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Sun, Soil, and Sustainability: Opportunities and Challenges of Agri-Voltaic Systems in India

GUL MOHAMMAD*, HINDOLA GHOSH, KUHELI MITRA and NABANITA SAHA

Department of Electronics, Dinabandhu Andrews College, W.B., India.

Abstract

The rise in green energies attempts to fulfil worldwide energy needs while substituting fossil fuels. It does, however, necessitate a vast amount of land. On the other hand, food security is jeopardized by the effects of climate change as well as an expanding population, particularly in India. As India strives for net-zero emissions by 2050, the integration of photovoltaics (PV) with agriculture has unlocked an emerging field known as agrivoltaics (AV). Agrivoltaics not only provides a long-term solution to the issue of land competition, but it also increases agricultural yields, conserves water resources, and lowers greenhouse gas emissions. To evaluate the elements influencing the efficiency of AV, studies on revolutionary technologies connected to solar systems and the latest generation of photovoltaics are examined. This paper looks at agrivoltaics as a climate-conscious farming option with its advantages and disadvantages in India. This article also reviews AV plant designs and how varied intervals, altitude, and density affect shadowing.

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Introduction

Fossil fuels play a significant role in current worldwide economic development and energy supply. It has been the dominant energy source for producing power throughout the past century. It produced 64.5% of the world's power in 2017 compared to 61.9% in 1990, showing a continuous rise, including both absolute and relative terms, in their consumption for electricity generation. India's energy system is currently supported by fossil fuels in a predominant way, and India is currently the 3rd largest energy consumer in the world.[1] In this state, there is another significant concern: when fossil fuels are burned, they emit greenhouse gases, resulting in long-term changes in weather patterns, with an average global temperature rise of 1.1°C (1.9°F) since 1880.[2] By 2030, India is projected to warm by 0.5°C, which is almost similar to the warming throughout the 20th century, and by the end of the 21st century, the northern part of India will likely

CONTACT Gul Mohammad gulmohammad111989@gmail.com Department of Electronics, Dinabandhu Andrews College, W.B., India.

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get warmed by 2-4°C. Greater tropospheric ozone pollution and associated air pollution in the main cities are predicted to result from global warming.[3] The majority of global models predict a worsening of the Indian summer monsoons. Rising aerosol emissions from energy generation and other factors may reduce rainfall, resulting in drier circumstances and additional dust and smoke coming from the burning of drier crop plants, which may have an impact on both the local and global hydrological regime and crop production. Farmers' decisions on what crops to grow and when they should grow them will be impacted by uncertainty about monsoonal shifts, which would lower productivity. Additionally, glaciers will become less full, and faster snowmelt will result in less stream flow from rivers needed for irrigation. The vast majority of the poor, which includes smallholder farmers and agricultural labourers who do not own land, may be the most severely affected, necessitating extensive government relief efforts. To cut GHG emissions and stop climate change, around 200 nations committed to working together under the Paris Agreement of 2015. Reaffirming the Paris agreement, India is set to fulfil the targets by 2030, which states that India's capacity for non-fossil energy will expand to 500 GW and it will derive 50% of its energy needs from renewable sources. The most economically competitive source of green energy on a global scale has become ground-mounted photovoltaics (PVGM)4. As a result, PVGM has a growing market share in the PV industry.[5] But the mainstay of humankind is land. It offers fresh water, food, and several other biological resources. Nevertheless, cropland is predicted to decrease across the whole world by 50,000,000 ha (the size of Spain) to 650,000,000 ha (double the size of India) by 2100 as a result of socioeconomic growth, including framework, industrial parks, and housing estates.[6] It can be predicted that the increasing demand for PVGM will cause more rivalry for land use, which could eventually result in economic, environmental, political, and social issues.[7] The Integrated Food-Energy System (IFES), which permits the concurrent production of both food and energy on the same plot of land, is one strategy for overcoming the difficulty of sustainable land usage. Additionally, it makes the most of co-acting effects by fully realizing the potential of both manufacturing systems, as is the case with agroforestry systems or the production of cascading agrofuels.[8] Therefore, it is more important than ever to find creative ways to install PV while lowering the associated land use. Some of these novel models are floating photovoltaics (FPV), which utilize available water surfaces; building integrated photovoltaics (BIPV), which utilize available building surfaces, and agrivoltaic systems (APV), which simultaneously employ land for food production and electricity production. They are a key component of the future's strategic plan and have enormous potential as a consequence of the move towards renewable energy.

