Harnessing the Synergy: Foreign Experiences with Agrovoltaic Systems for a Thriving Green Economy

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Abstract. The paper explores the integration of solar panels with agriculture, known as agrovoltaics, and its potential to enhance land productivity while meeting rising energy demands. The study systematically reviews international experiences using the Web of Science database, focusing on both power generation and agricultural productivity. It identifies crops that do not show significant productivity gains in agrovoltaic systems and discusses the implications for farming and animal husbandry. The paper emphasizes the importance of sustainable development goals and the need for renewable energy in agriculture, highlighting the challenges of climate change and global warming. The research concludes that agrovoltaics can be a viable solution for simultaneous electricity and food production, with certain crops like potatoes showing promise for large-scale systems. However, it also notes the experimental nature of current agrovoltaic systems and the need for further research to optimize crop selection and management practices.

Key words: Green economy; Agrovoltaics; Animal husbandry; Farming; Power generation; Solar panels.

1 Introduction

The global agricultural sector faces a complex challenge: ensuring food security for a growing population under the pressures of climate change. While production has increased to meet rising demand, recent years have seen a plateau in the expansion of agricultural land [1]. This situation is further complicated by the increasing frequency and intensity of extreme weather events like droughts and floods, a likely consequence of exceeding the 1.5°C global warming target [2]. In recognition of the urgency for sustainable development, UN member states adopted 17 Sustainable Development Goals in 2015 [3]. Similarly, the Paris Agreement, adopted at COP21, aims to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels [4]. Contributing to these global efforts, the

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European Union has set ambitious targets: a 55% reduction in greenhouse gas emissions by 2030 (compared to 1990 levels) and achieving climate neutrality by 2050 [5].

It was observed that it is required to speed work on strengthening green energy capacity in agriculture and the water sector, as well as drinking water supply firms with significant electricity use. Based on worldwide experience, farmers were directed to investigate the possibilities of implementing agrovoltaic methods and specific ideas to assist this path [6]. This necessitates an examination of international experiences with the installation of solar panels on agricultural land, sometimes known as "agrovoltaics".

Furthermore, global energy consumption is growing as the world population grows, living standards rise, and industrialization continues [7]. According to predictions, worldwide energy consumption will quadruple by the middle of the twenty-first century, with electricity accounting for 50% [8, 9]. The transition to a sustainable future necessitates a significant transformation of the energy sector. This includes the deployment of low-emission sources and a substantial increase in renewable energy use [5, 10]. Among renewable options, solar energy stands out as a leader, with photovoltaic devices projected to contribute over 40% of global renewable energy by 2050 [11]. Underscoring this potential, Uzbekistan has witnessed a remarkable surge in solar power generation. According to the country's statistics agency, solar power plants produced 435.8 million kWh of electricity in 2022, a significant increase from just 0.2 million kWh in 2018 [12]. Although the present area of solar panels placed is quite modest, current trends suggest that their expansion may result in competition for land and resources, namely with agriculture.

One promising solution to optimizing land use involves integrating solar panels with agricultural practices. This approach, known by various terms like agrophotovoltaics (APV), agro-PV, solar sharing, or PV agriculture, has been gaining significant research momentum since its initial exploration in the 1980s to enhance agricultural land utilization [13].

Agrovoltaic systems can be broadly categorized into three main configurations. The first type, interspersed PV arrays, involves strategically placing solar panels within the spaces between crop rows. The other two configurations involve mounting the solar panels above the crops. In greenhouse-mounted PV arrays, the panels replace all or part of the greenhouse roof. Alternatively, stilt-mounted PV arrays utilize an open-air structure positioned above the crops. Notably, these systems can incorporate either fixed (static) or adjustable (dynamic) solar panels. Dynamic panels offer the advantage of optimizing sunlight exposure for crops by adjusting their tilt angle [14]. Photovoltaic components that absorb certain wavelengths of sunlight can also be utilized to produce power. All of this is based on the notion that crops only consume a portion of the sun's rays and that a specific degree of light is required for photosynthesis to stabilize.

