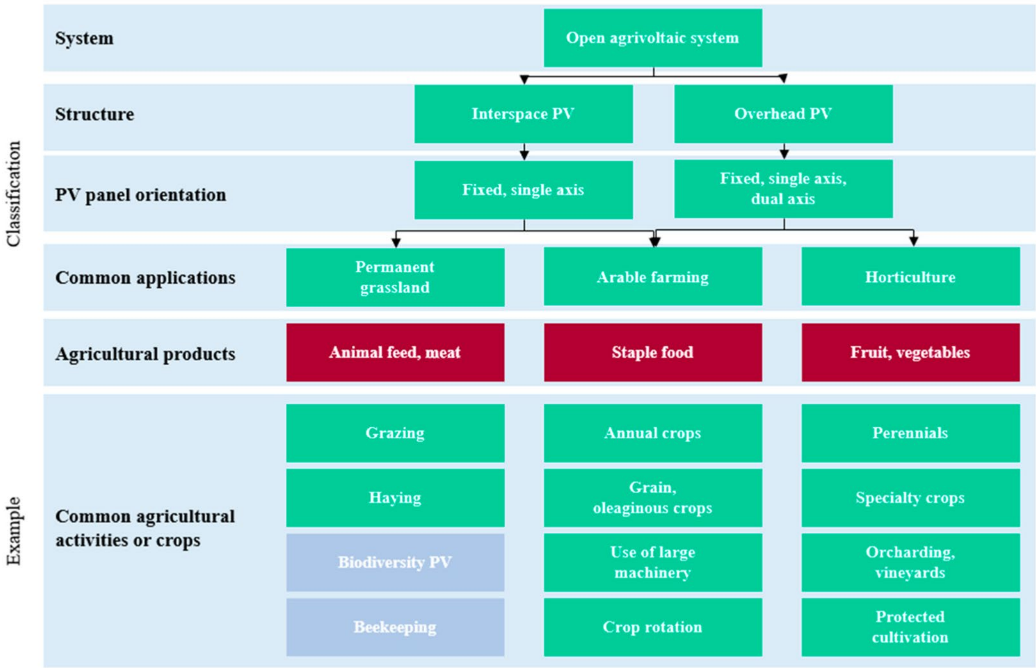

Figure 3. Summary of different agrivoltaic field systems [44,47].

3.2. Installation Techniques to Optimize the Agrivoltaic System

3.2.1. Mounting Height or Overhead of Agrivoltaic Systems Installation

The first agrivoltaic installation in the world was developed by Goetzberger and Zastrow at the Fraunhofer Institute (Germany) in 1980. It employed a height of 2 m and a spacing of 6 m between panel rows [23]. Since then, several studies have been carried out to determine the optimal elevation and spacing of solar photovoltaic modules to maximize energy and agricultural production. The ability of crops to grow and develop underneath PV modules raises structural issues in the case of aerial systems [44]. The height of the panels is an essential factor in the success of the various agrivoltaic practices. However, there are no recommendations for the panels' ideal height for an agrivoltaic installation. The height of the PV panels depends on several factors, including the geographical location of the site, the crop to be cultivated, the soil types, and financial resources. Thus, the height of the panels defines the crop to be grown on the site, the location of the crops in the systems (between the rows of panels or under the PV panels), and the equipment that can be used. Moreso, the solar panels installed in the agrivoltaic systems can have different configurations depending on the climate and soil to protect the structures from certain climatic hazards, namely high winds and freezing. For this purpose, a height of 1.8 m of the tubes supporting the PV panels is considered the minimum viable height for vegetable production under the panels. However, a tube height of 2.4 m is preferable for crops. This is because crops are grown between rows of panels at heights below 1.8 m, except for low-lying crops that appreciate shade. The elevation of the modules promotes a more even distribution of sunlight under the solar PV panels. In addition, these higher installations also allow the movement of equipment and people under the modules [29].

According to Trommsdorff et al. [44], overhead systems should be mounted at a minimum height of 2.1 m from the ground. In 2004, agrivoltaic systems started to be installed in Japan with installation heights of 3 m [31]. Dupraz et al. [24] used a 4 m elevation to assess the impact of this configuration on crop yields at Montpellier in 2010. This height was chosen to ensure access to large agricultural machinery on the site. In Germany, the impact of shading of the panels on crops was studied in 2016 by installing the PV panels at a distance of 5 m from the ground. In the USA, a 3.3 m high system was installed over the same period to assess the impact of agrivoltaic systems in arid environments [33]. Kim et al. [48] investigated the effect of agrivoltaic systems in South Korea using an elevation of 5.2 m. Several studies were undertaken involving a range of configurations of agrivoltaic systems on different crops [28,38,49–59]. In addition, standard heights of solar panels can be used for sheep grazing whereas higher panel heights are required for cattle grazing [29]. Figure 4 gives two example of elevated agrivoltaic installation.

Figure 4. (**a**) Panels installed at the height of 4 m in Montpellier © Dupraz, (**b**) Panels installed at the height of 5 m in Germany © Fraunhofer ISE [33].

For traditional industrial-scale solar installations, minimal spacing is required between rows to avoid the shading of one onto another, but spacing between PV modules of a same row is not necessary. For an open agrivoltaic system, the spacing between rows on the one hand and the spacing between modules in the same row on the other hand must be carefully determined according to the type of crop. A wide panel spacing increases the capacity and uniformity of solar radiation penetration to the crop, thus reducing the impact of shading from the panels. Spacings tested ranged from 0.2 m [29] to 6.4 m [50]. A typical image concerning the spacing between modules is depicted on Figure 5. The spacing between rows of panels increases the efficiency of elevated agrivoltaic systems (Figure 6). In addition to enhancing the uniformity of solar radiation distribution to the crops, this configuration also increases the number of crop rows under the panels, facilitates the movement of large farm machinery, and increases the space available for farm workers. The spacing between rows in the aerial systems tested in the field ranged from 0.71 m [55] to 9.5 m [58].

Figure 5. Panels spacing for an experiment in the USA [29].

Figure 6. Spacing between rows of panels allowing movement of farm machinery under the PV panels © Fraunhofer ISE [44].