Agri-photovoltaic plants are one developing option in the PV sector for reducing the effects of cultivable land acquisition. Agrivoltaic systems also provide a comprehensive solution to decrease emissions of greenhouse gases from the power sector, add more solar power, encourage more eco-friendly farming techniques, lessen agriculture's negative effects on the environment, and boost rural development. APVs have received a considerable amount of research attention recently because of their promise in the food-energy nexus. Through maximizing light availability, minimizing the demand for irrigation, and providing protection from harsh weather events, demonstration projects with innovative conceptual designs based on APV modules for covering open fields have shown encouraging results. Initially, agrivoltaic research and experimental systems have been created in Germany, Japan, the United States, Italy, Malaysia, Egypt, and Chile. An estimated 2,200 AV systems with a combined generation capacity of 2.8 GW already developed by 2020, which is substantially more than the combined installed capacity of all floating and concentrated PV power plants.[9] In addition to India and Germany, countries that have already used such systems in agriculture include South Korea, China, France, the United States (Massachusetts), and Japan.[10] The fundamental issue is that some crops' yields have decreased as a result of shade and modifications to the soil moisture regimes.[11] Alterations in soil moisture and sunlight patterns during the production of some crops have a negative impact.[12] The same impacts can benefit other crops,[13] reduce the impact of dry or wet seasons,[14] and maintain the revenue of an arable producer by diversifying their sources of income and ensuring year-round sales of energy.[15] To reduce the drop in crop profitability, designers must get over the physical limitations of covering crops with solar modules. As can be observed, APV does not adhere to conventional PV system design standards, which focus on optimizing inclination and orientation angles to maximize power production by selecting slopes near latitude and equator-facing orientations. Since energy performance can occasionally conflict with ideal agricultural advancement and landscape restoration issues, expanding PV to include farming operations is a constant challenge that requires numerous design adaptations depending on the local weather patterns, crop type, energy requirements, and landform. In order to ensure and comprehend the close relationship between energy, food production, and space, a new set of needs must be addressed. Therefore, the purpose of this paper is to examine the prospects and opportunities of agrivoltaic in India.

Concept

Agrivoltaics maximizes the utilization of land by combining photovoltaic panels and crops. Simply, it is a technique for integrating solar panels alongside vegetation on farmland, as shown in Figure 1. By producing both photovoltaic energy and field crops within the same location, it is possible to share light, increase freshness, and reduce moisture loss. The process of fusing solar technology and agriculture began in 1975 with the introduction of the first photovoltaic water pumps.[16] Since then, photovoltaic applications in agriculture have steadily shown a tendency towards diversification, moving from the first irrigation of agricultural land to present-day illumination, ventilation, agricultural machinery, agricultural automation, and agricultural robotics.[17,18,19] Agrivoltaic systems may be categorized using a number of factors. Figure 2 shows a uniform categorization that can accurately define each distinctive agrivoltaic system throughout the world while remaining consistent with local (weather-farming) variables.

