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Empowering Rural Farming: Agrovoltaic Applications for Sustainable Agriculture

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ABSTRACT

Agrovoltaics, also known as Agri-PV or AV, is an innovative approach that entails the shared utilization of land for both the production of agricultural commodities and energy generation. This concept has gained immense popularity in recent times owing to its ability to boost income per unit of land area significantly. The scope of AV systems is quite extensive, as it encompasses solar energy converters and other renewable energy sources like bioenergy. Current strategies for agrovoltaic (AV) in agriculture are the outcome of the gradual development of agroecology and the integration of photovoltaic (PV) power supply into the grid. These approaches could lead to a nearly doubled income per unit area. Without on-site power supply, reduced chemical fertilizers and pesticides, and on-site yield processing, AV has the potential to revolutionize large-scale unmanned precision agriculture and smart farming. These approaches might lead to significant changes in the logistics and value-added production chain, thereby reducing agriculture's carbon footprint. In the future, it is possible to reduce the cost of AV technology by half by utilizing decommissioned solar panels in the technology and to delay the need for bulk PV recycling by several years. This review presents a different perspective to the common discourse on the topic, by giving special emphasis to the potential to further integrate AV into agriculture, which has the potential to facilitate the resolution of relevant legal disputes over the use of AV.

1 | Introduction

With the continuous growth of the global population, the demand for increased food production becomes more pressing. The intensification of agriculture implies a greater energy requirement for farming operations. As part of the global energy transition, renewable energy sources are gradually replacing conventional fossil fuels. The capacity of solar photovoltaic (PV) power plants worldwide is experiencing exponential growth, accompanied by an increase in energy generation rates. In numerous countries, the cost of electricity in new projects utilizing solar PV power plants has already reached its lowest point when compared to alternative generation methods [1]. The international infrastructure for the transmission of long-distance electricity is not yet developed, but PV power plants typically are found in densely populated areas where a significant amount of treeless land is already being utilized for economic activities in conjunction with the power plants. Furthermore, economically developed countries witness the most rapid expansion of PV power plants [2], where land is costly and subject to numerous usage restrictions [3]. Therefore, the trend toward solar PV power plants will continue to provide energy for the growing food demands of the world's population while being built in locations where they are most needed and make the most economic sense.

Conflicts can often arise over the use of agricultural land, especially due to the growing demand for food to feed the rapidly increasing global population [4]. This issue is further exacerbated by the degradation of agricultural lands, with an estimated 50 million hectares being lost annually due to desertification and other forms of degradation [5]. As a result, there has been a significant decline of 48% in the amount of arable land available per capita from 1961 to 2016. To address this pressing concern, the United Nations Food and Agriculture Organization (FAO) has developed the concept of integrated food and energy systems [6].

The key to addressing this challenge lies in the shared utilization of land for both energy generation and other economic activities. One of the most promising solutions involves integrating photovoltaic modules into various structures, such as buildings [7]. Alternative options include utilizing underutilized land or leveraging the right-of-way of existing infrastructure, as well as installing solar panels at an elevated height to allow for other land uses, such as agriculture [8]. This approach, commonly referred to as agrophotovoltaics or agrovoltaic (AV), has gained significant traction in recent years [9]. Research has demonstrated that AV can substantially enhance the income per unit area of land by combining energy production with crop cultivation or livestock grazing [10].

While the concept of agrivoltaics was first introduced in 1981 [11], its implementation faced economic challenges due to the high costs associated with solar photovoltaic power plants. However, technological advancements and cost reductions have rendered it a more economically feasible option in recent years. By 2022, the installed capacity of agrivoltaic plants has exceeded 14 GW [12]. To put its potential into perspective, utilizing just 1% of arable land in Europe for agrivoltaics could generate over 900 GW of solar power, surpassing the current installed capacity by a significant margin [13].

Several countries, including Germany, Japan, United States, Italy, Malaysia, Egypt, and Chile, have taken the lead in establishing research and experimental agrovoltaic (AV) systems. These innovative systems integrate agricultural activities with solar energy production, enabling the dual-use of land and minimizing competition between agriculture and energy generation. There were around 2200 AV systems installed globally as of the beginning of 2020, with a total capacity 2.8 GW, as of beginning of 2020. This capacity of floating and concentrator photovoltaic (PV) plants has the ability to slightly exceed that of floating and concentrator photovoltaic (PV) plants, based on estimates that are currently available. In addition to Japan, South Korea, China, France, and the United States, other countries, such as India and Germany, have already implemented similar systems in their countries, while others, such as Japan and the Philippines, are actively exploring programs to promote the introduction of these systems [14]. AV systems are also undergoing research [15], which investigates how users perceive them and their potential effects, including the role they can play in stemming the exodus of young people from rural areas.

The utilization of a tandem of agriculture and photovoltaic (AV) systems brings with it several benefits and challenges. One of the primary advantages is the additional income generated through energy production. However, some crops may experience a decrease in yield due to shading effects and changes in soil moisture conditions. This was supported by a previous study [16]. Nonetheless, on average, the expected income per unit of farmland area increases by 60% [17], although it is possible for this figure to either decrease or increase up to 15 times [18]. Soil moisture changes and variations in lighting regimes can lead to negative outcomes in the cultivation of some crops [17], but can have a positive impact on others [19]. They can also mitigate the effects of both dry and rainy seasons [20] and other weather hazards [21]. Moreover, this diversification of income sources through energy generation can stabilize an agricultural producer's revenue by guaranteeing the sale of electricity throughout the year [15]. AV systems also have a lower environmental impact than traditional agriculture [22, 23]. Additionally, agricultural output can mitigate the impact of photovoltaic converter degradation on revenue sensitivity over time.

1.1 | Introduction to Agrivoltaic (AV) Systems

Agrovoltaic (AV) systems can be developed in three primary ways, according to the National Renewable Energy Laboratory (NREL): by power generation, by agricultural crops, and by joint use. Agricultural crops are grown using standalone PV systems with two-axis trackers, whereas power generation uses continuous rows of PV modules with minimal gaps. It is possible to combine elements of the first two approaches by adopting a joint effect approach that incorporates sparse PV lines into the process. There are active research projects in the field of AV systems that are aiming to investigate the influence of microclimate changes [24, 25], including shading [26, 27] and moisture redistribution [28, 29], on the productivity of specific crops, whether they are grown in open soil or greenhouses. Moreover, researchers are actively examining the overall economic implications [30, 31], including the potential for biogas production [32].

There has been evidence in the literature that shows that the presence of agrovoltaic (AV) systems can lead to a decrease in the amount of photosynthetically active radiation (PAR) available during the mid-day, while minimal decreases are observed during the morning and evening [33]. AV systems were found to result in a decrease of air temperature at midday by 2°C, and a decrease of 1°C at the beginning and end of the day, resulting in a decrease of 1.65°C on average for the air temperature (dry bulb) under AV systems. During the midday period under AV, we were able to compare the relative humidity of the air to that of the control site without noticing any significant differences. While it was 7%–10% higher in the early morning and 35% higher in the evening than the control site, it was lower during the early morning.

The utilization of agrovoltaic (AV) with this approach is anticipated to have the most significant impact in semi-arid and arid regions. In such areas, the prominent direction for energy utilization is to power pumps for water supply and land reclamation [34]. By combining solar energy generation with agricultural practices, AV systems can contribute to addressing the water supply challenges and facilitating land reclamation in regions characterized by limited water resources and aridity. Overall, the research on AV systems is aimed at developing sustainable solutions that can benefit both the economy and the environment. By understanding the effects of microclimate changes on crop productivity and biogas production, we can make informed decisions about the implementation of AV systems in various regions. This research not only has implications for the agricultural industry but also for the renewable energy sector as a whole [35, 36].

Research has demonstrated that a drop in temperature during AV night-time operations can be detrimental to agriculture in northern regions, as highlighted in [33]. However, Vidotto et al. [24] indicate that temperatures may rise if AV screens cover over 50% of the sky. Among the results of such an increase is earlier blooming of grapes [37]. According to Weselek et al. [38], AV parameters, local climatic conditions, and crop characteristics are all expected to affect air, soil, and shoot temperatures in complex ways.

In the current stage of research, the emphasis has shifted toward assessing the susceptibility of specific crops to the influence of agrivoltaic (AV), as well as exploring optimal spatial configurations of AV systems to maximize their overall impact. It is widely recognized that on-site energy utilization is the most economically efficient option. There are, however, many measures to enhance agricultural intensification that are not feasible due to the lack of direct energy sources in the field. Furthermore, there is a mismatch between the amount of energy produced by solar power plants and the amount that is being consumed by the grid, particularly in remote regions where solar power plants are not available. A discrepancy like this is apparent as one moves farther away from the equator and closer to the poles, where the discrepancy becomes more evident. It is noteworthy that solar power plants also experience seasonal fluctuations similar to those experienced by agricultural production. Therefore, for remote regions such as the Arctic, it becomes more advantageous to utilize the energy generated by AV for the purpose of agricultural intensification, which is particularly true of energy generated by AV.

Precision agriculture, vertical greenhouses, and unmanned electric machines [39] are currently in active development, and their implementation is impossible without the Internet of things (IoT) [40]. The successful operation of these systems requires a reliable power supply and support structures, both of which can be provided by agrovoltaic (AVs). In such systems, minimizing human labor can transform agricultural practices in several ways, including reconsidering the scale of chemical fertilization. By using AVs to produce on-site fertilizer, chemical fertilizers will be less needed, especially with the increase in the cost of "eco" products. The process would be particularly useful in hard-to-reach regions, where local natural gas must be processed into fertilizer and phosphate. An application of PV with irrigation system for cultivation is shown in Figure 1.

In Russia, the Arctic region serves as a source of raw materials, which are subsequently processed in southern regions before being transported to destinations worldwide. This intricate logistics process is subject to various factors, impacting the cost, carbon footprint, and overall sustainability of the supply chain. By implementing agrovoltaic (AV), the transportation and processing of raw materials can be streamlined, leading to a reduction in carbon emissions and enhanced efficiency throughout the supply chain [41]. AV implementation would also help minimize the reliance on human labor, thereby reducing the risks of accidents and improving workplace safety, particularly in hazardous environments.

AVs can also assist in monitoring the condition of crops and soil, enabling farmers to make more informed decisions about

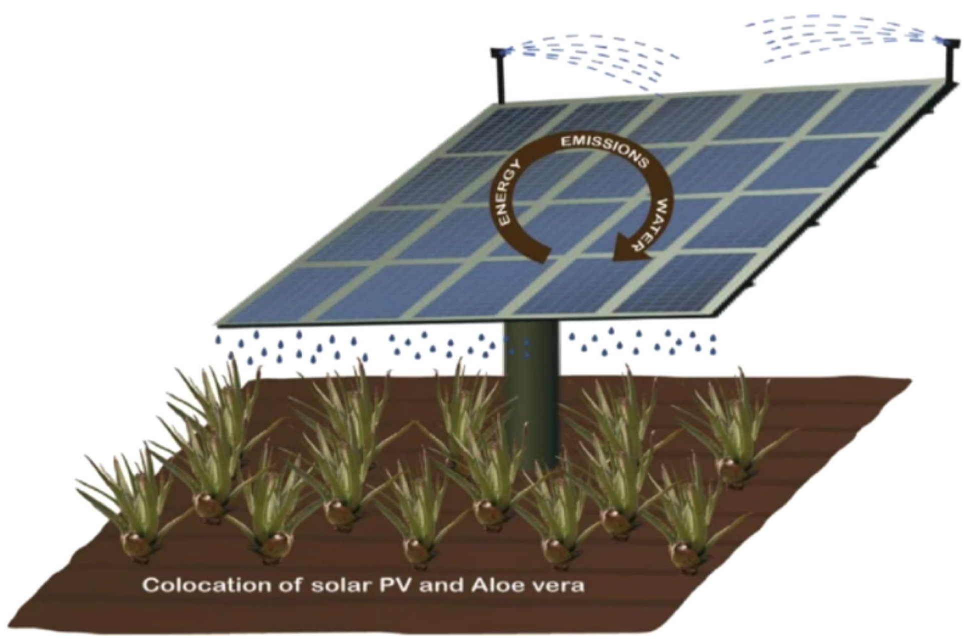

FIGURE 1 | Integration of photovoltaic (PV) module surface with irrigation system [34].

crop management and reducing the need for excessive use of chemical pesticides. This will lead to a more sustainable and environmentally friendly approach to agriculture. Furthermore, the use of AVs in agriculture can also contribute to the local economy by creating new jobs in the development and maintenance of autonomous systems [42]. Overall, the integration of AVs in agriculture has the potential to revolutionize the industry and promote sustainable practices.