Agrovoltaics is a new manufacturing method that is expanding and gaining popularity across the world. Laub et al. [15] performed a meta-analysis to investigate the yield variations of several crops under PV shadow and identify the most promising candidates for this system. Mamun et al. [16] and Sirnik et al. [17] did research on the circular economy and agrovoltaic deployment landscapes. However, in addition to changes in the microclimate environment caused by infrastructure, agricultural yield and agronomic outcomes have not received adequate attention. As a result, our findings can serve as a valuable guideline for future research. The goal of this research endeavour is to investigate international experiences with agrovoltaic systems and their effects on farming and animal husbandry in order to create a helpful database for individuals who use these systems in our country. Based on the goal of the study, the research objectives are as follows: analysis of agrovoltaic systems and their impact on electricity generation and agricultural goods; Identifying crops that are best suited for usage in agrovoltaic systems; Consideration of concerns of sustainable development and the demand for renewable energy in agriculture.

2 Materials and Methods

In 2024, research on agrovoltaics was analysed using the keywords Agrovoltaica, Agri-PV, and Agri-photovoltaic from the Web of Science database. Articles were reviewed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. The selection comprised only primary scientific studies. The final 54 papers covering qualitative and quantitative analyses of animal husbandry and agriculture were excluded. In the following stages, using Classification and analysis Methods, research is organized by agrovoltaic technique and agricultural product type. Meta-analysis is used for studying yield changes of various crops under the shade of photovoltaic panels to identify the most promising candidates for the system.

3 Results

3.1 Classification and description of the whole area of study

It was shown that the majority of agrovoltaic systems are placed in the northern hemisphere (Fig. 1). The map shows the spread of agrovoltaic systems in locations with abundant solar resources. However, this does not provide conclusive evidence on whether this area is suitable for agrovoltaics. Because it is dependent on climate and soil conditions. This helps to explain why these systems are most commonly implemented in Asia, Europe, and North America.

Due of their high cost, agrovoltaics are mostly used in industrialized nations. Of the 54 studies, 15% were in the United States, 13% in China and Italy, 11% in South Korea and France, with Europe having the highest rate at 44%, followed by Asia at 37%, and North America at 15%. Two-thirds of the analyzed agrovoltaics (33) were put in open-air buildings (stilt-mounted PV arrays), while 15 were installed in greenhouses (Fig. 2).

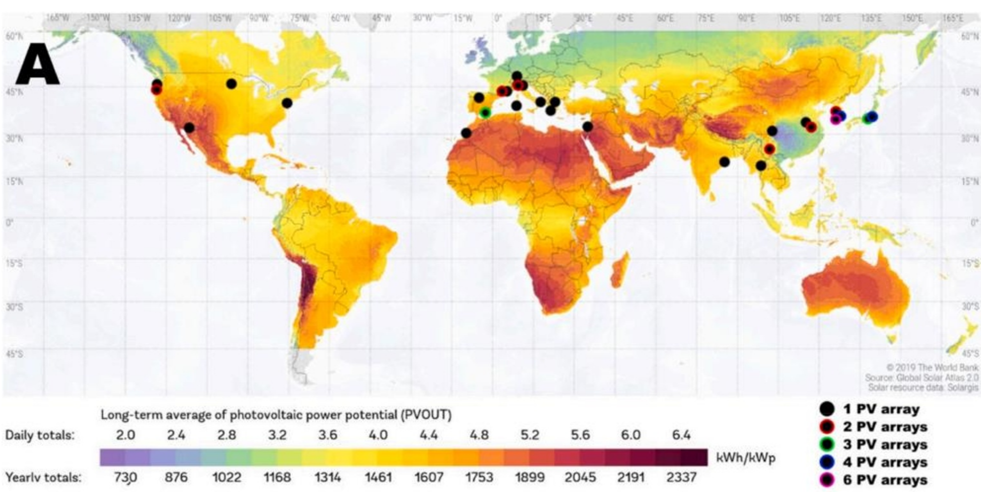

Fig. 1. The placement of the agri-photovoltaic installations.