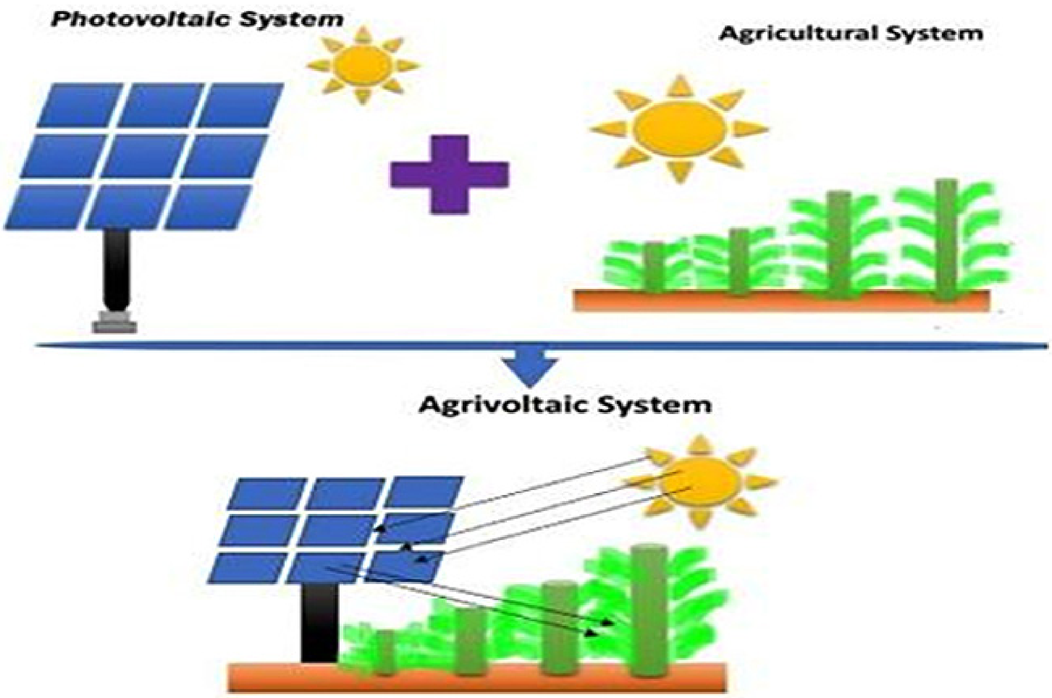

Fig. 1: Agrivoltaic System

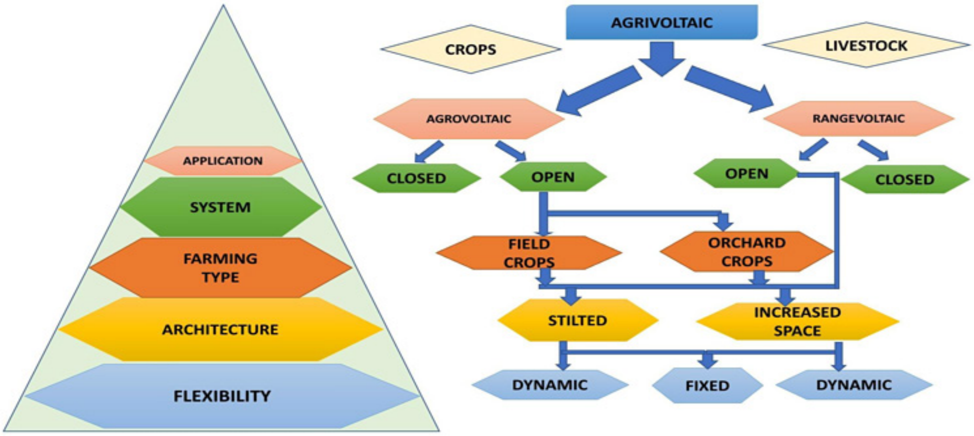

Fig. 2: Classification of Agrivoltaic

Methodology

The research methodology involved a systematic review of the literature by using Scopus and Web of Science. For the analysis, highly referenced peer-reviewed papers available up to the current date were considered. Conference papers and journal publications (articles or reviews) were taken into consideration. Key phrases for the search included "Agrophotovoltaics (APV)", "Agrophotovoltaics in India", "Solar sharing", "Agrivoltaics systems/ array (AVS/AVA)", "Photovoltaic agriculture", "Solar greenhouse", "Agro/Agri-PV", "Current status of agrivoltaics in india". Materials were looked at in the areas of regulations, application, policy, status, technical aspects, and future prospect of agrivoltaic in India. Apart from scholarly study articles, and to encompass the ongoing investigation and advancement of agri-photovoltaic systems the authors extended the search to some grey literatures, consisting of media articles, company reports and studies, and information available on government websites.