Another method of optimizing elevated agrivoltaic systems is to use an optimal tilt angle and orientation to increase the yield of the solar panels and the crops grown under them (Figure 7). Various tilts and orientations have been tested for different locations for fixed installations. According to Trommsdorff et al. [44], solar tracking modules allow for more flexible light management under the panels. The process of tracking PV systems involves installing a mechanical system that can adjust the orientation and tilt of the modules at different times of the day, with the goal of optimizing energy production. Two categories of solar tracking systems are used: single-axis trackers and dual-axis trackers. In the first configuration, the PV module array tracks the sun horizontally according to its angle of incidence (altitude) or vertically according to its orbit (azimuth). The second configuration combines the two, producing a more significant amount of energy. These mobile systems optimize crop yields through greater light availability during critical growth periods. In addition, the flexibility of the tilt angle provides constructive protection against hail or extreme radiation by adjusting their orientation as required.

(**a**) (**b**)

Figure 7. (**a**) Single-axis solar tracker module [44] and (**b**) dual-axis solar tracker module [60].

One of the main constraints of installing aerial agrivoltaic systems is the high investment and maintenance cost. The wide spacing of the panels can create favorable conditions for crop growth and development, but it leads to a reduction in energy density due to the reduced number of panels installed on the plot. Also, the spacing between rows of panels can increase the investment cost in areas with high land costs and limited land availability [29]. However, these systems face shading constraints [33], so these installations are favorable for viticulture. Moreover, dual-axis systems with large arrays of PV modules can create shading under the panels, while other parts of the ground surface receive maximum sunlight [44].

3.2.2. Vertically Mounted Agrivoltaic Systems

The mounting of solar panels vertically to the ground is also a method of optimizing agrivoltaic systems (Figure 8). It consists of an installation technique in which the modules are oriented in the east–west direction, which has proved to be more efficient for permanent crops, or in the north–south direction, where energy production is a priority [61]. These systems require a significant distance between consecutive rows of vertical supports. For example, [62] studied vertical arrays using a 10 m spacing between the rows. A report by [26] showed that the yield of oats and potatoes decreased by 50% when the distance between rows was decreased in length from 20 to 5 m. In addition, [26] reported that 10% of the land near the panels does not have to be cultivated and can be used as ecological zones. Bifacial panels are widely used in these systems.

Figure 8. Vertical agrivoltaic installation with bifacial modules in Sued [62].

Vertical panels are favorable to crops as they allow a homogeneous distribution of sunlight, facilitate farm machinery movement, cleaning of solar panels, and access to crop rainwater. It is more economical, as it reduces the support cost, which is lower than that of aerial systems [39]. However, according to Katsikogiannis et al. [61], the constraint of its usage is the reduction in the electrical energy produced. Indeed, these systems allow for a 50% increase in LER and for a 33% reduction in electrical production compared to conventional single PV systems. According to Reagan and Kurtz [63], electrical production can be increased by 10–20% compared to traditional techniques by using a 2 m spacing between the supports, which results in a substantial reduction in crop yield [26].

Table 1 gives the strengths and weaknesses of the different installations.

Table 1. Summary of the strengths and weaknesses of the different installations.

Type of Installation	Strengths	Weakness
Inter-row systems	• Considerable space in this type of installation facilitates the passage of large agricultural machinery • Low investment cost	• Crop yield reduction due to uncultivated space

Table 1. *Cont.*

Type of Installation	Strengths	Weakness
Elevated systems with spacing between rows of panels	• Spacing between rows of panels and between panels enhance the uniformity of solar radiation • Can create crop protection in temperate zones • Crops under panels increase crop yields • Facilitates the movement of large farm machinery • Increases the space available for farm workers	• High investment and maintenance cost • Can create a shadow under the panels • Reduction in energy density due to the reduced number of panels installed
Tracking systems	• Greater light availability during critical growth periods • Constructive protection against hail or extreme radiation	• High investment and maintenance cost • Dual-axis systems with large arrays of PV modules can create irregular distribution of light to crops
Vertical mounting systems	• Homogeneous distribution of sunlight • Facilitate farm machinery movement • Cleaning of solar panels • Access to crop rainwater • Reduced cost of the installation structure • Increased electricity production for small distances between installation structures	• Reduction in agricultural production for small distances between installation structures (2 m) • Reduction in electricity production for large distances between the installation structures (20 m)

4. Factors Affecting the Operation of Photovoltaic Systems

Agrivoltaics relies mainly on the distribution of sunlight for photovoltaic energy production and photosynthesis. Therefore, the solar radiation spectrum is shared between the solar panels and the crops underneath [34]. Indeed, the principle of photovoltaics is the conversion of sunlight into direct current electricity. This production of electrical energy is the result of the absorption of photons from photovoltaic cells exposed to the sun, which in turn release free electrons to produce electrical energy [64–68]. Furthermore, the solar cell is the main component of the solar photovoltaic system [69].

Solar cells can be grouped into four generations based on the specific constituent elements and their periods. The first generation of PV cells is based on silicon wafer technology, including monocrystalline and polycrystalline cells [70]. The cells have an efficiency of between 18% and 20%, depending on the quality of the silicon used. However, according to Blakers et al. [71], the maximum efficiency reported for polycrystalline silicon cells could be as high as 26–27%. The theoretical maximum efficiency of monojunction silicon cells is around 30% and is called the Shockley–Queisser limit. The basic structure of these cells usually consists of a glass front and back cover, encapsulation layers, a solar cell matrix, and solder joints to electrically connect the individual cells [72]. Second-generation solar cells are thin-film cells that have a reduced maximum thickness of a few nanometers or tens of micrometers, compared to first-generation cells. This reduction in thickness helps to decrease the material usage and cost of silicon solar cells. These cells are made of two heterojunction layers squeezed between two contact layers. Efficiencies of 22.6% have been achieved with cadmium telluride (CdTe) thin films [73]. Third-generation cells consist of dye-sensitized solar cells (DSSCs), perovskite, and organic solar cells. DSSCs are limited by the synthesis of organic dyes and their chemical stability. For this reason, perovskite has been used as an alternative to DSSCs, and more than 21% efficiencies have been achieved in a very small area. The fourth-generation tandem solar cells are made of composite materials, consisting of polymers mixed with nanoparticles to have the properties of a single absorbing layer. The tandem solar cell is characterized by a top and bottom solar cell and an intermediate buffer layer. The upper GaAs cells absorb solar radiation, which is then transmitted to the Si of the lower cells [74]. The electrodes extract the generated charge carriers, and a photo-current flows through the thin buffer layer between the two solar cells [75]. The four generations mentioned are shown in Figure 9.