The utilization of agricultural waste in biogas power plants can yield high-quality fertilizers. Coupled with thermal photoelectric modules, these plants can operate efficiently. Another promising development is the production of bio-hydrogen from agricultural waste, which has gained significant attention. In light of the global environmental agenda, hydrogen is now being recognized as an important energy carrier, and renewable technologies are being used to produce it in a sustainable manner, reducing reliance on fossil fuels.

1.2 | Overview Drawn From Introduction

This paper serves as a comprehensive guide for researchers and practitioners who are interested in utilizing agrovoltaic (AV) to enhance agricultural processes [43–46]. Unlike previous reviews found in literature, this paper focuses on filling the gaps in current understanding, specifically irrigation, aquaculture, and cold storage. The utilization of agrovoltaic (AVs) for on-site energy generation aligns with current global trends in the intensification and automation of agriculture, on-site processing of products, and the shift toward electric transportation and renewable energy sources. This approach holds particular significance in countries where agricultural producers face challenges in connecting to power grids, resulting in potential loss of agricultural or "green tariff" support. AVs can bridge this gap by serving as both agricultural and renewable energy ventures. Furthermore, this approach is beneficial in areas with decentralized energy supply and risky farming conditions, such as Arctic regions, especially when combined with wind power plants. Implementing AVs in these regions can bring about transformative changes in farming practices, ensuring food security in remote areas, improving quality of life, generating employment opportunities, and reducing energy costs by replacing costly fossil fuel deliveries. Typically, perishable products like fresh vegetables, which cannot be frozen, are transported to these regions by air, leading to inflated prices.

The next section discusses about the research on the implementation and current state of agrophotovoltaics. Similarly, Section 3 discusses the present endeavors, i.e., current activities of agrophotovoltaics. Section 4 includes anticipated future trends in agrophotovoltaics. Section 5 discusses the prospects and future applications of agrophotovoltaics. Lastly, the conclusion is presented.

2 | The Implementation and Current State of Agrophotovoltaics

2.1 | Exploring the Essence of Agrophotovoltaics

According to Goetzberger and Zastrow in 1982, agrophotovoltaics (APV) was first introduced as a method for increasing crop production within the same area by altering solar power plants. To prevent excessive shading of crops, the proposal suggested elevating solar collectors to a height of 2 m above the ground and increasing the spacing between them by at least a meter to prevent the collectors from covering too much surface area. Their hypothesis was that these systems would be able to produce crops using only one-third of the incoming radiation if further technological advancements were made. This would allow them to be more economically viable. Agrophotovoltaics, agroPV, agrivoltaics, or solar sharing is the name given to a concept that has been implemented in a wide range of projects and pilot plants around the world within the past 30 years. As per calculations, this technical approach has the potential to increase farm revenues by over 30%, as long as yield losses caused by shading effects are minimized by selecting the appropriate seeds to protect against the effects of shading [47].

This study is based on the land equivalent ratio (LER) method, originally proposed by Mead and Willey in 1980, to estimate the productivity of intercropping systems as compared to single-crop cultivation systems. The LER method was used in the evaluation of the productivity of intercropping systems. This study had the objective of assessing the benefits of an APV system that could be used for both farming and PV production over a monoculture and PV production system. The simulation results showed that an APV system has the potential to improve the overall productivity of land by up to 70%, depending on the conditions. It has been reported that a modeling study on biogas maize production was conducted by Amaducci, Yin, and Colauzzi [32] in a more recent study. APV can double the land productivity of renewable energy compared to ground-mounted PV modules that are used for the production of maize and energy separately. Based on the findings of this study, APV could potentially double the land productivity of renewable energy. To validate their assumptions, when it came to APV, Dupraz et al. [31] established an APV testing facility in 2010. Using two different densities of PV modules, they conducted experiments to determine which density of PV module produced the most amount of food while also producing the most amount of energy.

The LER method is a powerful tool to evaluate the productivity of an intercropping system. It allows for the assessment of the effect of intercropping on land productivity compared to single-crop cultivation systems. APV systems have shown great promise in increasing land productivity. Specifically, the use of APV systems has been shown to be advantageous in dual-use systems for agricultural and energy production. The results from Dupraz et al. [31] and Amaducci, Yin, and Colauzzi [32] demonstrate that APV systems have the potential to revolutionize the agricultural and energy production industries. The ability to increase land productivity by up to 70% and double renewable-energy land productivity is a significant achievement. This technology has the potential to help meet the increasing demand for food and energy production while minimizing the use of land resources.

In the study conducted by Dupraz et al. [31], it was observed that there was an increase in PV yield with higher panel density. However, Arena et al. [27] found that optimal crop production conditions were achieved with less dense PV modules.

To accommodate common agricultural machinery, the solar panels were elevated to a clearance height of 4 m. Several studies, such as those conducted by Hassanpour Adeh, Selker, and Higgins [48] and Santra et al. [49], have referred to these systems as agrivoltaic, as they allow for crop cultivation between ground-mounted PV rows. During this review, it is important to note that a distinction is made between ground-mounted PV systems and the concept of ad hoc photovoltaic panels (APVs) as defined in this report. To produce crops successfully through APV, the PV structure must be elevated off the ground and modified to meet the requirements that must be met for successful crop production beneath the PV structure.

This distinction is significant as it allows for a more nuanced understanding of the benefits and challenges associated with APV systems. APV systems have the potential to increase land use efficiency, enhance energy production, and promote sustainable agriculture. However, the design and management of such systems must be carefully considered to ensure that the crops are not negatively impacted by shading, reduced water availability, or other factors. Additionally, the economic viability of APV systems must be evaluated in light of the additional costs associated with construction, maintenance, and management.

Despite these challenges, APV systems offer a promising avenue for achieving the dual goals of renewable energy production and sustainable agriculture. To fully realize the potential of APV systems, further research is needed to optimize system design and management, evaluate the impact on crop yields and quality and assess the economic feasibility of such systems. As renewable energy and sustainable agriculture become increasingly important in addressing global challenges, such as climate change and food security, APV systems offer a unique and innovative solution that warrants further exploration.

APV systems are constantly evolving, and their technical specifications vary from region to region and company to company depending on the region and the manufacturer. A number of APV (alternative photovoltaic power) projects have started incorporating mobile photovoltaic modules that enable tracking of the sun's position. It is intended by this method to maximize solar yield while also enhancing the availability of light so as to support adequate crop growth while maintaining PV yield [30]. The use of 1-axis steerable PV systems with various tracking settings was investigated in a recent study by Valle et al. [30] to investigate their effectiveness. In their study, the researchers demonstrated that by utilizing dynamic PV modules in addition to the existing PV modules, it is possible to enhance both energy production and crop production in the long run. To optimize the efficiency and productivity of APV systems, this dynamic approach has the potential to enhance efficiency and productivity.

When APV systems are operating in the regular solar-tracking mode, the modules automatically adjust to the solar altitude of the sun, optimizing the electricity generation and increasing the solar radiation at the crop level when compared with PV modules that are installed at a fixed height [30]. Moreover, Valle et al. [30] tested a controlled tracking mode that took into account diurnal changes in solar radiation to further enhance crop productivity by maximizing radiation exposure to the crop. Photovoltaic panels were positioned in a way that minimized shading on crops during the early morning hours and late afternoon hours so as to maximize their efficiency. There were measures taken to reduce the detrimental effects of high temperatures and excessive radiation on plant growth and evapotranspiration at solar noon by increasing shading on the plants. Compared to the regular solar-tracking mode, the controlled tracking method resulted in an increase in crop biomass, but a decrease in electricity production [30]. APV systems have successfully been implemented in commercial rooftop PV facilities, and it has also been evaluated in the context of solar greenhouses in recent years [50]. The implementation of solar tracking technology has been observed to significantly increase the efficiency of APV systems. Researchers have identified that solar tracking technology can maximize the solar radiation that reaches the PV modules, thereby increasing the overall generated energy. Furthermore, it can also improve light availability for the crops, resulting in increased crop yields.

The use of mobile PV modules is a key characteristic of APV systems. The mobility of these modules enables them to automatically adjust to the sun's position, ensuring that the maximum amount of solar radiation is captured. Additionally, the mobility of these modules also improves the light availability for crops, resulting in increased crop productivity. However, the effectiveness of mobile PV modules is dependent on the tracking technology used, which differs across regions and companies. The author of [50] have demonstrated that the application of dynamic PV modules can significantly enhance the overall performance of both energy and crop production. The regular solar-tracking mode increases electricity generation and solar radiation at the plant level compared to fixed PV modules. The controlled tracking mode, on the other hand, results in increased crop biomass, but decreased electricity production. Therefore, the choice between these two tracking modes depends on the specific goals of the APV system. The implementation of solar tracking technology in APV facilities has been observed to greatly improve the efficiency of these systems. This technology maximizes the solar radiation that reaches the PV modules, resulting in increased energy generation. Additionally, it also improves the light availability for crops, leading to increased crop yields. The use of solar tracking technology in PV greenhouses has also been investigated, and it has been shown to improve the overall efficiency of these systems.

The research indicates that the density of solar panels has a more significant impact on the amount of radiation available beneath the APV array than the panels' mobility. When mobile PV panels are utilized, the light utilization efficiency for both crop and PV production is improved, and rainfall distribution beneath APV systems is also enhanced. As the concept of APV has evolved over the years, it has been explored in many cropping systems including viticulture and intensive fruit production systems in addition to traditional agriculture. The implementation of APV in these systems, where supporting structures are already common, could potentially engender synergistic effects due to the commonality of supporting structures [51]. It was reported in [52] that the author has conducted a study in which he examined the potential for APV on Indian grape farms. Based on their findings, the researchers concluded that implementing the APV system on grape farms could significantly increase the income of grape farms compared to conventional farming methods, while at the same time maintaining the grape yields on grape farms. A study conducted by Majumdar and Pasqualetti [19] projected an APV output of 16,000 GWh from the grape cultivation area in India, which was estimated to be around 34,000 hectares, which could supply the energy required for over 15 million Indians, based on the estimated area of grape cultivation. It has been demonstrated that APV has the potential to improve both the agricultural productivity and the generation of renewable energy in the viticulture sector, as a result of these results.