Scope of Agri-Voltaic in India

In order to achieve various goals, including compliance with the Paris Agreements, food security, and employment, it is essential to develop novel solutions for a highly populated nation like India. PV systems, which have just emerged as a potential candidate for India's energy portfolio, will play a significant role in the country's energy mix and are a crucial solution for energy transformation. In addition, agriculture is regarded as the foundation of the Indian economic system. According to the 2011 census, 70% of Indians are directly engaged in farming. So, considering the need for energy transition and the socio-economic structure, India is currently highlighted for having high potential and immense scope in the agri-voltaic sector. India receives a lot of solar radiation because it is situated inside the equatorial solar belt. The India Meteorological Department (IMD) has a national network of radiation stations that track solar irradiance as well as the length of each day's sunshine. 250–300 days a year are spent with clear, sunny weather throughout the majority of India. The range of annual global radiation, which is comparable to radiation experienced in tropical and subtropical climates, is 1600 to 2200 kWh/sq.m.[20] Around 6,000 million GWh of energy per year are contained in the equivalent energy potential,[21] and it can generate 500,000 TWh of energy annually, according to Kar *et al*., 2016.[22] Here, just 10% of the energy transfer is taken into account when calculating the production. The estimated amount of land that may be used for solar energy in India is between 50000 sq.km and 75000 sq.km in order to meet the country's goals of 500 GW of non-fossil fuel energy by 2030 and a net-zero aim by 2070.[23] According to the report by the Indo-German Energy Forum Support Office (IGEF-SO) and the National Solar Energy Federation of India (NSEFI),[15] operational solar projects on agriculture plots have been functional since January 2021, collectively generating 48.4 MW of electricity at present. They are referred to as three major plant types: R&D-focused initiatives or academic projects, projects subsidized by the government, and commercial ventures developed by private companies,[24] as shown in Table 1.

Table 1: Ongoing Agrivoltaic Project in India[25]

Project Name	Project Type	Solar-energy Generation Capacity
CAZRI plants in Jodhpur, Rajasthan	Academic project	100kW
Junagadh Agriculture University plant, Gujarat	Academic project	7kW
Amity University plant Noida, Uttar Pradesh	Academic project	10kW
NISE plant near Gurgaon, Haryana	Academic project	100kW
Dayalbagh Agriculture University plant Agra, Uttar Pradesh	Academic project	200kW
Jain Irrigation plants, Jalgaon, Maharashtra	Academic project	14.4kW
GSECL Harsha Abakus plant, Panandharo, Gujarat	Government supported project	1MW
GSECL Harsha Abakus plant, Sikka, Gujarat	Government supported project	1MW
GIPCL plant Amrol, Gujarat	Government supported project	1MW
GIPCL plant Vastan, Gujarat	Government supported project	1MW
Krishi Vigyan Kendra, Ujwa, Delhi	Government supported project	110kW
Cochin Airport plant, Kerala	Commercial Project	40MW
Abellon Energy plant, Aravalli, Gujarat	Commercial Project	3MW
Hinren Agri-PV Rooftop (APVRT), Bangalore	Commercial Project	3kW
Mahindra Susten plant, Tandur, Telangana	Commercial Project	400kW

But India has to increase solar power generation to meet 500 GW of clean energy capacity. 60 percent[26] of India's land area is cultivated, which is significantly greater than the global average of 39 percent. IEEFA's recent research shows that agri-voltaic technologies in India are better positioned than in most other nations to ease strain on additional land and ecosystems.[27] So, for the construction of more agri-voltaic plants, uncultivated lands must be utilized for possible crop production, and some of the farmlands would need to be transformed into non-agricultural land. According to India's geographical structure, its overall land area is classified into 9 categories, as shown in Figure 3.