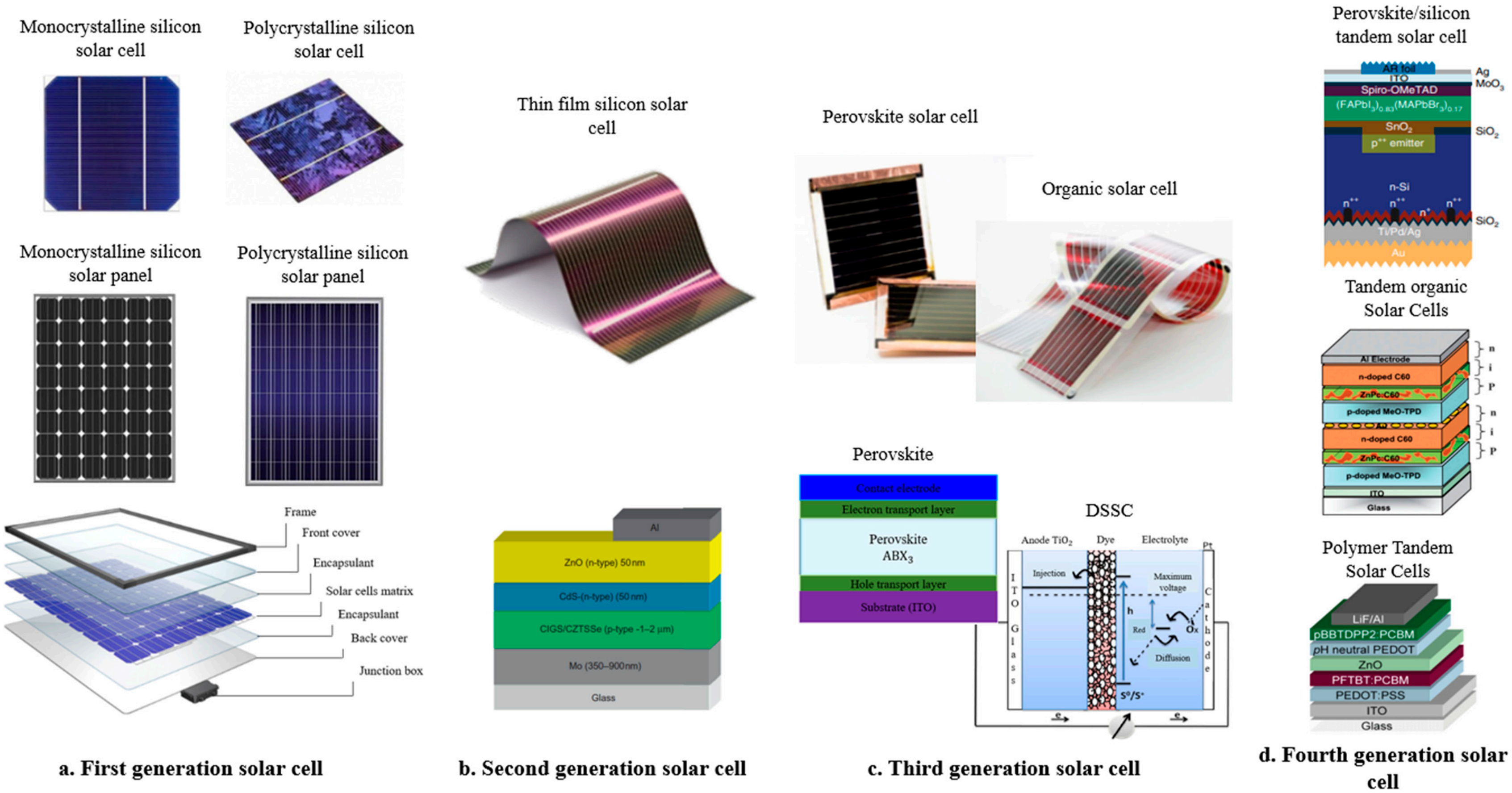

Figure 9. The four different generations of solar cells and their structures [74,76–80].

First-generation solar cells, namely monocrystalline and polycrystalline silicon-based cells, are the most commonly available in the commercial world [74]. According to Zhang et al. [76] and Rabanal-Arabach [77], 80–85% of the panels on the market belong to silicon technology.

In temperate regions with much sunshine, solar radiation is often too intense for some crops, especially in the summer. Shading screens are often installed in the systems to reduce the intensity of this radiation. These are semi-transparent solar panels [28,81,82]. Indeed, different opaque, transparent, and semi-transparent technologies are used in agrivoltaic systems and lead to different changes in sunlight availability throughout the day [29]. Bifacial panels are also widely used in agrivoltaic systems, as they use the light from the ground side (opposite side of the module) to generate electricity. Depending on the level of radiation on the back side, this can increase electricity production by up to 25% [44]. Agrivoltaic systems must be designed to grow appropriate vegetation depending on the available solar energy, soil, ambient climate, and other conditions. Therefore, the optimal conditions in agrivoltaic systems should be specific to the area where the system is implemented.

The PV module energy production mainly depends on the cells' temperature and the solar radiation. These parameters are related to the following factors: azimuth, tilt, latitude, solar declination, the slope, vertical shadow angle, hourly angle, zenith angle, elevation height, presence of vegetation at the bottom of the panels. The performance of a solar panel is determined by the amount of solar radiation it receives, whereas the temperature can create power losses (high temperature) or enhance the power (low temperature). The amount of solar radiation that the PV array receives changes depending on the geographical location, the sun's movement, the climatic conditions of the area, and the orientation of the panels [83]. Ideally, a photovoltaic installation should have the incident solar flux perpendicular to the array surface to maximize the panels' energy potential [84,85]. Thus, the optimal orientation must be determined due to the perpetual movements of the sun.

The orientation of the panels is determined through two parameters i.e., the azimuth and the tilt. The movement of the sun is a function of its elevation which depends on two parameters, namely the latitude and the solar declination. Furthermore, according to Jafarkazemi and Saadabadi [86], the azimuth angle of the surface, latitude, time of day, slope or tilt angle, day of the year, and incident radiation angle determine the amount of solar radiation received by the PV panels installed on a given area (Figure 10).