The potential of APV systems to offer promising outcomes is highly anticipated in regions that have arid climates, as there can be a range of synergistic effects that take place. The reduction in evapotranspiration and the harmful effects of excessive radiation can lead to increased water savings, which in turn may benefit crop production. Furthermore, the economic viability of such systems is enhanced, and this makes rural electrification a possibility. The research conducted by Majumdar and Pasqualetti [19] and Ravi et al. [34], attests to this fact. Moreover, Amaducci, Yin, and Colauzzi [32] demonstrate that APV systems can lead to reduced soil evaporation, which may reduce yield losses during dry periods and improve yield stability. Overall, APV systems have the potential to transform agriculture in arid regions and make it more sustainable and resilient. In conclusion, APV systems hold great promise for revolutionizing agriculture and energy sectors by enhancing land productivity and optimizing resource use. By integrating renewable energy with sustainable farming, APV offers a viable solution to global food and energy challenges, aligning with sustainable development goals and warranting further research and innovation.

2.2 | Examining the Agronomic Factors

This section delves into the implications of APV technology on the agricultural sector. The adoption of this technology is expected to have a significant impact not only on crop cultivation but also on agricultural practices as a whole. It is important that we differentiate between the effects of APVs on technical aspects and operational practices in field management, as well as how they affect microclimate conditions and the implications that may follow for crop production, to gain a comprehensive understanding of the impact of APVs. Furthermore, it is currently being investigated within the realm of APV research whether crop models can be used to assess the effects of environmental factors on crop production, and this will be discussed in this manuscript. By examining these various dimensions, we can comprehensively analyze the broad-ranging effects of APV on agricultural systems and their surrounding environments. By thoroughly examining the effects of APV technology on agriculture, we can gain a better understanding of how this technology can be utilized to optimize crop production and improve the overall efficiency of agricultural practices.

2.2.1 | Exploring the Consequences of Field Management

The implementation of APV systems requires careful consideration of various requirements for crop production and technical management. One crucial aspect is adapting the mounting structure of APV arrays to accommodate agricultural machinery requirements. It is essential that PV panels are elevated to an appropriate height to allow traditional agricultural equipment to pass through them. There is a need for a clearance of at least 4–5 m during a cereal cropping season, especially when using large combined harvesters that can reach large fields. There must be an alignment between the spacing between the pillars and the planting distances as well as the working width of the machinery to minimize the amount of usable land lost because of the pillars. During the APV field trial, we found that it is necessary to drive machinery beneath the APV facility and lay out driving lanes in a way to avoid damage to the structure, which requires both experience and increased concentration on the driver's part [53]. It is also necessary to adjust the working width to the distance between the support pillars in addition to the working width. As autonomous driving and precision farming technologies advance, these constraints are expected to become less significant in large-scale arable farming in the future. However, it is important to consider the unavoidable loss of production areas between the support pillars, which may be challenging for agricultural machinery to access, when assessing the potential impact on agricultural yields. According to [53], the pillars themselves can occupy at least 2% of the land. For anchoring the pillars, a variety of methods can be used, including a specialized anchoring system [38] used in the APV facility at Heggelbach to avoid the need for concrete foundations, to protect the soil, and to allow the complete removal of the structure when the need arises.

A number of technical and mechanical modifications can be made to the system so that the solar radiation is not reduced by photovoltaic (PV) panels, and minimized the challenges associated with crop cultivation arising from this. To ensure that adequate light is penetrated into the crop canopy, it is critical, to ensure adequate light penetration, that the density of the PV arrays is lower than that of conventional ground-mounted PV installations. Row spacing is traditionally considered appropriate at approximately 3 meters, the ideal spacing being one that strikes a balance between maintaining adequate energy yields while also ensuring that the crop receives a sufficient amount of light for optimal growth. During the development of the patent, a simulation was conducted by Beck et al. [54] and it was discovered that to achieve uniform light conditions beneath the PV panels, orienting the PV arrays in the southwest or southeast direction would be the most optimal approach. There was a projected 5% reduction in electricity yield as a result of this orientation, but on the bright side, the light distribution and crop performance were much better than conventional south-oriented arrays.

An important consideration when installing an APV system is the angle of tilt at which the PV modules should be tilted. According to [54] and [31], the average value in Central Europe is around 20°–25°, which is in agreement with [54]. The only drawback to this approach is that a smaller angle of inclination can cause dust deposition due to the fact that rain is unable to easily wash it away. It is also important to note that this may also be true in regions that receive regular snowfalls, where snow might be covered. During specific periods of the year when crops are at their most sensitive stages of development, Dupra et al. [31] proposed modifying the tilt of the panel during these periods to resolve these issues. According to a study published in the *Journal of Agricultural Research*, wheat is highly susceptible to shade during emergence and the pre-anthesis period. It has been shown that shading can have a significant impact on grain yield [55]. By adjusting the panel tilt during these critical growth stages, the potential negative effects of shading on crop productivity can be minimized. To accommodate crop-specific needs as well as diurnal and seasonal variations in light intensity, mobile PV modules allow for automatic sun tracking, as suggested by Valle et al. [30]. This is particularly useful for adjusting the PV panel orientation and tilt angle as needed. Several other approaches have been suggested to improve the performance of PV panels in relation to crop cultivation. One such approach is the use of semi-transparent or translucent PV panels, which allow for the passage of a portion of the incident light to reach the crop canopy. This approach can enhance crop growth and yield while also generating electricity.

Another approach involves the integration of PV panels into greenhouses, providing both electricity generation and crop protection. This approach has been shown to improve crop yields, reduce water requirements, and increase overall energy efficiency. Additionally, several studies have suggested the use of agrivoltaic systems, which integrate PV panels and crop cultivation on the same land area, resulting in mutual benefits [56, 57]. Such systems can increase land-use efficiency, reduce water requirements, and enhance crop yields while generating electricity. Various other modifications can be implemented to minimize the negative impact of PV panels on crop growth and yield. Such modifications include the use of reflective surfaces to increase light intensity reaching the crop canopy, the use of shading nets to prevent excessive shading of the crops [49], and the use of ground covers to minimize soil moisture loss. Additionally, the use of PV panels for water pumping and irrigation can improve water availability and crop yield while generating electricity [58].

According to the study conducted by Cossu et al. [59], Park et al. [60], and Loik et al. [61] as a result of technological advancements, semi-transparent, wavelength-selective, and bifacial photovoltaic (PV) modules are beginning to develop in the near future. Innovations like these have shown promising results in the past. As an example, Li et al. [50] conducted a study in a greenhouse using both semi-transparent bifacial panels with adjustable tilt angles to measure the transmission of light. By using this configuration, the PV modules would be tilted parallel to the greenhouse ceiling, providing shade to the crops being cultivated in the greenhouse while producing electricity for the greenhouse. As an alternative, the PV modules could also be tilted vertically to maximize the use of agricultural radiation during periods of low solar irradiance [50]. As a potential concern, a deposition of dust on the panel surface can lead to a decrease in electrical performance due to dust accumulation as a result of agricultural activities such as tillage and harvesting, which can have a detrimental effect on the performance of PV modules. It is particularly critical to pay attention to this decline when the weather is dry or there is little precipitation in the region, such as tropical or monsoon climates. There is a recommendation to periodically clean the surfaces of the modules to maintain optimal electric yields [47]. There was a slight delay in the growth of crops during the APV trial carried out in Heggelbach that has also been noticed in other studies evaluating the impact of APV and shading on crop growth. This delay can be attributed to the altered microclimatic conditions created by the APV system and can have implications for field management and crop marketing strategies. It is important to consider these factors when implementing APV systems and managing crops in such environments. In conclusion, the successful implementation of APV systems hinges on careful integration of agricultural and technical requirements. By optimizing panel height, spacing, and tilt, and considering advanced technologies, APV systems can enhance crop production while simultaneously generating clean energy, paving the way for a sustainable agricultural future.

2.2.2 | The Influence of Microclimatic Alterations on Crop Cultivation

In agricultural settings where APV arrays are present, the alteration of microclimate conditions is a significant consideration that can impact crop cultivation. Other microclimate characteristics may also be impacted, even though the reduction in solar radiation beneath the APV canopy is the most obvious alteration. Air temperature is one such element that is directly impacted by solar radiation. There were no discernible variations in daily mean temperatures and thermal time between an unshaded control plot and an APV experiment, according to a Montpellier, France research [24]. However, temperatures under the panels tended to be greater on days with little wind or strong sun radiation [24]. According to other research, when exposed to shade as opposed to full sun, soil temperature [62] and maximum air temperature [63] dropped. It is crucial to remember that these results might differ because of the uneven shadowing circumstances under APV facilities and the direct effects of solar panels that have been seen in research involving ground-mounted solar parks [64]. On the other hand, Armstrong, Ostle, and Whitaker [65] discovered that the mean air temperature beneath photovoltaic panels stayed constant, exhibiting reduced diurnal temperature fluctuations as a result of greater minimum and lower maximum temperatures. It is essential to acknowledge that these findings do not translate directly to APV systems with PV modules positioned above the crop canopy.

It is important to carefully assess the possible effects of shading-induced variations in air and canopy temperature on crop cultivation, particularly in areas with strong sun radiation. Studies on potatoes have indicated that excessive heat from shadowing can have a detrimental impact on crop yields, as marketable tuber yields have been reported to decrease [66]. The photothermal quotient, which measures temperature and radiation, is a key factor in determining cereal grain yields. Furthermore, crops' nutritional value might be impacted by temperature. For example, it can affect the starch content of potatoes and the fatty acid composition of oilseed rape [67–69].

Under APV systems, soil temperatures normally drop while air temperatures tend to rise. It has been noted that during the day, crop temperatures of durum wheat, lettuce, and cucumber grown under APV rise, and vice versa. Understanding the possible effects of temperature fluctuations on crop cultivation requires taking into account changes in the air as well as inside the crop canopy as a result of shade. This is especially important in areas with strong sun exposure, since too much heat can have a negative effect on crop yields and nutritional value.

As previously noted, the installation of a solar panel canopy alters the distribution of water beneath it, as research by Hassanpour Adeh, Selker, and Higgins [48] has shown. The risk of soil erosion can be increased by heavy precipitation since it can cause water to spill onto the soil's surface. Uneven rainfall distribution might result in less water available in more sheltered locations. Notwithstanding these possible drawbacks, the shading that the PV panels offer may also be advantageous, especially when it comes to lowering the prevalence of fungal infections during extended wet spells. According to research, the severity of anthracnose, a prevalent postharvest disease that affects mangos in humid places during wet seasons, diminishes under plastic roofing [70]. Similar results have been seen for grapevines in China's wet areas, where sheltered grapevines showed a reduction in the severity of various fungal infections [71]. It is significant to remember that in these investigations, fully covered and unsheltered crop stands were contrasted. It is important to note, nevertheless, that depending on the arrangement, dimensions, and density of the installed modules, APV systems usually only occupy around one-third of the whole space. Consequently, it is unclear how much the sheltering effect would affect disease infestation in the cultivated crops. To assess the precise impacts of sheltering inside APV systems on crop disease control, more investigation is required.

The existence of an APV system may have an impact on the overall water balance in addition to issues with water distribution. According to the author of [25], evapotranspiration is lowered under PV arrays as a result of the decreased transpiration and evaporation brought on by the lower light intensity. However since crop cover rate affects evaporation, they pointed out that the precise impact differed based on the type of crop. For cucumbers, the crop cover rate dropped under APV, whereas for lettuce, it increased. Based on their research, Marrou, Dufour, and Wery [25] concluded that, when the right crop species are chosen, APV systems may increase water use efficiency (WUE) and reduce water losses in dry conditions. This aligns with the results observed in citrus cultivation under shading nets, where WUE increased with reduced solar irradiation [72].