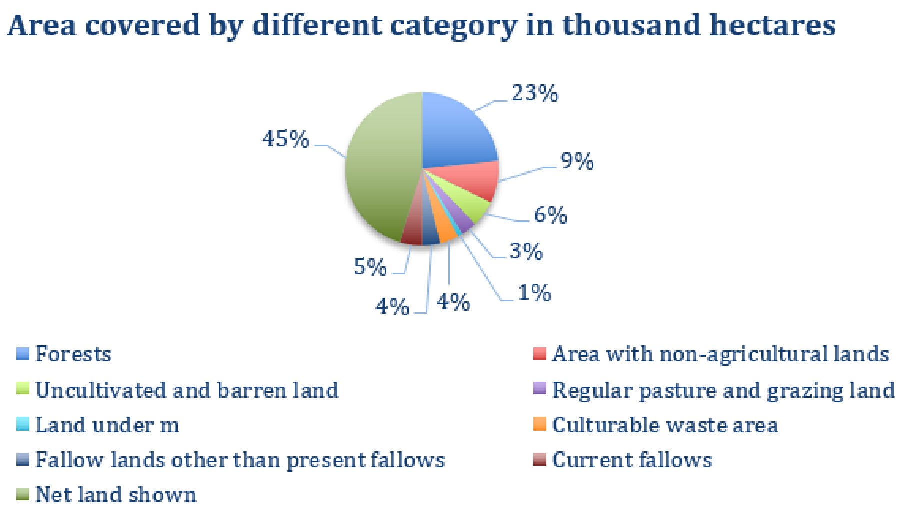

Fig. 3: A Representation of the Area Covered by Different Category in India[29]

To install more agri-voltaic plants, the total agricultural land can be considered by adding the culturable waste areas, land under misc. tree crops, current fallow lands, fallow land other than present fallows, and the net land sown. The regular pasture and grazing lands can be converted and utilized as agri-voltaic plants with animal husbandries. The final performance of the herd is increased by AV construction since it reduces the cost of fencing the area and protects animals from attackers and bad weather. Grazing beneath agri-photovoltaic modules can improve the environment and the welfare of animals while also increasing land productivity by up to 200 percent.[28] Uncultivated lands should have been explored and studied thoroughly to employ agri-pv applications.

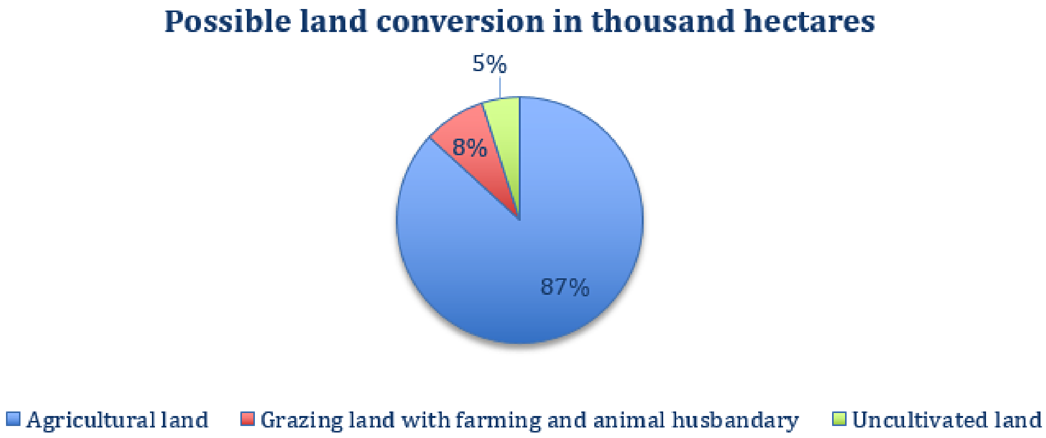

Fig. 4: Possible Land Conversion for Installing Agri-voltaic Plants[29]