Note: The placement of the installations is depicted on a map with different colored dots indicating multiple installations in the same region. This map illustrates the photovoltaic power potential, where darker colors represent higher long-term average potential. The map is adapted from © 2020 The World Bank, utilizing data from the Global Solar Atlas 2.0 and solar resource information from Solargis [18].

Most of them have installed statistical solar panels. Agrovoltaic installations vary in size from 4 m2 to 2.4 hectares. Almost two-thirds of them are located on an area less than 1000 m2. 79% of agrovoltaics occupied less than 40% of the land. In general, it has been discovered that covering up to 25% of the ground with PV shadow has no significant effect on crop growth or quality [19].

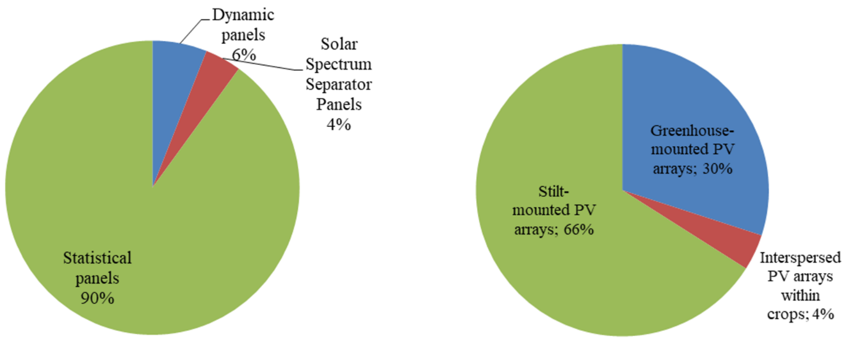

Fig. 2. Distribution of installed agrovoltaic systems by type.
Source: [18].

When the PV shadow approaches 50%, many crops suffer from reduced growth. Three studies provide information on the management of lambs and dairy cows in an agrovoltaic system. The remaining significant studies focused on lettuce and tomatoes, with grains and legumes accounting for 11% and 10% respectively. Although strawberries are better suited to this system, limited study has been conducted (Fig. 3). It has been discovered that grains and legumes are not very compatible.

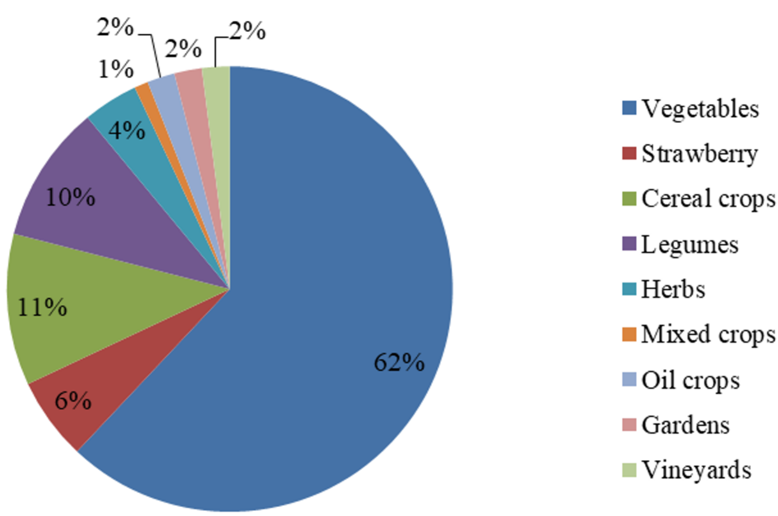

Fig. 3. Distribution of installed agrovoltaic systems by crop types.
Source: [18].