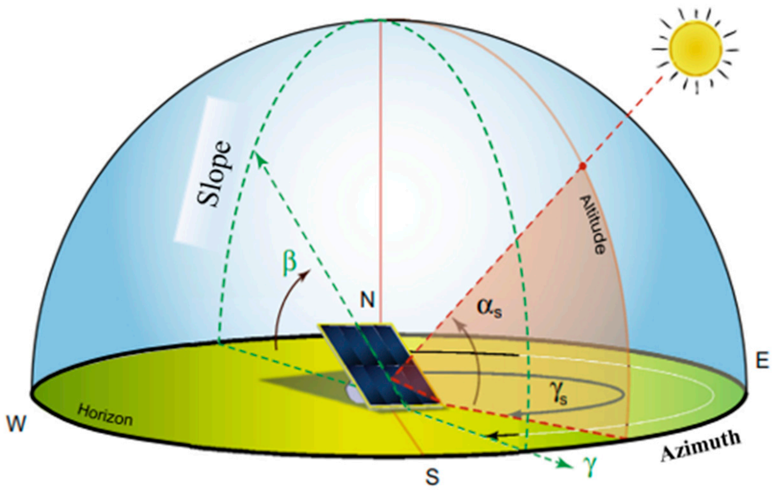

Figure 10. Factors affecting the performance of solar PV panels [87].

In particular, the electrical energy resulting from the transformation of the solar energy absorbed by the panels is strictly related to the slope (the tilt angle) and the azimuth angle [88]. The tilt angle (elevation angle) represents the angle formed by the horizontal plane of the installation and the PV panels for a fixed structure [85,89]. A change in the tilt angle simultaneously leads to a change in the amount of radiation reaching the surface of the PV panels [89]. However, as a general rule, the tilt angle for a PV array installation is nearly equivalent to the latitude of the area [90,91]. The solar azimuth is the horizontal angle between the vertical plane normal to the surface and the vertical plane in which the center of the solar disc is contained, oriented in the north–south direction [91]. For this purpose, the azimuth values of 90°, 0°, +90°, 180° correspond to the positions east, south, west, and north of the panels, respectively [85,92]. Thus, the panels are oriented to the north in the southern hemisphere and the south in the northern hemisphere [93].

Other parameters that can likely affect the performance of photovoltaic modules are (i) the albedo, which is the amount of radiation reflected from the ground surface across the solar spectrum and (ii) the vertical shadow angle, sometimes referred to as the vertical profile angle, which is the direction in degrees of rotation of the center of the solar disc [91]. To these parameters, Oudrane et al. [94] and Nfaoui and El-Hami [95] added the hourly angle, which is a function of the daily spinning of the earth with respect to its axis, and the declination, which is the angle between the "center of the earth-sun" vector and the equatorial surface of the earth. Yilmaz et al. [96] considered in addition to these parameters the zenith angle which is the angle between the sun's direction and the vertical of the location.

In addition, the elevation height and the occupation of the surface where the PV array is installed can have an impact. These factors have been highlighted by Chemisana and Lamnatou [97], Ogaili and Sailor [98], Alshayeb and Chang [99], and Osma-Pinto and Ordóñez-Plata [100]. They evaluated the electrical energy generated by a photovoltaic array on rooftops using different elevations and different ground level supports. According to Alshayeb and Chang [99], the presence of vegetation at the bottom of the panels can be advantageous, resulting in an increase of 0.25 to 0.4% in the efficiency of the solar panels when the panels are installed at the height of 50 to 75 cm from the roof [100]. According to Chemisana and Lamnatou [97], vegetation below the panels leads to a decrease in ambient temperature that can cause an increase of 1.29–3.33% in the maximum power output of the PV array. Furthermore, Ogaili and Sailor [98] showed that the presence of vegetation could cause an increase in the energy output of 0.8% to 1.2% compared to a white or black colored substrate, respectively, when the panels were elevated at 18 cm from the roof.

5. Impact of Agrivoltaic Systems on Crops

5.1. Importance of Solar Radiation on the Process of Photosynthesis

Sunlight is the key factor in photosynthesis. Photosynthesis consists of the production of oxygen and glucose that crops can use for growth and development [101,102] as a result of the reaction between water and carbon dioxide absorbed through the stomata, which are small holes in the lower epidermis, and controlled by sunlight [103]. Equation (3) is a summary of the photosynthetic reaction.

$$6H_2O + 6CO_2 \overset{Solar\ energy}{\rightarrow} C_6H_{12}O_6 + 6O_2 \tag{3}$$

$$\Delta_r G^{o'} = +2870\ \mathrm{kJ/mol}, \Delta_r G^{o} = +2875\ \mathrm{kJ/mol} = \Delta_r G^{O''} \tag{4}$$

Photosynthesis can be broken down into two stages. The first step, called the light reaction, consists of the absorption of sunlight by the chlorophyll pigments [104], resulting in the production of electrons and protons, which are responsible for the production of adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH) at the thylakoid membrane [103]. The second step is the dark reaction in which NADPH and ATP generated in the light reaction is used to produce carbohydrate from CO_2 through the Calvin–Benson cycle in the chloroplast stroma [104–106]. Figure 11 gives an overview of the importance of light in the process of photosynthesis.

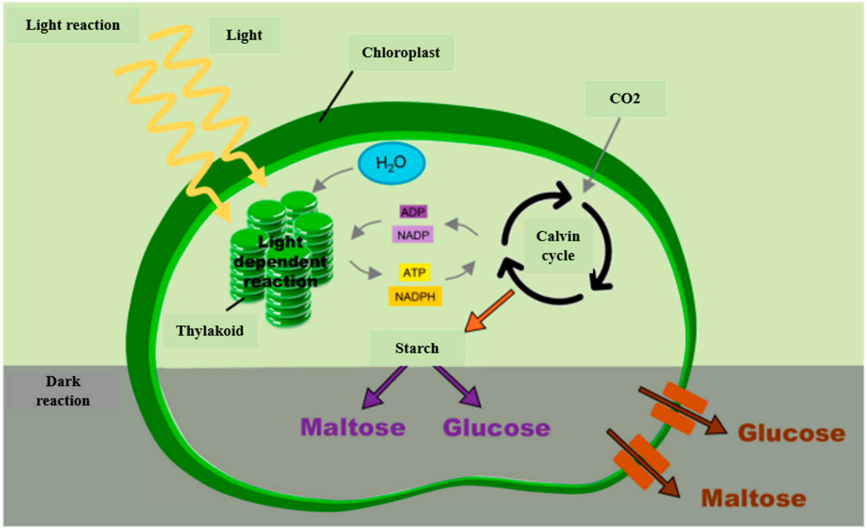

Figure 11. The overall process of photosynthesis at the chloroplast level [107].