Using data from 40 years of simulations, the author of [22] discovered that growing maize under APV without irrigation decreased soil evaporation and raised average production. The circumstances of full sun showed the largest difference in output. As a result, they came to the conclusion that APV systems may help to reduce production losses and stabilize yields during dry years [22]. These results demonstrate the potential advantages of APV systems for raising agricultural output and optimizing water consumption, especially in water-constrained areas. In conclusion, while agrophotovoltaic systems can introduce complex changes to microclimate conditions, they also present promising opportunities for optimizing agricultural productivity and water efficiency, particularly in regions facing water scarcity. Careful consideration and further research into these dynamics are essential to fully harness the benefits of APV systems.

2.2.3 | The Impact of Shading on Crop Yield and Quality

A number of variables, such as the system's technical setup, placement within the array, and seasonal solar altitude, affect how much solar radiation is reduced beneath an APV canopy. The degree of shade is determined in part by orientation, tilt angle, panel size, and spacing between panels, among other factors that are covered by Beck et al. [54]. The APV facility's shadowing is not consistent throughout the day and fluctuates depending on solar height because of the way the PV modules are arranged. Crop-available radiation can vary from 60% to 85% of open-field conditions, according to research on APV systems tailored for crop production, as noted by Praderio and Perego [53]. Because of boundary effects, the effect of shade is less noticeable in smaller APV facilities, especially during low light when sunlight may enter from the sides.

Different lettuce cultivars grown under an APV system with a decreased module density and a panel row distance of 3.2 meters were used in a field experiment by the author of [25]. They discovered that lettuce yields varied from 81% to 99% of the yields in full-sun control plots, with some types even exceeding the control values, and that up to 73% of incoming radiation was accessible at the plant level. According to simulation studies conducted by Praderio and Perego [53] with climatic data spanning 37 years, average yields of wheat and maize under APV will only be reduced by 0.5% to 1.5%. Attaining such yields in reality is yet unknown, though. After modifying a crop model to take into consideration the shadowing circumstances under APV, the author of [73] discovered that a 20% decrease in sun radiation corresponded to a 20% decrease in rice yields. They came to the conclusion that having enough light available in the early phases of development is essential for determining production.

These findings highlight the complexity of the relationship between solar radiation reduction and crop yields in APV systems. While studies have shown potential for maintaining high yields under reduced radiation conditions, the specific outcomes may vary depending on crop type, shading intensity, and management practices. Further research is needed to better understand and optimize the interaction between solar radiation and crop productivity in APV systems.

The impacts of APV on agricultural productivity are not well understood, hence data from similar research such as agroforestry trials or studies using artificial shade must be used. It is crucial to remember that the circumstances in these studies which frequently included consistent shadowing across the research area are not the same as the dynamic shading patterns found in APV systems. As a result, conclusions from these research should not be applied to APV systems without care. A range of shade intensities, classified as "moderate shading" (up to 50% reduction in solar radiation compared to full sunshine) and "severe shading" (more than 50% reduction in solar radiation compared to full sunlight), were used in the majority of the included investigations. These divisions serve as a means of distinction and do not evaluate the effect on crop yield directly. Studies on potatoes provide evidence that even under modest shade circumstances, crop output and quality can be significantly impacted [74]. When it comes to APV, these light circumstances fall into the category of moderate shade, since crop-available radiation is decreased by around 15%–40% [25]. These results underline the need for more APV system-specific research to fully comprehend the implications of lower solar radiation on agricultural productivity under these particular circumstances.

It should be emphasized that the findings of artificial shade studies cannot be directly extrapolated to APV systems since the latter have a different shading pattern. The shading pattern beneath an APV system is more dynamic than that under artificial shade, which could have an impact on crop production. The shading intensity of an APV system is determined by various factors such as the angle of incidence, the position of the sun, and the time of day. As a result, the effect of APV on crop production is dependent on the type of crop being cultivated, the location of the APV system, and the time of year when the crops are grown. Although there is a limited amount of information available on the effects of APV on crop production, there is evidence to suggest that it can have both positive and negative impacts. APV systems can help to mitigate the negative effects of climate change by reducing greenhouse gas emissions and improving soil health. However, they can also reduce the amount of sunlight available to crops, which can have a negative impact on crop yield and quality. As a result, it is critical to conduct further research to determine the potential impact of APV on crop production. Agricultural practices are changing rapidly as we seek to adapt to the challenges posed by climate change. APV systems are one approach that has gained traction in recent years as a way of reducing the environmental impact of agriculture. However, the potential impact of APV on crop production is not well understood. There is a need for further research to determine the potential benefits and drawbacks of APV systems. This research should be conducted under a variety of conditions to ensure that the findings are applicable across a wide range of farming scenarios.

Numerous studies, such as those that show relationships between solar irradiance and grain yield in cereals including wheat, rice, and maize, have been conducted [75–77]. The degree and length of shade, as well as the crop's developmental stage at the time of shading, all affect how much the yield is reduced. For example, in rice, extreme shadowing circumstances that cause incoming radiation to drop by up to 77% can result in yield decreases of up to 73% [78]. It was discovered that in wheat, a drop in both the quantity of grains per spike and spikes per unit area is responsible for the yield decline. Depending on the crop's phenological stage at the time of shadowing, this decrease varies in degree. The 30 days before blooming are when wheat crops are most susceptible to shade; treatments that stop 45 days before anthesis have no discernible impact. Similar trends have been seen in rice, where yields are unaffected by slight variations in light intensity during the vegetative stage. These results highlight the significance of taking into account crop stage-specific shade sensitivity and its possible effects on grain output in cereal crops.

In contrast to the data previously indicated, it was discovered that wheat cultivars under mild shade circumstances, from jointing to maturity, produced higher grain yields with an 8% reduction in full sunshine. According to research done on maize, Reed et al. [79] revealed that applying shade during the vegetative stage reduced grain output by 12% and reduced incoming radiation by 50%. However, yields were decreased by 20% and 19%, respectively, when shade was applied during blooming or grain filling. In maize, similar results were reported by Mbewe and Hunter [80], who found that losses in grain production were greatest during the reproductive stage. It's interesting to note that during the reproductive stage, shade had very little effect on stover output, suggesting a larger effect on grain yield. These results highlight the complex relationship between shading and crop yield in cereals such as wheat, rice, and maize, with the magnitude and direction of the effects depending on the specific shading conditions and crop stage. Understanding the impact of shading on grain yield is crucial for effective crop management strategies. Farmers and researchers need to consider the timing and intensity of shading, as well as the specific crop and its growth stage, to optimize yield outcomes.

Studies like [81, 82] have shown that shading typically has a detrimental effect on tuber number and production in potatoes. However, it has been discovered that certain shade circumstances can boost yields in areas with strong sun irradiation. For instance, it has been demonstrated that providing shade at midday [81] or early in plant growth [82] increases plant survival rates, which in turn increases yields. When evaluating data, especially under varied climatic circumstances, it is vital to take into account the possible impacts of the photovoltaic (PV) canopy on microclimate, including variations in evapotranspiration. The outcomes of research conducted in a dry Mediterranean climate should be taken into account. It has been shown that in semi-arid regions with high light intensities, tomatoes grown under moderate shade circumstances (25%–36% decrease of full sunshine) yield more fruit and grow taller plants [83–85]. On the other hand, extreme shadowing (50%–75% reduction of direct sunlight) produced adverse consequences and reduced fruit production. Comparable outcomes were noted for sweet peppers cultivated in the Negev desert, wherein mild shade (a reduction of 12%–26% of full sunshine) resulted in elevated plant heights and yields [86]. It is evident that shading can have varying effects on crop yield depending on the plant species and the environmental conditions. Potato yields were generally decreased by shading, but can be increased under specific shading conditions in regions with high solar irradiation. In contrast, tomato and sweet pepper yields increased under moderate shading conditions in semi-arid and desert regions, respectively. However, excessive shading had negative effects on both crop yields. It is important to consider the potential effects on microclimate when interpreting data on crop yield under different shading conditions.

Furthermore, it appears that the influence of shading on crop yields is contingent upon the specific plant component that is being harvested. Shading effects on crop yield vary depending on the crop species and varieties involved. In the case of lettuce, certain varieties were found to be minimally affected by shading, while others actually produced higher yields than those grown under full-sun conditions. The shade-tolerant lettuce strains exhibited adaptive strategies such as increased total leaf area, modified leaf orientation, and altered morphology, resulting in longer, wider, and thinner leaves but in fewer numbers. On the other hand, studies on wheat showed that maximum leaf area index remained unaffected by shading, although some varieties exhibited increased straw biomass. Research conducted on various temperate grassland species using shading cloths demonstrated consistent or even greater yields under moderate shade conditions, depending on the specific strain [87]. The author of [87] has considered APV experiments which indicated that shading approximately one-third of photosynthetically active radiation (PAR) led to increased vegetative plant biomass in wheat and celeriac, with a negligible effect on total yields of clover grass. Furthermore, it was discovered that the stover yield of maize was not significantly affected by shade, irrespective of the stage of growth at which it was implemented. In light of these results, shade's impact on vegetative plant components should be taken into account. Additionally, choosing the right crop species and kinds may help. Reduced sun irradiation may help forage crops and leafy vegetables like lettuce and cabbage by increasing the amount of leaf area and total biomass of the plant.

The impact of altered microclimate conditions in APV cultivation systems on crop yield and quality remains understudied for many crop species. Research on netting and agroforestry systems may not be entirely applicable to APV systems, which highlights the necessity for specialized studies in the development of APV crops. However, the main element affecting plant development in APV systems is the decreased availability of light, which is probably going to cause yield reductions in most crops. The local climate, especially solar radiation, and the APV system's technical setup will have an impact on the amount of these losses. In dry areas with strong solar radiation and considerable water loss, more shade can be advantageous and help maintain yield stability.

Depending on whether crops are grown in the spring or the summer, different seasons will have different effects on the microclimate and shading patterns under APV systems. It is predicted that species that respond to shade well or that produce more vegetative biomass would either maintain or even boost yields. This may be especially the case for herbaceous plants, leafy vegetables like lettuce and cabbage, and fodder crops [88]. For certain species, mitigating predicted yield losses due to shading may be possible by extending the vegetation period through delayed harvest. Recent research supported this notion by observing a slight delay in the development of lettuce grown under APV. To fully understand the impact of APV systems on crop yield and quality, a comprehensive study of a wide range of crops is required. It is also important to note that the effects of APV on soil temperature, water availability, and nutrient uptake need to be thoroughly investigated as they may also affect crop production. Furthermore, the physical characteristics of the APV system, such as the height and density of the canopy, should be considered as they will influence the amount and quality of light reaching the crops.

Studies have demonstrated that shading nets have had positive effects on crops such as blueberries and blackberries, leading to extended harvest periods and potentially higher market prices [88]. Medicinal and spice crops like cardamom and pepper, which naturally grow in forest environments, are being explored for cultivation in agroforestry systems that incorporate APV [89–91]. Coffee, a major tropical cash crop, has shown benefits from shade provided by agroforestry systems [92, 93]. Other specialty crops like blackberries and blueberries, which thrive in moderate light conditions, have also shown potential benefits from shading [94]. Blackberry yields have increased by 9% to 34% with shading, while the effects on blueberries have been more variable, depending on climate conditions and duration of shading application.

Because of the variability of climatic conditions and experimental setup, transferability is restricted even with the preliminary insights offered by numerous shading studies on the shade tolerance of different crop species. A more universal solution to this problem would be to use crop models, which allow you to change the affecting factors without requiring large-scale field research. Furthermore, the use of crop models can provide valuable insights into the potential benefits and drawbacks of shade application under various climatic conditions and agroforestry systems. The application of shade in agroforestry systems has been found to have significant potential benefits for crop production. Shade can extend the harvest period and lead to higher market prices. Agroforestry systems offer additional shade, which is beneficial for several medicinal and spice crops, including pepper and cardamom, as well as coffee. Blackberries and blueberries, two specialist crops that typically grow in environments with moderate light levels, have also been shown to benefit from shading.