3.2. Agronomic results of agrovoltaics

3.2.1. Using solar energy with animal husbandry

Studies have demonstrated that lambs raised in an agrivoltaic system had no effect on their daily live weight increase [20]. However, these findings were obtained under settings in which the average dry nutritional value of forages is lower than in open ground. Nonetheless, the quality of feed under the agrovoltaic system is superior, thus this drawback is mitigated. Both a decline [21] and an increase [22] in grass beneath solar panels were reported. These variances might be attributed to variations in climate and soil fertility. Animal wellbeing was evaluated and quantified by ocular observation of animal behavior. No change in the lambs' behavior was seen [20]. Even in healthy cows, no alterations were seen under solar panels [23]. However, their activity was decreased, which can be explained by the fact that ruminants remain under the panels during the hottest part of the day. The herd's general nutrition remained same; however, their body temperature was much lower. However, none of these factors had any effect on milk quality. One explanation for this might be because the cows were only kept under the solar panels for 22 days from June to September, when if they had been kept for longer durations, the quality and quantity of milk would have risen.

3.2.2. Solar energy and farming

3.2.2.1. Vegetables

More than 23% of research included lettuce as the most investigated crop. This can be attributed to its simplicity of cultivation, quick growth, and the fact that it takes minimal area to flourish.

Some research showed a rise in average weight, whereas others found the reverse. A single research revealed an 87.6% rise in weight. under this example, it was kept under settings that provided 18% less light than in the open air [24]. However, in certain circumstances, output reduced by 50% [25, 26]. This indication has been reported to alter with the seasons [24, 27]. Crop dry weight was consistently lower with agrovoltaics. Seasonal effects on this parameter were also identified. According to studies, the number of lettuce leaves has grown. Some studies found a considerable increase in lettuce leaves under solar panels, while others found a decrease of up to 25% [28]. Furthermore, research found that crop leaf development reduced during the first three weeks of exposure to solar panels.

Tomatoes were the second most studied crop in agrovoltaics. It was discovered that the change in production was varied amongst them. When photosynthetically active radiation (PAR) was lowered by 30%, yield decreased significantly [29], however when PAR was reduced by 45%, yield increased twofold [30]. Fruit weight changes varied, with some studies showing an increase [31, 32] and others showing a decrease [33, 34]. under two trials, yield did not alter at all, although another research found increased yield under full sunlight [35]. Such disparities in outcomes can be explained in part by the cultivars used, as well as differences in temperature and sunshine under agrovoltaic settings. High temperatures have been found in studies to reduce tomato output, while shade has not been demonstrated to increase it [36]. Tomato yield also decreased when PAR was reduced to 28.8%. Such a negative change becomes more pronounced when PAR decreases from 46.6% to 66.3%. However, in some cases, tomato yield and leaf growth were observed under agrovoltaics [37, 38]. This shows the adaptability of plants to the agrovoltaic system.

According to a study done in Germany over two seasons, potatoes grown under solar panels outperformed those cultivated outside [21]. However, it was shown that the output of potato tubers declined by 18% in the first year but increased dramatically by 11% the following year. However, yields beneath the panels exceeded the national average in both years. According to a number of studies, installing agrovoltaics enabled the production of power without compromising potato productivity. At the same time, there was essentially little change in the potato nodules. Another research [39] found similar findings, indicating that potatoes are an appropriate crop for agrovoltaics.

When sweet peppers were grown under solar panels, the output and quantity of fruits per plant rose but the quality remained same [40, 41]. There was no discernible difference in yield when wild rocket (Diplotaxis tenuifolia (L.) DC.), cabbage, broccoli, or celery were grown using agrovoltaics [42]. In contrast, growing garlic, onion, basil, or spinach beneath solar panels resulted in a considerable drop in production or biomass [43]. Pak choi output was also lowered by more than tenfold when grown in the full shadow of solar panels [44].