Chlorophylls are the primary pigments in crop cells that absorb sunlight in the blue (450 nm) and red (650 nm) wavelengths and give the crop its green color. However, there are other pigments in crop cells, namely carotenoids, which absorb blue light and give the leaves their yellow color. Furthermore, the excitation of ions in the process of photosynthesis is driven by the absorption of specific wavelengths of light in the visible range [103], as shown in Figure 12.

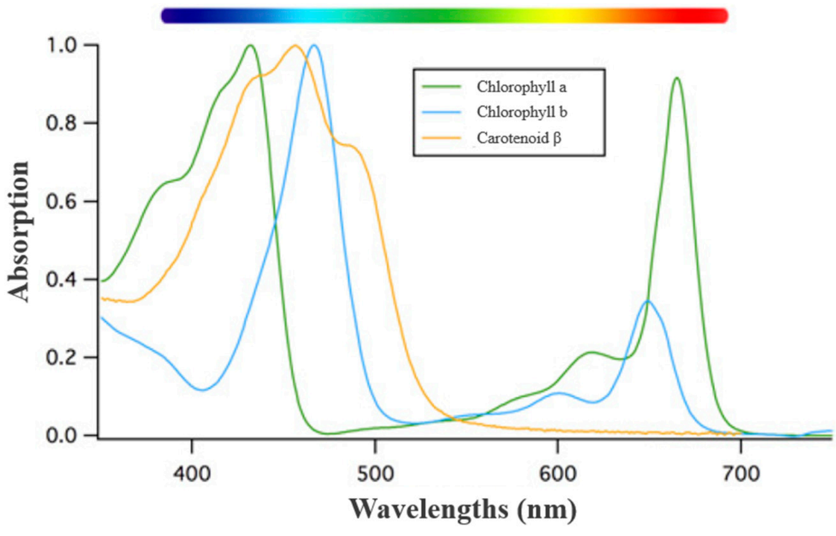

Figure 12. Basic absorption spectra of crops' main chlorophyll and carotenoid pigments [103].

Indeed, wavelengths from 430 to 500 nm are effective in chloroplast development and photosynthetic function [106,108]. In addition to promoting photosynthetic activity, wavelengths from 640 to 670 nm are necessary for leaf growth and crop biomass production [106,109]. Furthermore, according to Wang and Folta [110], the wavelengths 500–600 nm are of great importance in chlorophyll content, photosynthetic function, and consequently crop growth.

This part of the solar radiation of wavelength 400–700 nm is called photosynthetically active radiation and represents the part of solar radiation mainly used for photosynthesis [111,112]. However, the total proportion of solar energy in the photosynthetically active band represents only 48.7% of the average solar spectrum measured at the Earth's surface. At the same time, the chlorophyll pigment is considered as an imperfect radiation absorber in the 400–700 nm band because it weakly absorbs solar radiation in the green band. Therefore, it is estimated that 90% of the radiation is photosynthetically absorbed by vegetation, and 10% is reflected [113]. According to Amthor [114], the solar radiation intercepted at the Earth's surface depends on the area's location, the presence or absence of clouds in the sky, and the sun's elevation. In addition, the fraction of incident solar radiation intercepted by crops is a function of leaf area and orientation. Furthermore, the total photosynthetically active radiation absorbed by chlorophyll pigments for a crop that has reached whole leaf area development is estimated at 92%.

5.2. Factors That Can Affect Crop Growth in Agrivoltaic Systems

Agrivoltaic systems are systems in which crops are grown, considering factors that may affect crop growth, including the level of shade, climatic factors, and water consumption [115].

Access to the limited amount of sunlight needed for the photosynthetic process is the main challenge for crop productivity under PV panels [24,116], as sunlight is the key factor playing a significant role in crop growth and development [117].

Touil et al. [118] reported that PV panels can cause a reduction of over 40% in the amount of solar radiation received by crops. A coverage rate of 50% or more can also hinder crop growth. For example, a panel-induced shading level of 50% led to a decrease in crop height and stalk diameter, and a decrease in net leaf photosynthesis rate, leaf specific weight, dry matter accumulation on leaves and stalks, and grain number of maize. To this end, the optimal level of shading to ensure energy requirements for photosynthesis consists of a level of photosynthetic photon flux density capable of both saturating CO_2 assimilation and favoring the stabilization of shading conditions and reducing photoinhibition [24].

Nevertheless, the shading induced by the photovoltaic field can be beneficial by reducing the amount of water lost through evaporation and therefore increasing water use efficiency [119]. To this end, these devices are favorable in drought-prone areas during hot periods, as they reduce crop water demands due to reduced evapotranspiration [38,53,54,120]. According to Yue et al. [121], agrivoltaic systems can increase soil moisture by 14.7% for fixed installations and 11.1% for mobile installations. Moreover, based on a study conducted by Adeh et al. [52], panels in agrivoltaic systems allow for more efficient water use (estimated at 328%) by maintaining higher soil moisture levels compared to soil moisture in a full-sun growing area. Barron-Gafford et al. [54] showed that the positive effect of agrivoltaic systems on water conservation is exacerbated by applying water to the crops based on a two-day irrigation frequency that maintains 15% higher soil moisture compared to the soil under full sun. However, although soil moisture remained higher under the panels, it was reduced by 10% based on a daily application of the crop's water requirements. Furthermore, studies conducted in dryland environments on the impact of agrivoltaic systems on specific crops showed that water use efficiency under the panels was estimated at 157%, 65%, and 12% for chili, tomato, and lettuce, respectively, for a 4 m panel elevation [50,118]. Furthermore, a simulation study by Elamri et al. [40] showed a reduction of less than 20% in the water requirement of lettuce as a result of the effect of panel shading.