It is crucial to remember, nevertheless, that because of the variability of climatic circumstances and experimental setup, shading study results are not always transferable. Crop models offer a more global solution to this problem. They make it possible to change the contributing factors without conducting lengthy field tests and can offer insightful information about the possible advantages and disadvantages of applying shade in different climatic situations and agroforestry systems. Overall, the application of shading in agroforestry systems has great potential to enhance crop production. The use of crop models can further aid in understanding the potential benefits and drawbacks of shade application. As research in this area continues, it is important to consider the unique requirements of each crop species and the climatic conditions under which they are grown to maximize the potential benefits of shade application. In conclusion, while Agrivoltaic (APV) systems show promise in optimizing both energy and agricultural production, their impact on crop yields is complex and varies widely depending on specific crop types, shading patterns, and environmental conditions. Further research tailored to the unique dynamics of APV systems is essential to fully understand and harness their potential benefits.

2.3 | Exploring Modeling Approaches in Agrophotovoltaic Research

The effect of APV on agronomic parameters is a complicated subject affected by a number of previously mentioned components. Developments in PV technology offer possibilities for adjusting APV setups to crop production needs. Estimating the impact of APV on crop cultivation is more difficult than calculating the electrical performance of PV systems [95]. Various research works have been carried out globally, taking into account particular regional climates. Variations in observed effects may result from differences in the shading techniques used in these experiments, as well as differences in sun energy, temperatures, and water availability. Some studies implemented uniform shading throughout the cropping period, while others applied shading at specific stages of crop development. Comparing these studies, particularly regarding the dynamic shading patterns in APV systems, can be challenging.

It is worth noting that the effects of shading on crop growth are influenced by a variety of factors, including the crop species, growth stage, and light requirements. Some crops, such as lettuce and spinach, are more susceptible to shading than others and may experience reduced growth rates and yields when subjected to shading. On the other hand, certain crops, such as tomatoes and peppers, are more tolerant of shading and may even benefit from it in certain situations. Therefore, the impact of APV on crop production depends on the specific crop being grown and the shading conditions that are present [95]. One of the key challenges in estimating the impact of APV on crop production is the dynamic nature of shading patterns in these systems. Unlike traditional shading structures, APV systems are designed to track the sun's movement throughout the day, which results in constantly changing shading patterns. As a result, the effects of shading on crop growth can vary significantly over the course of a day, a season, or even multiple growing seasons. Therefore, accurately predicting the impact of APV on crop production requires a detailed understanding of the dynamic shading patterns in these systems.

Another challenge in evaluating the impact of APV on crop production is the fact that different types of shading can have different effects on crop growth. For example, uniform shading can reduce the amount of direct sunlight that reaches crops, which can have negative effects on growth and yield. In contrast, scattered shade can reduce the intensity of direct sunlight while still allowing some light to reach the crops, which can have positive effects on growth and yield. Therefore, the specific type of shading used in an APV system can have a significant impact on the overall productivity of the system. Despite these challenges, numerous studies have been conducted to evaluate the impact of APV on crop production. These studies have used a variety of methods to quantify the effects of shading on crop growth and yield, including measurements of plant height, leaf area, photosynthetic activity, and yield [95]. In general, these studies have found that APV systems can have both positive and negative effects on crop production, depending on the specific crop being grown, the shading conditions present, and the type of APV system being used.

One of the key advantages of APV systems is that they can help to reduce water consumption in crop production. By providing shading to crops, APV systems can help to reduce evapotranspiration rates, which can result in significant water savings. Additionally, APV systems can help to reduce soil temperature, which can also help to conserve water by reducing the amount of water lost to evaporation. Another advantage of APV systems is that they can help to improve the overall efficiency of land use [95]. By combining crop production with energy production, APV systems can help to maximize the use of available land, which can be particularly beneficial in areas with limited arable land. Additionally, APV systems can help to reduce the need for land-intensive energy production methods, such as fossil fuel extraction and large-scale hydropower projects.

Crop models have been created by a number of researchers, including Valle et al. [30] and Dinesh and Pearce [47], to address the dynamic and complex character of APV systems. This method was pioneered by some, who used two distinct kinds of models to describe the complexities of APV. Abiotic variables including soil, microclimate, and farming techniques were combined with crop-specific characteristics in the STICS model to simulate the effects of environmental variables on crop growth. To forecast the distribution and availability of light beneath the APV array, a different model was employed. As mentioned by Flénet, Villon, and Ruget [96], it was discovered that the STICS model was an effective tool for modeling crop performance under APV. Its integration with PV modeling and the LER technique made it possible to assess the land productivity of the APV system. The STICS model has limits when it comes to modeling crop development under situation of severe shade, though. By utilizing data from their APV field trial, several models were modified to better reflect the microclimatic dynamics under APV systems, thus advancing the modeling technique. They put in place a thorough microclimatic monitoring system that achieved great temporal precision by recording incident radiation, air temperature, humidity, soil temperature, and soil moisture at hourly intervals.

In the study, various parameters including wind speed, precipitation, crop cover rate, crop temperature, and stomatal conductance were measured to improve the accuracy of field data and the correlation with the radiation model. The researchers emphasized the importance of measuring these parameters at increased spatial and temporal resolutions [96]. The author also developed a theoretical model to better understand the dynamics of the water balance beneath an APV system. While the studies revealed heterogeneity in the distribution of rainwater under the APV system, the researchers assumed that the inputs of rainwater in their models were similar to the unsheltered treatment. These efforts aimed to enhance the understanding and modeling of water dynamics in APV systems.

The author conducted a field experiment and developed a rain distribution model to address the heterogeneity of rain distribution under an APV system [96]. This model allowed them to identify key factors influencing rainwater distribution caused by the PV panels and achieve a higher resolution of spatial heterogeneities in water supply. Expanding on earlier modeling techniques, a more thorough model that takes into account a number of factors was created in a follow-up research [96]. These factors include rain distribution, the efficiency of water and land usage, and the optimization of shading strategy. They discovered that their model worked well for APV system size, irrigation optimization, and panel position adjustments. They did, however, recognize that there was still room for development, particularly with regard to temporal resolution and the inclusion of soil surface characteristics in the assessment of soil water distribution. Despite these drawbacks, consider their model to be a useful tool for APV system optimization; more sensitivity analysis is necessary for its general application.

The modeling approach in APV research has undergone development and refinement, allowing for the simulation of APV impacts based on specific local climatic conditions and technical implementations. However, to enhance the reliability of simulated results, it is essential to conduct additional field experiments that provide comprehensive data on microclimatic heterogeneities. Some progress has already been made in this direction by researchers, who collected data on various microclimatic factors. To attain a more accurate spatial and temporal resolution, it is important to integrate supplementary factors, such as the condition of the soil surface as proposed. Validating anticipated values with field trials including extensive microclimatic condition monitoring is essential. To obtain information on the distribution of rain, measurements should be made throughout the APV facility's solar panels. The advantages of agrophotovoltics on environment is summarized in Figure 2.

Indeed, the current state of microclimatic modeling in APV systems is relatively advanced. However, there remains a significant gap in modeling crop performance under such systems, particularly for complex crops and their light requirements throughout various stages of development [97]. This limitation is further exacerbated by the lack of field validation and experimental data on crop responses to altered light conditions. To address this gap, it is crucial to conduct additional field experiments with diverse crop species. These studies will shed important knowledge on the morphological characteristics unique to crops and how they react to varied lighting levels at various phases of growth. The validity and accuracy of crop models may then be improved with the use of the data gathered from these experiments. Long-term, complete models that incorporate local climate conditions, specific crops, technical details of the APV system, and crop performance simulation are required to account for energy and crop performance. By overcoming this gap, we may pave the road for more sustainable and efficient APV systems. In conclusion, advancing the understanding of APV's impact on crop production requires a holistic approach that integrates detailed field experiments with refined modeling techniques. By addressing the current gaps in crop performance modeling and incorporating diverse crop species, we can unlock the full potential of APV systems for sustainable agriculture and energy production.

3 | Present Endeavors: Current Activities

3.1 | The Art and Science of Horticulture

The implementation of agrovoltaic (AV) in agriculture can lead to either losses or significant increases in income, depending on a variety of factors including climatic conditions, crop type, and market prices for agricultural and energy products. The main areas of current research in this field are the impacts of varying soil and air irradiation, temperature, and humidity; also, the effects of AV-powered heat pumps on aquaculture pools and agricultural product storage are being studied. Researchers have looked at systems with sun monitoring capacity to optimize

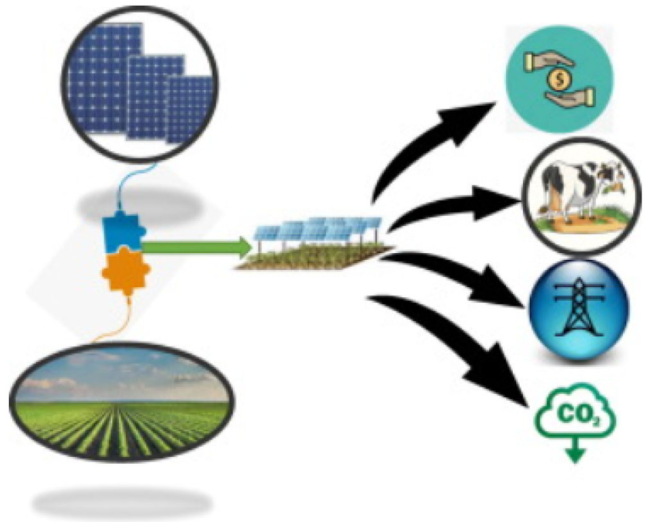

FIGURE 2 | Advantages of agrophotovoltaic [97].

output while avoiding shadowing to get the best microclimatic benefits from AV [30], which can be especially important during specific times of crop development. Still, not much research has been done on the impacts of low-potential concentration solar radiation, including wavelength selection.

Researchers have looked at how AV affects the nutritional [73–76] and commercial [98] qualities of crops in addition to its influence on biomass growth. This is significant since AV is known to cause declines in nutritional value due to climate change [99]. Prior research has demonstrated that the quantity of protein taken from plant leaves, trunks, and roots rises significantly when photosynthetically active radiation (PAR) is used under transparent photovoltaics [100]. Additionally, the majority of the energy used for metabolism was directed toward aerial tissues, and the phenotypic of the plant's aboveground portion differed markedly from that of the control. These findings highlight the potential benefits of implementing AV-powered systems in agriculture, but further research is necessary to fully understand the long-term impacts on crops and the environment as a whole.

Furthermore, research has shown that harvesting crops later typically 1–2 weeks later or boosting the proportion of bigger tubers in potatoes may totally offset a decrease in crop production and sugar content of grapes that results from slower plant growth [100]. Adopting this strategy might result in lower agricultural harvesting and transportation costs when manpower and machinery are not in high demand, as well as higher market prices for goods provided outside of the customary high-offer window. Furthermore, the presence of artificial vegetation can benefit the growth of crops that often thrive in shadowed environments under a forest canopy, eliminating the drawbacks of farming near trees and bushes. As a result, the agriculture sector and the parties involved may need to adjust to these discoveries.