3.2.2.2. Cereal crops

Surprisingly, although maize is commonly thought to be a sun lover, it has been shown to tolerate a modest amount of shadow [45]. In our study, there was no significant difference in maize production when grown in around 20% shade. A modest density of solar panels was shown to improve biomass and yield (+5.7%) compared to plants growing in full light. In contrast, increasing the density of solar panels reduced biomass and production. High yields at low solar panel densities are essentially explained by maximizing maize's light saturation point and lowering soil water evaporation caused by shade [18]. The yield of corn grown in agrivoltaics improved even when the shade level reached 21.3% [46], while production decreased at greater shades. There were no significant variations in maize plant size or output throughout two years of investigation [47].

Studies done on several farms over several years found that increasing Pv shading output dramatically lowered rice yield [48]. This was partially apparent in the shortening of each plant's stem. In contrast, solar panels had no effect on the number of spikes per plant or the weight of the grain. Significant production losses were also seen in rice crops cultivated under three different agrovoltaic systems with 25% to 32% shadow [39]. Another study found that yields reduced from 9% to 19% when using solar panels [47].

The biomass of winter wheat cultivated with solar panels rose for two years in a row [21]. The yield reduced dramatically in the first season, but the difference did not persist the following year. In addition, the average grain weight has consistently been much lower. Furthermore, the yield and plant height of two sequentially planted rye harvests were same whether grown in broad sunshine and under solar panels [47].

3.2.2.3. Legumes and oilseeds

Agrivoltaics was used in a modest number of tests with legumes and oilseeds. Nonetheless, increasing the amount of PV shadow under the panels in crops including sesame, mung bean, red bean, and soybean reduced their output [46]. Production decreased from 7% (sesame) to 26% (red bean) at a shading ratio of 21.3%. When solar panels were shaded by 32%, yield reductions ranged from 30% to 53% (soybean and sesame). Soybean and sesame yields and development have also decreased significantly [39]. While there were no variations in soybean or red bean growth or output during the first year, all results were considerably lower in the second season [47]. The bad results from the second season might be attributed to climatic circumstances and a succession of severe rainfall over the summer. Furthermore, when green beans were cultivated using solar panels, the output reduced by 49% [49].

3.2.2.4. Berries, grape and tree fruits

Some research have examined the impacts of three agrovoltaic systems with solar panel coverage of 19.0%, 30.4%, or 38.0% on kiwifruit during a three-year period [50]. In this situation, when the shadow level increased, plant growth reduced. There were usually higher yields without solar panels. However, there was no substantial variation in the shade of 19.0% (ranging from 2.6% to 6.5% depending on the year). In contrast, increased shadow lowered yields by at least 20%.

The impacts of a dynamic agrovoltaic system on a Golden Delicious apple orchard were examined [51]. The study's goal was to assess the influence of the panels on trees over three seasons by optimizing their electrical production (average solar radiation decrease was 50-55%). There was no change in phenology during the three growing seasons. Trees cultivated with solar panels have much greater specific leaf area (leaf area per unit leaf dry weight) and fewer blooms. In the first two years, the installation of agrovoltaics had a detrimental impact on tree output, reducing it by 32% and 27%, respectively [51]. In the final year of the experiment, an opposite trend was observed as the yield of trees under the panels nearly quadrupled. This discrepancy can be partly attributed to the decrease in air temperature during the blooming cycle, which led to a significant physiological loss of blossoms in the open control plots. In these circumstances, agrivoltaics provided protection for the trees by mitigating the temperature drop.

An experiment conducted in northern Italy over three years examined grape output under solar panels that shaded 75% of the crop. The results showed that agrovoltaics had a consistent negative impact on productivity, with a significant decline observed in the last two years. On the other hand, the mass of grape seeds remained constant. The reduced number of berries under the panels accounts for some of the yield variation. Strawberries grown in greenhouses partially covered with PV panels produced a higher yield and maximum weight [52, 53]. In addition, favorable improvements were detected in the strawberries.

All of the investigations mentioned above also found that the chemical makeup of the products grown under agrovoltaic conditions had changed [18].