The shading caused by the panels and the increase in soil moisture affects the microclimate of the area cultivated under the panels. Adeh et al. [52] established that the elevation of the PV panels by 1.2 to 2 m causes a considerable change in air temperature, relative humidity, and wind speed on the surfaces near the PV panels. In a study conducted in the USA on tomato cultivation, it was observed that the air temperature varied between 21.5 °C and 22.3 °C in the subplots cultivated in the open air, whereas it decreased to 19.8 °C under the panels (for an elevation of 2.2 m and a tilt angle of 18°). The rows had the highest average relative humidity at 79.38%, followed by sub-plots cultivated in the open air at 74.63%, and sub-plots located under the panels had an estimated humidity of 73.54%. The soil temperature was estimated to be 20 °C, 24.7 °C, and 25.6 °C under the PV panels, between the panel rows and the control, respectively. In addition, the wind speed was lower (0.65 m/s) between the rows of panels, whereas it was 0.89 m/s in the open field [119]. According to Noor and Reeza [122], the microclimate under the panels varies differently depending on the area's climate and the land's topography. Their study in the tropics showed that the air temperature was the same in the open field and the higher and middle areas under the panels. However, it was higher in the areas of lower topography under the PV panels. Regarding relative humidity, these studies showed that relative humidity was higher under the PV panels, estimated at 65%, compared to 63.7% between the rows of PV panels and 53.5% in full sun.

The panels reduced the average soil temperature of 5.2 °C in summer with a minimum of 3.5 °C and a maximum of 7.6 °C, and an increase of 1.7 in winter in the UK [21,121]. Abu-Hamdeh [123] showed that the soil temperature under the panels recorded a decrease of 3.1 °C in arid zones and 1.1 in equatorial and temperate zones. Moreso, the soil temperature can vary depending on the installation technology. For example, the ground temperature under fixed panels was found to be lower than under mobile panels since the radiation intercepted by the panels is higher for mobile technologies [51,121]. Weinstock and Appelbaum [124] showed that agrivoltaic systems can lead to a reduction in soil temperature of 4 °C for fixed and 1.5 °C for mobile installations.

5.3. Impact of Solar Panels on Crops

The success of production in agrivoltaic systems is highly dependent on the choice of crops to be grown. Crops grown under PV panels are often subject to different climatic conditions than those grown in full sun because of the shading created by the solar panels. Furthermore, crops of different varieties of the same species may respond differently under the same conditions [29]. For this purpose, the impact of agrivoltaic systems on crops is summarized in Table 2, considering different crops and locations.

Table 2. Impact of photovoltaic panels on different crops in different localities.

Crops	Study Area	Height and/or Spacing or Shading Rate	Impact on Culture	Sources
Durum wheat	Montpelier, France	Height of 4 m Spacing 1.64 m (distance between the lower side of two consecutive panels) Tilt of 25°	• 11–29% reduction in dry matter • 8 to 11% reduction in yield	[24]
Lettuce and cucumber	Montpelier, France	Height of 4 m Tilt of 25°	• Reduction of evapotranspiration by 62% and 70% for lettuce and 73% to 81% for cucumber • Crop cover was significantly higher in the shaded treatments (150% between days 124 and 144)	[50]
Lettuce	Montpelier, France	Height of 4 m Two spacings: 1.6 m in full density and 3.2 m between rows in half density Tilt of 25°	• Crop axis under PV panels was 7.4 cm with 2.0 g dry matter per axis compared to 6.6 cm and 2.5 g per axis in full sun • Significantly reduced number of leaves in the shade • Increased leaf area	[49]
Lettuce	Kansas, USA state	Height of 4 m Two spacings: 6.4 m in half density and 3.2 m between rows in full density	• 42% reduction in yields for the 3.2 m spacing and 19% for the 6.4 m spacing in summer • No impact on yield for the 6.4 m spacing in spring but 21% reduction for the 3.2 m spacing	[38]

Table 2. *Cont.*

Crops	Study Area	Height and/or Spacing or Shading Rate	Impact on Culture	Sources
Chili and tomato	Tucson, USA	Height of 3.3 m above the soil surface at their lowest point Spacing of 1 m Tilt of 32°	• For Capsicum annuum var. glabriusculum, production is three times higher under the panels • For C. annuum var. annuum, there is no impact • For S. lycopersicum var. cerasiforme, production is two times higher under the panels	[54]
Maize	Chiba Prefecture, Japan	Height of 2.7 m Two row spacings: 0.71 m for high-density and 1.67 m for low-density Tilt of 30°	• Yields of 3.54 kg/m^2, 3.35 kg/m^2 and 3.23 kg/m^2 at a distance of 1.67 m in full sun and at a distance of 0.71 m, respectively	[55]
Grape	Ongjin-Gun, Republic of Korea	Height of 2 m Tilt of 15° Shading level of 30 of the total roof area	• Germination period, number of flowers and grape growth are identical in all treatments	[56]
Basil and spinach	Italy	-	• Reduction in marketable biomass yield by 15% and 26% for basil and spinach, respectively	[28]
Sesame, mung bean, kidney bean, corn and soybean	Jeollanam-do, South Korea	Height of 5.42 m Shading rates of 32%, 25.6% and 21.3%	• Yield reductions for all crops except maize at 21.3% shade • At 21.3%, yields increased by 6% for maize and decreased by 7%, 13%, 21% and 26% for sesame, soybean, mung bean and kidney bean, respectively • At 25.6%, yield reduction of 14% for sesame and 35–44% for beans • At 32%, yield reduction of 53% for sesame and 30–44% for other crops	[48]
Oilseed rape, onion, faba bean and forage maize in rotation with potato melon, carrot, onion and dry pea in rotation with tomato	Sevilla, Spain	Height of 5 m Spacing of 9.5 m between suppoted structure Tilt of 27°	• Reduction in crop yields under shade following a correlation of studies already carried out on the effect of shade on the area (reduction of 10%, 7%, 17%, 6%, 20%, 23%, 15% and 5% for carrot, maize, melon, onion, rape, potato, dry pea and tomato, respectively)	[58]
Celery	Southwest Germany	Row distance: 9.5 m (2.8 times module row width)Height (free space in the direction of the work/top edge): 5.5 m/8 m	• Crop height was 30.6% and 14% higher under panels in 2018 and 2017, respectively • Dry matter yield of above-ground biomass was 48% and 31.9% higher under panels • Bulb yield decreased by 18.9% in 2017 and increased by 11.8% in 2018	[59]