Crops such as wheat [24, 101], corn, rice [102], beans, peanuts, potatoes [33, 103], sweet potatoes, beetroot [104], grapes [37], lettuce [24, 27], Welsh onion [105], basil [98], spinach [100], celery, fennel, chard, tomato, pepper, zucchini, cucumber [24], eggplant, watermelon, pumpkin, different cabbages, aloe vera [34], agave, taro, clover, alfalfa [106], other pasture crops [38], raspberry, strawberry, cherries, citrus fruits, and mushrooms were among the crops mixed with AV. In conclusion, the integration of agrovoltaic (AV) in agriculture presents a complex yet promising avenue for enhancing crop yield and quality. While the potential benefits are significant, they are highly dependent on various environmental and economic factors. Continued research is essential to fully understand and harness the long-term impacts of AV technology on agriculture, ensuring sustainable and profitable farming practices.

3.2 | Exploring the Realm of Livestock

Insufficient research has been conducted so far to evaluate the impact of agrovoltaic (AV) constructions on livestock production. The only available published studies have focused on lamb [106–108] and rabbit [109]. However, it has been demonstrated that low-lying AV and herbivores have a mutual influence, whereby animals that graze on the grass remove the need for mowing it, thereby reducing costs.

AV constructions offer several advantages to livestock farmers, including lowering the cost of fencing the territory, which is typically the most expensive capital cost for rabbit farms. Furthermore, by shielding the animals from predators and unfavorable weather, such as intense sunshine, these structures raise the herd's total production. Furthermore, the revenue ratio from the selling of power and raising rabbits might vary from 4 to 40 to 1, based on local conditions and process structure [109].

Studies have indicated that raising rabbits has less and milder environmental effects than raising cattle, especially when it comes to carbon footprint, water use, and fertilizer use. Breeding cattle and rabbits differ by more than an order of magnitude in terms of total CO_2 emissions per kilogram of meat. The short 8-week production cycle of rabbits makes them very useful in difficult climates, since it coincides with the length of the vegetative season [108, 109]. This implies that keeping a big herd of animals over the winter is not necessary. Raising rabbits has several advantages, including high protein conversion rates and cycles that provide up to 20 kg/ha of pure meat from pasture alone. Furthermore, rabbit breeding produces fur that is highly sought for, locally.

Research indicates that there was no appreciable variation in the growth of lamb live weight per hectare of pasture, indicating that the agricultural component remained unaffected [107]. The increased nutritional forage value of the AV pasture made up for its decreased herbage bulk. Conversely, sheep needed less water and favored to remain in PV-shaded regions when exposed to sun irradiation above 800 W/m2 for idling [108]. Sheep make up around 15% of all livestock and are employed to mow grass at PV power facilities in North Carolina, according to studies. This practice increases revenue by 2%–8%. In this situation, internal transportable electric fence is a useful feature. Regarding other livestock, there are fragmented reports indicating that goats are not fit for the task since they like to jump on everything and eat wires, horses are too picky, and cows need too much room.

To create ideal pollinator circumstances at PV installations, the Pollinator-Friendly Solar Act was passed in Minnesota, United States. Consequently, "Solar Honey" became a trademark. This law's criteria are completely met by the license for its usage, which should contribute to an increase in revenue. This type of AV seems to be increasingly prevalent throughout more than 11,000 acres in the USA. In conclusion, while the current body of research on the impact of agrovoltaic (AV) constructions on livestock production is limited, the existing studies highlight promising benefits, particularly for species like rabbits and sheep. These advantages include cost reductions, environmental sustainability, and improved animal welfare. As the adoption of AV grows, further comprehensive studies are essential to fully understand its potential across various livestock species and farming environments, ensuring that its benefits can be maximized globally.

3.3 | From Harvest to Plate: Techniques for Harvesting, Storage, and Processing

AV installations have been developed to support the power needs of various agricultural operations, such as fur farms, remote dairy farms, and electric agricultural machinery. These installations typically involve the use of PV systems, which can power air-conditioning units, refrigeration machines, and auxiliary devices. Depending on the crop being cultivated, the estimated unit costs for kW*h/ha can vary [110]. While most agricultural machines are currently powered by internal combustion engines, there is a possibility of switching to electric batteries. However, this may result in higher capital and operational expenses. In the absence of batteries, on-board power sources or grid connections are required. Since grid connections are often not feasible, on-board power sources are considered, but they still require batteries, which can be limited by the capacity factor of solar panels compared to AV.

A significant portion of unmanned agricultural equipment depends on GPS/GNSS navigation, which is not always reliable and occasionally unavailable via public networks [111]. Energy availability across fertile land can greatly improve the efficiency of travel for agricultural drones, both airborne and terrestrial [112, 113], hence lowering the capacity demand on batteries. The unmanned machinery can function as efficiently as possible with the support of the accurate navigation signals and data networks that the AV structural posts can offer. By providing a reliable source of energy, AV installations can help address various agricultural challenges, including the need for efficient and sustainable power sources. As such, it is clear that AV installations have the potential to revolutionize the agricultural industry, making it more sustainable, efficient, and cost-effective in the long run.

While cold storage is a standard practice in affluent countries, the absence of energy in poorer nations makes it impractical [114]. As a result, 5% of greenhouse gas emissions in the global food chain are caused by cold. Energy-independent ice cellars, which were common in the Arctic before, are fast deteriorating due to climate change [115]. Global food loss from harvest to retail is around 14% on average; roots, tubers, and oil-bearing crops account for the largest portion of these losses at about

25%, followed by fruits and vegetables at roughly 21%, and meat and animal products at 12%. 37% of food items in sub-Saharan Africa spoil in the first mile after harvesting and processing. More than half of the tomatoes grown in Rwanda are lost within the value chain, and one major contributing cause is the absence of cold storage.

Due to its ability to export numerous processed goods at once and eliminate the need for multiple intermediaries who take the lion's share of the final cost, small agricultural manufacturers mainly rely on solar electricity. A great replacement for batteries in battery storage might be solar ice production, which stabilizes cooling capacity with biogas. The demand for cold storage capacity can be decreased and added value can be produced by on-site solar-powered processing such as milling [115], drying [116], extraction (pressing) [117], fermentation [118], prepacking, sterilization, heating, preservation (sealing) [119], and so forth. This is especially important in regions where electricity is not readily accessible, but solar power is abundant. There are several benefits to this approach. For example, the solar-powered system could be used in remote areas where electricity is not available, leading to a reduction in food waste and spoilage. Additionally, it could help farmers increase their income by allowing them to process their crops on-site, thereby eliminating the need to transport them to processing facilities. This would reduce transportation costs and allow farmers to sell their products at a higher price. Furthermore, solar-powered processing plants could create jobs, promote local economic growth, and improve food security. By reducing the amount of food waste, these plants would also help to reduce greenhouse gas emissions, which is beneficial to the environment. In conclusion, AV installations and solar-powered processing systems present a transformative opportunity for the agricultural sector, enabling more efficient, sustainable, and cost-effective operations. These advancements hold the potential to significantly reduce food waste, enhance food security, and promote local economic growth, particularly in remote and energy-scarce regions.

3.4 | Aquaculture and Irrigation: Bridging the Gap Between Land and Water

The utilization of AV has resulted in several benefits, including the conservation of water resources by reducing direct sunlight exposure [120]. According to research, the water-use efficiency for jalapeno and cherry tomato plants in the arid southwest United States was considerably higher, with a 157% increase for jalapeno and a 65% increase for cherry tomatoes. Furthermore, the AV shading effect resulted in soil moisture remaining up to 15% higher than usual. During the day, the AV solar panels were about 9°C cooler than the conventional arrays, which led to increased efficiency. Furthermore, PV and irrigation may be done using the rainfall collected by AV. Similar to an earlier project in Gujarat, India [121], 110-foot-wide PV shades called Project Nexus are being put over irrigation canals in California's Turlock Irrigation District. These shades will be paired with long-term iron-water flow battery storage [122]. It is anticipated that these actions will significantly reduce the amount of water and energy used.

By using water to cool solar panels, a method known as "floating PV" [123], or "floatovoltaics," lowers water temperature and evaporation. When used in conjunction with atmospheric water collecting [124] and desalination plants [125], this strategy may be advantageous for aquaculture [126] in arid coastal locations. Above- and floating-water photovoltaic systems are utilized in fish breeding ponds to supply local demand and cut water evaporation by up to 85%. Furthermore, China has 60 MW of these plants, which are employed in water treatment facilities. Water pumping may be done using AV-generated electricity [127], and solar pump inverters with great efficiency have been created specifically for that function. By combining frequency converters and MPPT controllers, these pump inverters eliminate the requirement for a battery buffer by enabling the pump output to track real PV production. Such a system is quite effective on sunny days since it can handle the increased water demand. When comparing rain-fed pumps to solar-powered irrigation, Indian farmers reported a revenue gain of at least 50%. Yields were nearly one-third greater in Rwanda, which made dry-season farming possible. But it's crucial to keep in mind that groundwater supplies may run out as a result of inexpensive solar irrigation. Depending on the crops cultivated and the number of crop cycles, the payback period of such irrigation in Africa ranges from 6 months to 3 years. Aquaculture farms [128] and hydroponic farms [129] can also use AV to power heat and mass transfer for process improvement [130]. In conclusion, the integration of agro-voltaic (AV) presents a promising approach to enhance water and energy efficiency in arid regions, offering substantial benefits such as increased crop yields and reduced evaporation. By leveraging innovative technologies, AV not only conserves vital water resources but also supports sustainable farming practices, paving the way for a more resilient agricultural future.

4 | Unveiling the Path Ahead: Anticipated Future Trends

Energy has versatile applications in agriculture, ranging from the conventional use to power machines and mechanisms, to more innovative uses such as optimizing conditions and stimulating physiological processes. The latter includes energy conversion, processing, and on-site product storage to reduce transportation costs and maximize profits in electronic commerce. Energy can also be used to repel pests [131]. The energy gained can be applied to mechanical [132], electrical [133], thermal [134, 135], magnetic [136–138], and acoustic [139] plant growth stimulation. Controlling temperature and light, chemical composition, humidity, air, water, and substrate flow, as well as the power supply for agricultural machinery and equipment, are among the research topics. It is also suggested that AV structures be used to make protective barriers, plant supports, and rails for machinery and mechanisms. Nevertheless, unlike the current worldwide research majority, this article does not focus on passive microclimate changes linked with AV [24].

A new problem that has surfaced recently is recycling photovoltaic (PV) modules that have outlived their useful lives [140, 141]. Older PV modules have a 20-year lifespan [142], however TISO-10 in Switzerland, the first PV power plant in Europe, is still going strong 40 years later [143, 144], running at 80% of its nominal capacity (despite having had five inverters rebuilt). On the other hand, more recent solar panels have a 30-year warranty that may be extended to 50 years [145]. It is crucial to understand that this time frame does not relate to technological malfunction, but rather to a drop in production that usually equals 20% of the starting rate. Recycling with the aim of recovering and reusing materials isn't always cost-effective because PV converter costs are still declining. As a result, exporting these PV modules to nations where a decline in production is not as significant as a drop in capital expenditures is growing in popularity [140]. The availability of waste land to support solar photovoltaic power plants is the primary factor in these situations [32, 146]. Additionally, this method could work with a variety of AV systems. AV techniques could present chances to set up the prerequisites for farming in upcoming extraterrestrial outposts. There are plans to establish such a base on Mars, while the Moon also holds the potential for similar bases. However, a significant challenge in this regard is the need for a sustainable source of energy to support these bases' operations. Solar energy could be an attractive option in this regard, given that both Mars and the Moon receive ample sunlight. Moreover, solar panels could be transported to these bases and assembled on-site, with the possibility of recycling them after their useful life. However, the challenges of transporting and assembling these panels in harsh extra-terrestrial environments cannot be ignored. Another important consideration is the need to ensure that the solar panels used in extra-terrestrial bases are designed to withstand the harsh conditions prevailing on other planets. For instance, Mars has a thin atmosphere, which means that the solar panels would be exposed to higher levels of radiation than on Earth. Similarly, the Moon experiences extreme temperature fluctuations, which could have adverse effects on the panels' performance. To overcome these challenges, researchers are exploring new materials and designs that can withstand the extreme conditions encountered in space.