4 Discussion

Current research is focusing increasingly on agrovoltaics, as indicated by the growing number of papers on the subject in recent years. However, it is impossible to compare agrovoltaics accurately because they all differ in terms of design and solar panel selection. Furthermore, the soil and climatic circumstances of a certain location might have a significant impact on the results achieved, since the weather may be good one year but unfavorable the next. Another crop-level constraint is the enormous number of species and cultivars evaluated, as each cultivar has its own optimal development circumstances and is thus influenced differently by the production system. Two-thirds of the research involved veggies. As a result, there is a scarcity of knowledge on other crops, making it difficult to establish which species are most suited for agrovoltaics at the moment.

Few agrovoltaic experiments with animals have been conducted, and data is few, making it difficult to judge the viability of such a system. However, the initial findings indicate that it is conceivable to raise animals in conjunction with energy. More research should be undertaken with extended maintenance durations. Dairy farming should be the primary focus of research owing to temperature stress, which can affect milk output, and the enormous quantity of agricultural land needed for cow breeding across the world. This area has considerable potential for food and power production, as well as the development of agrovoltaics using animals.

Crop research has mostly concentrated on vegetables, particularly lettuce and tomatoes. Depending on the research, yield development for these two plants was found in opposing directions, demonstrating the difficulty of generalizing the influence of agrovoltaics on yield. Furthermore, crops that are now thought to be difficult to grow in the shadow, such as corn, can be produced under specific conditions using solar panels. It is important to note that only a few studies have focused on berries, which may hold potential due to their tolerance to shading. Additionally, there is a current lack of information regarding agrivoltaic perennials. Future developments should emphasize these. Furthermore, numerous cultivars of the same species may need to be evaluated concurrently and over a period of several years to validate the presence of varietal variations. One of the study's key constraints is the size of the agrovoltaic installations under consideration. More than two-thirds of agrovoltaics require less than 1,000 m2 of land, limiting the impact of shadow on crops and output.

Solar panels with light spectrum separation is an emerging technology that has not been extensively studied yet. Analyzing this technology could be beneficial, as it prevents direct shadowing of plants and decreases the wavelengths required for photosynthesis. However, research has not been able to identify a general limit of shadow that has no detrimental impact on crops. In reality, the outcomes vary based on factors like plant species, crop location, agrovoltaic array design, and season. Therefore, it would be preferable to first determine the optimal daily light integral level for each crop species and then design the agrovoltaic system accordingly.

5 Conclusion

The global population growth has led to increased food consumption, necessitating higher agricultural land productivity. Similarly, the demand for renewable energy, particularly electricity, is expected to rise in the coming years, leading to an expansion of solar panel installations as part of the green energy initiative. However, this development can create competition for land between agricultural production and solar energy generation.

To address this challenge, the concept of combining these two lands uses on a single field, known as agrophotovoltaics, was first proposed in 1982. Research in this area is ongoing, and the preliminary findings are encouraging. Certain livestock and crops, such as potatoes, appear suitable for large-scale agrovoltaic systems. Crops that require abundant sunlight, like tomatoes and maize, may also be cultivated under solar panels.

The amount of photosynthetically active radiation (PAR) received by crops and their specific requirements significantly impact their production performance. Additionally, it is crucial to consider the influence of agrovoltaics on crops in the context of climate change. Agrovoltaics can help minimize the effects of climate change by directly modifying crop selection to mitigate the impacts of extreme weather conditions. Furthermore, the reduced water demand for crops grown under solar panels, coupled with increasing water scarcities, presents a clear advantage of this innovative technology.

The findings from this research can be applied in future agrovoltaic studies to identify the most promising crops and expand the system globally. Initially, trials should focus on regionally significant crops, followed by larger-scale efforts. It is beneficial to conduct variety trials over multiple seasons to assess performance under diverse growing conditions and select the most suitable options. Lastly, the installation of solar panels can have varying impacts on the growth parameters of different crops, which must be considered.

While agrovoltaics hold promise, the technology is currently in the experimental stage and requires further improvements in crop and variety selection, water and fertilizer management, and crop protection to enhance its agrotechnical performance.

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