Table 2. *Cont.*

Crops	Study Area	Height and/or Spacing or Shading Rate	Impact on Culture	Sources
Red beet, winter wheat, potato and red clover	Southwest Germany	Height of 5 mSpacing of 6.3 mTilt of 20°	• Increase in crop height for all crops • Between 2017 and 2018: −19 to +3% for winter wheat, −20 to +11% for potato and −8 to −5% for red clover and	[125]
Rice, onion, garlic, rye, soybean, bean, maize, forage crop	South Korea	Height of 3.3 mSpacing of 1.5 mShading rate of 30%	• For rice, stem height was 3.8 cm higher under the panels and yields decreased by 18.7% in 2018 and 8.9% in 2019 • For soybeans and beans, yields decreased by 68.7% and 73.3%, respectively • For garlic and onions, yields decreased by 18.7% and 14.6%, respectively • For fodder crops, the height was 7.4 m higher under the panels, nevertheless the yield decreased by 3.1 t/ha	[126]
Rice, potato, sesame, and soybean	South Korea	Height between 4 m and 4.5 m	• No impact on growth except for sesame (lower stem length, number of branches and 1000 seed weight) • Yield reduction of 3% for potato, 19% for sesame, 18–20% for soybean and 13–30% for rice	[42]
Soybean	Monticelli d'Ongina, Italy	Height of 4 to 4.5 mSpacing between rows of trackers of panels of 12 mfour treatments: 27%, 16%, 9% and 18% shading	• Crop height of 98.25 cm at 27%, 90.81 cm at 18%; 86.95 cm at 16% and 85.04 cm at 9% shade under panels and 87.8 cm in full sun • Number of pods reduced by 19.4% at 27% shade and 18.2% at 18% shade compared to treatments with 16% or less shade • Grain yield reduced by 8%, 4.6% and 11.8% for 27%, 9% and 18% shade respectively compared to full sun versus 4.4% increase for 16% shade	[127]

6. Influence of Agrivoltaics Systems on PV Module Performance

Few studies have focused the impact of agrivoltaic systems on the performance of solar panels. This is because crops are most affected by these types of installations. However, Table 3 gives an overview of some of the advantages and disadvantages of these installations on solar panels highlighted by some authors.

Table 3. Impacts of agrivoltaic systems on the performance of solar PV panels.

Advantages/Disadvantages	Description	Source
Advantages on PV panel	Increase energy production due to increased area through the LER	[39,117]
	Decrease in temperature of solar panels could be achieved by using agricultural moisture, evaporation from agricultural activities, and transpiration from crops which results in the increase in electricity generation	[128]
	PV panels in agrivoltaic systems can generate between 3.05% and 3.2% more energy compared to PV installations without cultivated crops	[129]
	Decrease in ambient temperature can cause an increase of 1.29–3.33% in the maximum power output of the PV array	[97]
	The presence of surface green due to vegetation at the bottom of the panels can results in an increase of 0.25 to 0.4% in the efficiency of the solar panels	[99]
Disadvantages on PV panel	Agrivoltaic can reduce the efficiency of electricity generation or agriculture when taken separately	[39]
	Decrease in the electricity produced with the reduction in the density of solar PV panels	[38,48,55]

7. Models Already Developed in the Agrivoltaic Field

One of the first models developed to optimize agrivoltaics was carried out in Montpelier by [24]. This is a model for intercepting the radiation available on the panels (developed on R software) and simulating the crop's development (generic crop model STICS). The light interception model calculates the daily radiation at any point on the ground using a ray-tracing algorithm. The crop simulation model was used to predict the behavior of crops under the panels. For the light simulation, ray tracing algorithm was used to make the simulation. The daily direct and diffuse radiation quantity striking any point of the ground below the array consisted of the output.

The authors of [38] utilized the STICS model, which comprises four primary modules. These modules include the crop growth module, soil interaction module, crop management module, and microclimate module. The crop model determines the effects of climate and soil moisture content on the immediate microclimate surrounding the crops. Indeed, they set up a solar PV system model and a crop model to optimize the performance of the agrivoltaic system. In their PV model, they formulated an optimization problem whose objective was to maximize the incident solar irradiance on the PV, while considering the additional land cost due to minimizing inter-row shading. They proposed to reduce panel density or use semi-transparent panels to reduce the effects of shading. In order to optimize the geometry of an agrivoltaic system, the crop, solar irradiance, mounting height, environmental climate, and tilt angle are crucial. The module production model was developed on PVsyst.

The use of the STICS model is advantageous because it allows the assessment of the impact of the configuration of a given agrivoltaic installation on crop growth. Therefore, real data from field experiments are required to use the model.

Amaducci et al. [120] had developed a software platform on Scilab by coupling the radiation and shading model to the generic crop growth simulator (GECROS). The GECROS crop model predicts crop biomass and yields as a function of climatic factors such as radiation, temperature, wind speed, and partial vapor pressure, as well as the amount of water and nitrogen available in the soil. Regarding the shading radiation model, it consisted of calculating direct and diffuse radiation at ground level with a time step ts = 0.5 h and a spatial resolution of 0.12 m by developing a procedure to calculate whether a portion of soil that is shaded or that receives direct radiation. This study was conducted using a tracking system.

Malu et al. [130] carried out agrivoltaic system modeling to study the electrical performance of agrivoltaic systems when combining grape and energy production in the Nashik

District of Maharashtra State in India using the National Renewable Energy Lab's System Advisory Model (SAM) version 2014.1.14, which uses weather data, location of the study area, PV array size, DC/AC ratio, azimuth angle, required axis type, and tilt angle. Inputs data consist of the weather data, the ratio of DC to AC power, the azimuth angle, the tilt angle, the type of axis required, the size of the system array, and the tilt angle. However, the study focused more on energy production.

Elamri et al. [40] investigated the variations of water in soil and the productivity of crops under PV panels. For this purpose, they used a model called "AVirrig" adapted based on the existing "Optirrig" model. Optirrig was built to generate and optimize irrigation scenarios that operate at a daily time step. The inputs used in this model are rainfall, radiation, air temperature, reference evapotranspiration, soil water reserves, leaf area index, dry matter, and crop yield. "AVirrig", which also includes the "AVrain" model that describes the redistribution of rainfall by solar panels depending on the method of panel installation, consists of a reservoir model that assumes the presence of three water reserves in the soil. This is a specific adaptation of "Optirrig" for AV installations that take into account the fluctuation of the shadow created by the PV modules. In opposition to Malu et al. [130], this study focused more on agricultural production.