4.1 | Transitioning to Biogas: Converting Waste Into Renewable Energy

The implementation of anaerobic bioconversion systems, also known as biogas plants, holds immense potential in the effective utilization of agricultural organic waste and production of highly efficient fertilizers. Through the conversion of agricultural waste, it becomes possible to capture CO_2 that would have otherwise been released into the atmosphere during putrescence. Nonetheless, there exists a major drawback in this process, which is the energy required to maintain the conversion processes, such as substrate heating, electric mechanism driving, and monitoring of the production process. Typically, this energy is produced by burning the resulting biogas.

Fortunately, the use of solar energy through the application of solar thermal collectors and solar panels, also referred to as AV, can be employed to power the necessary equipment in biogas plants. The machinery in the biogas plants is powered by energy produced by the solar panels [147], which are also used to heat the substrate of the plants. Furthermore, a single solar module may produce both heat and electric energy. High temperatures may be attained to support the several technical processes of anaerobic bioconversion systems by using solar concentrators. Higher biogas net production results from using AV energy, and biogas may be stored as energy for use in stand-alone systems as a dispatchable power source [147–150]. Moreover, trigeneration systems including an adsorption heat pump and an internal combustion engine can include these combinations [151]. This enables the simultaneous production of heating, cooling, and power. PV panels may also be used in biogas facilities to give a DC power source for small-scale microbial electrolysis cells, which accelerates the anaerobic digestion process [152]. All things considered, the incorporation of AV systems into biogas facilities offers a workable way to meet the energy needs involved in turning agricultural waste into fertilizer and biogas.

Because of the different distribution of heat and power consumption, solar modules can only be used in a portion of the system energy supply in anaerobic bioconversion systems. This happens when local demands are predominantly met by thermal energy rather than electrical energy. With the help of solar thermal collectors at various places, the substrate is heated to 35°C–55°C during the anaerobic treatment process of organic waste. Some systems have unusual designs, such the one that creates a sealed building below earth by placing solar thermal collectors on top of a tank used for fermentation [153]. Heat recovery systems [154] and systems with active substrate mixing [155] both make use of solar thermal collectors. The efficiency of such systems is also increased by incorporating heat pumps.

A hybrid system (solar, thermal, and electric) that offers the required mesophilic conditions for biogas plant operation is proposed as a solution to the problem of night-time solar radiation unavailability. Thermally insulated tanks, which provide an anaerobic reactor with a consistent supply of warm water, can be used to store thermal energy from solar thermal collectors. A phase change heat storage device may also be used to store thermal energy, increasing the wintertime efficiency of solar anaerobic bioconversion systems. In thermostatic anaerobic bioconversion systems, solar thermal collectors can also be used to address farmers' needs for cooking fuel in chilly rural areas [156]. Efficient and stable operation of biogas plants in mesophilic and thermophilic conditions can be ensured when the plant is supplied with heat using solar thermal collectors, even in cold and arid regions [157], but optimization plays an important role in operating conditions and anaerobic digestion temperature [158, 159]. In summary, because of the distribution of power and heat consumption, the usage of photovoltaic modules in anaerobic bioconversion systems is restricted to a certain portion of the energy supply. Using solar thermal collectors, the substrate is heated during the anaerobic treatment of organic waste. These systems, which are employed in systems requiring heat recovery and active substrate mixing, might have unusual architectures. Heat pumps can increase these systems' efficiency. A hybrid system is proposed to solve the unavailability of solar radiation at night. Furthermore noteworthy is the application of solar thermal collectors in thermostatic anaerobic bioconversion systems. By adding solar thermal collectors, biogas plants may operate steadily in both thermophilic and mesophilic environments. Lastly, anaerobic digestion temperature and operational parameters require adjustment.

Solar thermal converters, in addition to photovoltaic modules and solar photovoltaic roofing panels, are of significant interest. The shape of these converters in the form of roofing panels has the additional advantage of reducing roofing costs. Furthermore, the use of recycled plastic in their construction enhances the ecological state of the environment. The thermal solar roofing panel design is devoid of costly photovoltaic converters, resulting in low panel costs, which even the most underprivileged households can afford. These solar modules, which are especially intended for agricultural operations, are integrated into the structural components of buildings' roofs and are intended to provide heat either autonomously or in tandem with the current heat network.

In terms of cost and energy flow optimization, the integration of photovoltaic and thermal solar radiation converters into anaerobic bioconversion systems is a very promising development. This method offers a number of advantages by allowing the substrate to be heated thermally and electricity to be supplied simultaneously. Studies on the techno-economic viability of this strategy have shown its applicability [160]. A solar photovoltaic thermal module may be made by building the photovoltaic module and solar thermal collector as one unit. Recycled plastic may be used as the basic material for this module, which can be constructed as a solar photovoltaic thermal roofing panel [161]. The resultant structure has an electrical rating of around 40–50 years and serves both energy-generating and defensive purposes. Up to 20% electrical efficiency can be attained by high-efficiency photovoltaic converters that are sealed using a two-component polysiloxane material.

Plane solar photovoltaic thermal modules are a great option for greenhouses, chicken houses, and cowsheds, among other agricultural structures and facilities, as a finishing material. With this method, more thermal and electrical energy may be produced without requiring more land to accommodate the placement of solar modules. On a farm, however, the ideal slope of solar modules in a specific location can also yield excellent output levels all year round when they are situated above ground. Furthermore, from an economic perspective, planting crops beneath solar modules at a ground-based site balances the area allocated for the solar installation's construction through the sale of agricultural goods. For the purpose of providing heat for agricultural facilities and anaerobic bioconversion systems, it is recommended to use heat pumps, specifically air pumps. The power supply and heated coolant required for these pumps may be obtained from air-cooled solar photovoltaic thermal modules, which can be fashioned like siding panels. This method is also utilized as a construction material for building walls. This arrangement of the solar modules produces a lot of electricity, even on cloudy days. It also guarantees that the building walls are cooled during times of intense solar radiation and enhances the removal of dust and precipitation from the module's surface. Better thermal insulation during the winter months results in lower energy usage for domestic heating and air conditioning. It is also possible to dry agricultural goods using warm air from air-cooled photovoltaic thermal modules.

In conclusion, integrating solar thermal collectors and photovoltaic modules into anaerobic bioconversion systems represents a significant advancement in sustainable energy solutions. This hybrid approach not only enhances the efficiency of biogas plants by providing essential thermal and electrical energy but also leverages renewable resources to address energy and environmental challenges. By optimizing both energy production and cost-effectiveness, this innovative strategy contributes to more resilient and eco-friendly agricultural practices.

4.2 | Stimulating Growth: Boosting Plant Development

The field of agricultural science has amassed a substantial amount of data on managing the growth, flowering, and fruiting of crops, as well as their productivity, commercial properties, tillage and harvesting methods, and product storage and processing. A technical and economic feasibility analysis is required to combine this data with AV, which is not currently present in published literature. Several methods have been considered, including increasing the intensity [162] and duration of exposure to photosynthetically active radiation through the use of LEDs and luminescent concentrators [163], altering air composition and movement, stimulating plant growth [164] through various means such as electric [165], thermal, magnetic, acoustic, and mechanical methods, providing power for agricultural equipment and using structures for pest barriers, plant supports, and equipment. These strategies have the potential to revolutionize agricultural practices and increase efficiency and yield.

Research indicates that the efficiency of solar energy conversion in contemporary photovoltaic (PV) technology surpasses that of photosynthesis by a large margin [166]. Furthermore, studies have demonstrated that the flux of photosynthetically active radiation (PAR) might be greater in artificial than in natural illumination [167]. It follows that there is a chance that agricultural output may rise if plants could use the power produced by photovoltaic cells [168]. When taking into account energy processes that incorporate other environmental energy sources, this idea becomes even more exciting. Moreover, studies have demonstrated that narrow-band LEDs may convert power at an efficiency higher than 50% [166]. At a PAR level of around 125 $mol/m^2/s$, photosynthesis and respiration are balanced in terms of plant growth [169]. It's interesting to note that increasing the leaf area of crops like lettuce [27] and potatoes [33] under artificial illumination caused the PAR level to drop, which had important economic ramifications for the latter.

A techno-economic examination of the usage of agrovoltaic (AV) in greenhouses located in Sweden and Spain has been provided in two master theses, which are recent research projects [170, 171]. According to the research, the use of AV greenhouses is not a financially appealing alternative in Sweden because of unfavorable factors, such as high power prices, a lack of subsidies for renewable energy, and winter sun irradiation. It is advised in the northern areas to combine greenhouse heating with the pricy process of thermally stabilizing the permafrost beneath structures and buildings [172]. Heat pumps may help transport heat from the latter to the former, which makes this especially important in light of global warming. It's crucial to keep storage facilities heated throughout the winter so they don't freeze. We repeated the experiment reported in Reference [173] in the Arkhangelsk area of Russia and were able to produce yields of tomatoes and cucumbers that were nearly twice as high as those from a traditional, unheated greenhouse. The expense of flying fresh veggies to isolated northern villages makes such a combination economical, no doubt.

In conclusion, integrating advanced technologies such as photovoltaic cells and autonomous vehicles into agricultural practices holds significant promise for enhancing efficiency and yield. While challenges remain, particularly in regions with harsh climates and high energy costs, innovative approaches and techno-economic analyses suggest a transformative potential for modernizing and optimizing agricultural production.

4.3 | The Emergence of Electric and Unmanned Agricultural Vehicles: Advancing Toward Agricultural Robotization

The use of manual labor in agriculture has been replaced by agricultural machines. These machines are now being replaced by computers as operators [174, 175]. Agricultural robots are more than simply an alternative to conventional machinery since they can carry out a wide range of new tasks including yield estimation, artificial pollination, mapping, insect pest monitoring, and phenotyping [176, 177]. Unmanned agricultural vehicles still face significant obstacles, such as navigation, stability, power, and data [178, 179], even with a market valued at USD 10 billion [180]. In addition to securing pipes for irrigation and spraying, AV constructions may offer accurate navigation and stability for automobiles. The new agricultural vehicles should ideally run on electricity, but how well they function would rely on how big a battery they could hold or how easily they could recharge. With a wireless power supply and energy distribution throughout arable land, AV reduces battery consumption and offers a number of recharging sites [181]. The quality of power in rural regions is frequently quite low, causing voltage dips and blackouts that interfere with the operation of sophisticated electrical gadgets. This problem will be fixed and a more dependable power supply will be ensured with the introduction of local AV sources. In conclusion, the power supply's accessibility opens up nearly limitless options for data transfer, on-site analysis, and monitoring, giving the agriculture industry a significant chance to advance and grow.

4.4 | Digital Transformation in Agriculture: Harnessing the Power of the Internet of Things

The process of digital transformation [182, 183] in agriculture is presently taking place mostly in well-developed areas. However, the remote, unpopulated regions that lack skilled staff are expected to benefit more from this transformation. The availability of electricity and data transmission networks is a significant obstacle that has to be overcome to reap this benefit [184]. Due to insufficient demand, these essential infrastructural elements are frequently lacking, resulting in a closed cycle. One key obstacle is the excessively large necessary investment in the lack of agricultural 4.0 [182] infrastructure on site. Since they may service several customers, satellite-based information technologies like remote sensing and navigation are currently the most widely used. Nonetheless, the lack of sufficient spatial and temporal resolution in these technologies has been a topic of discussion within the precision agricultural community. Moreover, the devastation of satellites as a result of international conflict or the advancement of the Kessler syndrome is another less evident but potentially dangerous concern [185]. Undoubtedly, there would be an economic shock if space communication and navigation systems were lost. If this has a significant impact on food production technology as well, the repercussions would be even worse.

This highlights how important it is to have local backups for navigation, data collection, and transmission systems to guarantee food security. This also holds true for energy, since in a conflict of interest, oil refineries and large-scale power facilities would be top targets. The deployment of agrovoltaic (AVs) presents opportunities to create the necessary dispersed and highly robust systems [186]. These systems are essential for ensuring that the effects of the destruction of satellites on agriculture are minimized. AVs are beneficial because they can operate in remote areas where skilled labor is scarce, and they can also execute tasks that are dangerous for humans. In addition, they can be programmed to perform repetitive tasks, freeing up skilled human labor for more complex tasks. AVs can also be used to perform precision farming tasks like soil preparation, planting, fertilization, pest control, and harvesting. Moreover, AVs can provide real-time data on soil moisture, temperature, nutrient levels, and other critical factors. This information can be used to make decisions about the appropriate fertilizer levels, planting times, and harvesting times. In addition to AVs, other technologies that can be used in agriculture include artificial intelligence (AI), the Internet of Things (IoT), and blockchain. AI can be used to analyze data from sensors and drones to identify crop diseases and pests, allowing for timely intervention. IoT can be used to monitor soil moisture levels and adjust irrigation systems accordingly. Blockchain can be used to create a secure and transparent supply chain, allowing consumers to trace the origin of their food and ensure its quality. In conclusion, embracing digital transformation in agriculture particularly through advancements like autonomous vehicles, AI, IoT, and blockchain can address infrastructure challenges and enhance food security, even in remote and underserved regions.

4.5 | Redistributing Added Value: Unlocking Equitable Benefits

Logistics agents are essential in the intermediary stages of the supply chain for agricultural products, which include the supplier, farmer, processor, distributor, retailer, and client. Value chains can vary greatly depending on the commodity; nonetheless, even for something as basic as apples, the added value is always greater than 100% from farmer to store. Farmers have a fantastic opportunity to profit from this and split the earnings. Bulking, cleaning, grading, processing, and packing are important supply chain steps that were formerly less expensive to carry out on a bigger scale. To cut down on the costs associated with raw material transportation and long-distance delivery, many of these operations have, however, moved to the farm or neighborhood scale with the emergence of retail food markets and automation. While many rural areas still find it difficult to set up even cold storage due to the lack of power, the emergence of alternative energy sources may significantly alter the options available for processing, packing, and storage. In particular, the use of AI and machine learning can significantly improve the efficiency of these processes, leading to reduced costs and increased profits for farmers. Additionally, the rise of e-commerce platforms has allowed farmers to reduce the number of intermediaries, helping to eliminate unnecessary costs and streamline the supply chain. In conclusion, by following the C2C business model, farmers can sell their products directly to consumers, cutting out middlemen, and earning a fairer share of the profits.

5 | Prospects and Future Applications: Expanding Horizons

Since APV systems are still in their infancy, there is still space for technological development and expansion of application areas. Research has indicated that the combination of dynamic photovoltaic modules and controlled tracking can augment incident radiation availability on the plant canopy. This, in turn, leads to more productive crop production and increased outputs of power and biomass. To better tailor PV systems to the unique needs of crops in co-productive systems, researchers are now looking into the application of wavelength-selective PV modules in horticulture [187]. Additionally, electricity yields can be amplified by combining wind and solar energy production in APV plants, using wind turbines as an upgrade. These innovations hold significant potential for optimizing and expanding the use of APV systems. However, there is still much to learn about the technical and practical aspects of these systems, and further research is necessary to fully unlock their potential. New developments in APV technology could revolutionize the way we approach renewable energy production and could ultimately contribute to a more sustainable and efficient future for our planet.

5.1 | Enhancing Agricultural Efficiency, Sustainability, and Energy Independence

Apart from technological enhancements, there are other prospects for APV deployment, dependent upon the regional climate and the size of the establishment. Utilizing the electricity produced by APV to optimize the farm's current operational flows, such as the processing of harvested goods or energy-intensive operations, like cooling and ventilation, is one such possibility. Farm machinery or vehicle electrification is another possible application for APV. Enhancing storage infrastructure may lead to even higher self-consumption of power. In underdeveloped nations and other places with just a crude electrical system, APV might serve as a decentralized energy source for electrifying rural areas. This was also picked up by Harinarayana and Vasavi [188], who believe that APV has a great deal of potential to help India fulfill its future renewable energy objectives by increasing the amount of energy produced off-grid in rural areas and reducing the need for expensive infrastructure expansion.

The electricity produced by APV might be immediately used to irrigation and water-pumping systems at the farm level. As an alternative, water might be purged into a reservoir and stored, enhancing both food security and water availability for subsequent use in irrigation. The potential of solar water-pumping systems for fodder production in China was recently examined by the author of [189]. They came to the conclusion that while these pumping systems mitigate the negative impacts of climate change and grassland degradation, they provide enormous promise for improving grassland production. Additionally, APV could make a significant contribution to organic farms' holistic farming methods or to large-scale initiatives like the Sahara Forest Project and Sekem, which both aim to recultivate desert regions through agricultural production utilizing cutting-edge and sustainable technologies.

Since these projects are situated in dry areas, it is possible that the APV panels will have a synergistic effect on agricultural productivity by reducing excessive solar radiation and evaporation. China is likewise pursuing and effectively implementing this method in large-scale projects. As a result, APV may be a strategy for desert agriculture that is sustainable. The adverse climatic circumstances linked to climate change, such as heat and drought, may potentially be mitigated by the impacts on agricultural productivity that have been reported. One of the main tenets of a sustainable energy and climate strategy in the EU and other developed nations is the advancement of renewable energies. The restricted amount of land used for agriculture in these nations, along with sustainability goals, have created an ethical dilemma regarding the use of land for the production of food or bioenergy. The use of APV might lessen this. APV has the potential to contribute to sustainable agriculture, particularly in areas where water resources are scarce or unreliable. APV could also be used to power farm buildings, thus reducing dependence on fossil fuels and grid-supplied electricity. The use of APV in agriculture could also help to reduce greenhouse gas emissions, which have been identified as a significant contributor to climate change.

APV could also have a positive impact on the economic viability of farms. The use of APV could lead to cost savings, particularly if the power generated can be used to replace grid-supplied electricity. The implementation of APV could also lead to the creation of new jobs, particularly in the installation and maintenance of APV panels. Moreover, APV could help to reduce the dependence of farms on fossil fuels, which are subject to price fluctuations and supply disruptions. The implementation of APV in agriculture is not without its challenges. One of the most significant challenges is the initial cost of installation. However, the cost of APV panels has been decreasing steadily in recent years, making it a more accessible technology for small and medium-sized farms. Other challenges include the need for adequate maintenance, protection from weather-related damage, and the need for appropriate storage facilities to ensure that excess power is not wasted.

5.2 | Problem Related to APV

There can be several obstacles to overcome in the use of APV technology. It's a given norm that whenever new technologies are unveiled, there will inevitably be some degree of public debate around them; this is also true with regard to APV systems. The unchecked proliferation of ground-mounted photovoltaic arrays in Germany has resulted in a decline in public approval and subsequent legislative limitations on the development of PV installations. Furthermore, the EU Common Agricultural Policy's area subsidies are forfeited when ground-mounted PV plants are installed since arable land is irreversibly converted to surfaced land (European Commission 2003). To distinguish between ground-mounted PV arrays and APV arrays in this context, it is necessary to clarify the legislative restrictions governing the building of APV facilities. To guarantee enough crop output and prevent rivalry with energy generation, APV needs to meet a specific minimum agricultural yield. Avoiding "pseudo agriculture" in any form is essential, especially when it comes to agricultural subsidies. Farmers participating in our real-world APV study said they could live with agricultural output losses of up to 20%. Limits for acceptable yield decreases must be established, though, as subjective views and opinions may differ. The growth of renewable energies is widely supported by society, but social acceptance at the local level is sometimes lacking, especially when concerns about the environment, cultural landscapes, or the loss of visual landscape quality are present [190, 191].

Despite APV's ability to prevent the loss of arable land and the ensuing conflicts between the production of food and energy, there is no denying that the landscape will change, which will unavoidably spark social discussions—particularly when it comes to large-scale plants, as in China. But unlike ground-mounted PV plants, APV won't result in the extinction of animals because fencing isn't required and would actually interfere with agricultural operations [192]. An expansion by APV in cultivation systems with scaffolding structures is likely to be less contentious because the presence of supports is already established. Selective integration with the surrounding landscape while taking local conditions into consideration might be another strategy for enhancing societal acceptability. There are a few different ways to do this, such as using organic materials, designing specifically, or dying the PV cells. Involving the public in decision-making processes might enhance the adoption of renewable energies, as Zoellner, Schweizer-Ries, and Wemheuer [191] found from case studies in Germany. It is important to consider the opinions and perceptions of the local population when implementing APV technology, as it can have a significant impact on the success of the project.

In addition to social acceptance, there are also technical challenges that must be addressed when implementing APV. For example, the efficiency of APV systems is lower than that of conventional PV systems, which may limit their widespread use. However, recent advancements in technology have increased the efficiency of APV systems, making them a viable option for many applications. In addition, the cost of APV systems is higher than that of conventional PV systems, which may limit their adoption in certain markets. To overcome these challenges, it is important to continue research and development in APV technology, with a focus on improving efficiency and reducing costs. This will require collaboration between industry, academia, and government to ensure that the necessary resources are available. In addition, it will be important to educate the public about the benefits of APV technology, including its ability to reduce carbon emissions and promote sustainable development. In conclusion, while APV technology faces obstacles such as social acceptance, legislative restrictions, and technical challenges, ongoing research, public engagement, and strategic design improvements can help overcome these issues and enhance its potential for sustainable development.

6 | Conclusion

APV systems offer a multitude of opportunities that differ based on geographic and climate conditions. The true utility of APV technology is its capacity to produce both food and energy at the same time, offering farmers certain financial benefits in addition to other possible synergistic effects. This is especially true in heavily industrialized nations where the growth of renewable energy sources is becoming more and more important, but productive farmlands need to be protected. APV will inevitably lead to modified microclimatic conditions, such as decreased solar radiation and adjustments to water balance. Since radiation is one of the most important factors influencing crop performance, a decline in agricultural yields is most likely to occur from culturing.

However, the results of shading tests are only partially transferable because of microclimatic heterogeneities under APV. Microclimatic adjustments made under APV can help stabilize production in dry years by offsetting seasonal variations in agricultural productivity and weather. Because of the predicted changes in the climate, this could become even more important in the future. Additionally, crops that are acclimated to shade as well as hot, dry conditions where enhanced water conservation and defense against the damaging effects of high temperatures and excessive radiation are favorable may benefit. Since this technology's effects on crop yields and quality have only been briefly studied, more study that takes into account a variety of climatic factors, crop species, and variety types is necessary to assess the technology's suitability for use in future agricultural systems.

Such studies have to take into account how PV technology and agriculture might work together, as well as how APV can be integrated into various processing cascades and farming systems. In this situation, modeling may be a useful method for turning field trial data into universal models that can be modified to fit particular meteorological circumstances and APV system implementations technically, resulting in the identification of suitable solutions for the relevant areas. However, APV has the potential to be a crucial part of agricultural systems in the future, tackling some of the most important socioeconomic and environmental issues of the day, including land use, food security, climate change, and the need for energy globally.

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