Similar to Amaducci et al. [120], Potenza et al. [127], performed modeling to optimize the growth of crops under panels in Italy by coupling the GECROS crop growth model with a set of algorithms to estimate and specialized shading, radiation, and crop-related parameters. The system simulates the entire crop growth cycle, carbohydrate distribution, and grain yield of crops under the panels. Crop height, leaf chlorophyll content, leaf area index, and specific leaf area were measured throughout the experiment. Radiation mapping, calculated on the cells with a resolution of 0.12 m $\times$ 0.12 m and a time step of 30 min, was used to determine the shadow depth. GECROS is advantageous because it allows the prediction of biomass and yield based on the knowledge of climatic parameters. Thus, a knowledge of the variation of climatic parameters under the panels allows to determine the adequate configuration of an agrivoltaic system.

Trommsdorff et al. [43] investigated the electrical efficiency of PV systems applied to crops and the behavior and productivity of crops under panels in Germany's largest agrivoltaic research facility. The study was conducted according to the variation of solar radiation available to the PV panels and the crops. All light simulations for the PV modules were performed with Radiance, which is a back ray tracer for optical calculations in virtual environments that takes into account both direct and diffuse fractions of the irradiance, allowing the simulation of ground reflections to analyze the electrical gains on the back side of the PV panels. In addition, they used ZENIT software tool, which considers, among other things, temperature coefficients, specific efficiency curves, maximum power points, and inverter power limitations to evaluate the overall electrical efficiency. Virtual sensors measured the radiation under the panels. Simulations were performed for different orientations of the APV field between South and South–West (0°, 15°, 30°, 45°) and different distances between rows of panels. Moreso, the photosynthetically active radiation under the panels was converted into biomass yield.

Kim et al. [48] focused on the electricity production of agrivoltaic systems and the increase in revenue when implementing such a system. Thus, they implemented a polynomial regression to develop a model for estimating the system's electricity production using machine learning. The model considered eight (8) parameters, including solar radiation, daily minimum and maximum temperature, daily rainfall, humidity, wind speed, shading ratio, and type of solar panel. However, the shading data used in the study was calculated as panel area over the system area. Therefore, the model does not provide an indication of the optimal configuration in terms of spacing, elevation, and inclination for the crop to be grown.

Pulido-Mancebo et al. [131] have developed a model for optimizing agricultural production under the panels to convert photovoltaic power crops into agrivoltaic systems. It consists of a mathematical model that simulates the solar incidence in a network of representative points on the ground, depending on the geometry and design of the PV crop to be converted to agrivoltaics. The study focused on photovoltaic installations with rectangular collector planes inclined towards the south and one side of the rectangle (wider) oriented in an east–west direction and parallel to the ground and with the shorter side oriented in a north–south direction. The model is based on the representation of the sun's position with respect to the geometry of the collector array (latitude of the location, solar declination, day angle, and solar time) as well as the geometry of the PV system itself (a rectangle represents the system). The model geometrically determines the shading at any point on the ground by determining the direct and diffuse radiation on the horizontal ground without obstacles. The inputs were the declination, the latitude, solar time, and daily angle. This model is advantageous because it allows a quick overview of the radiation in the ground in agrivoltaic systems.

Nevertheless, these models do not directly give a specific elevation, spacing, and inclination for a given crop and given locality. These models are used to determine whether or not a selected configuration is suitable for a given crop and need to be optimize. All these modeling studies have been set up to study and verify the performance of a specific installation to see the impact of this installation on the yield of the crop being grown in this system. Moreover, Pulido-Mancebo et al. [131] have developed that simulates the solar incidence in a network of representative points on the ground; nevertheless, it does not directly give the optimal spacing between rows of panels and between panels and the elevation to choose for a given crop.

Therefore, considering the limited number of decision support studies that have been conducted to determine the ideal configuration, i.e., elevation, panel row spacing, and panel spacing and tilt for any given crop, this review article has been developed to clearly explain agrivoltaics. We believe that this review can be used as a guide to set up a model that will take into account geometric, geographical, climatic, crop, and PV panel factors which will have as outputs the optimal spacing between panels, elevation, and tilt that will result in maximizing the crop yield and power of the PV system in agrivoltaic systems.

8. Conclusions

The agrivoltaic system was first used in 1980. However, only a few studies were carried out in this field during this period. It is only since 2011 that many have started to work in this field. To this end, several studies have emerged in this field in recent years. These studies have mainly focused on implementing a given configuration of photovoltaic solar panels to reduce the effects of shading on crops. Several panel elevations and spacings were tested on several crops in different areas. However, these proposed arrangements were specific to the site and crop being tested. Thus, no study has been carried out to establish a model that allows for optimal panel elevation and spacing for a given area and crop. It is within this framework that this review was carried out. It gives a clear explanation of the agrivoltaic systems in full sunlight, the principle of operation of the panels, and the photosystem, both of which depend on solar radiation, as well as the factors that can affect their operation. It also shows the key factors that should be considered in an optimization model. This review examined the strengths and weaknesses of each type of installation to better select the system to be used and to optimize both the yield of the crops to be planted under the panels and the yield of the solar panels installed. For this purpose, the choice of an optimal elevation height, spacing, and tilt of the solar panels will reduce the impact of shading and increase crop yields, but also increase the power output of the solar photovoltaic panels, which is a twofold benefit. According to us, setting up a model that can be used for any area to find an optimal panel arrangement in the locality being studied would be an innovative solution that will be of high interest, especially in areas where the agrivoltaic system has never been tested. Furthermore, in the future, other studies may be conducted in the field of agrivoltaics, namely the evaluation of the environmental impact of the use of the panel structure which is becoming more imposing in elevated systems. Moreover, further research could also explore the economic implications of using agrivoltaics for pumping water to support crop production and generating electricity for sale by small-scale farmers in rural areas where electricity access is limited.

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Nomenclature

β	Slope
γ	Azimuth
α_s	Coordinates of solar altitude
γ_s	Solar azimuth
AC	Alternating current
A_i	Uncultivated agricultural area
A_n	Cultivated agricultural area
ATP	Adenosine triphosphate
CdTe	Cadmium telluride
DC	Direct current
DSSCs	Dye-sensitized solar cells
E	East
GECROS	Genotype-by-Environment interaction on CROp growth Simulator
h_1	Installation height greater than 2.1 m
h_2	Installation height less than 2.1 m
LER	Land Equivalence Ratio
N	North
NADPH	Nicotinamide adenine dinucleotide phosphate
PV	Photovoltaic
S	South
SAM	System Advisory Model
STICS	Simulateur mulTIdisciplinaire pour les Cultures Standard, or multidisciplinary simulator for standard crops
W	West
x	cultivated crop
y	electricity

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