Only agricultural lands may realize a total potential energy output of 629.69 GW. Figure 4 illustrates the potential of agri-voltaic for grazing land and uncultivated lands, where a study shows that uncultivated land can provide solar power of 56.6 GW.[29] Although these goals seem exceedingly lofty, the government might opt to begin with a modest goal of 20–30 MW in the initial year and increase it over the following ten years. According to the projected trajectory shown in Figure 5, the Indian government may decide to target 15 GW of agri-voltaic during the course of the next 10 years.[24]

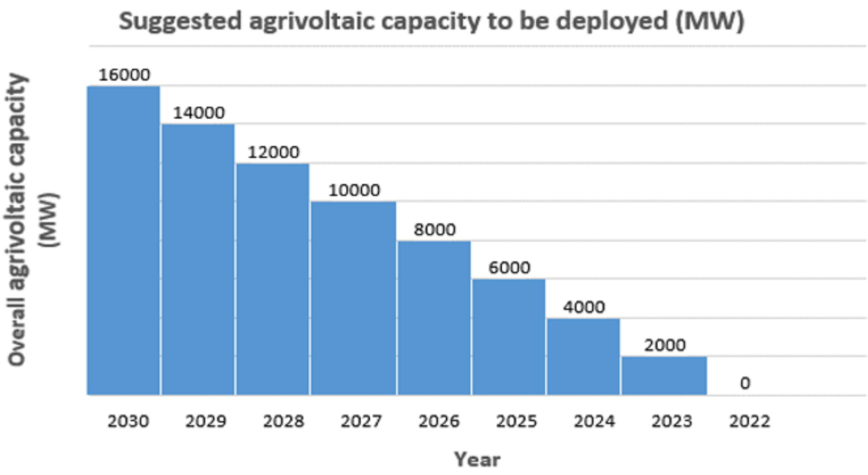

Fig. 5: Prediction of Growth of Agrivoltaic in India[1]

Initiatives Taken by the Government

In order to increase electricity production using solar energy, India must deploy solar systems across the country. To implement this, the Indian government has already introduced a variety of policy interventions and programmes, such as JNNSM, or Jawaharlal Nehru National Solar Mission (2010), and the PM KUSUM, or Pradhan Mantri Kisan Urja Suraksha Evam Uthaan Mahabhiyaan (2019), the Solar Park Scheme, The Grid-Linked Solar Rooftop Scheme, The Viability Gap Financing Scheme, etc. GoI has also made several efforts to encourage people to adopt *solar energy.* These include

- Allowing up to 100% automatic route foreign direct investment ("FDI") in the renewable energy sector
- Waiving interstate transmission system fees for interstate sales of solar power from the projects completed by June 30, 2025.
- Granting standards via Bureau of Indian Standard certification for the deployment of solar photovoltaic systems and devices.
- Standard bidding guidelines for tariff-based competitive bidding for the procurement of power from grid-connected solar PV projects

India founded NABARD with the goal of advancing sustainable and equitable rural and agricultural development via collaborative financial as well as non-interventions, innovations, technology, and institutional development. The Kisan Credit Card Program was established with the goal of supporting farmers' access to financing in a straightforward manner. The Kisan Credit Card Program's goals include, among others,

- to fulfil farmers' short-term loan needs for agricultural production and post-harvest costs;
- to provide operating cash for agriculturally related operations and the upkeep for farm assets.
- to provide the home of a farmer's needs for consumption

Additionally, numerous state-specific laws and programs are being implemented to advance agri-voltaic projects across India,[24] and they are shown in Table 2.

Table 2: Different Schemes to Encourage Agrivoltaic in India

Scheme	State	Description
Mukhyamantri Kisan Aay Badhotri Solar Yojana	Delhi	Land is leased by a developer from a farmer in exchange for a power purchase agreement with a government entity. It intends to give farmers a source of additional income starting at Rs. 8333 per month per acre with an increase of 6% every year.[30]
Surya Raitha Scheme	Karnataka	It is adopted primarily to solarise farm pumps. Old, ineffective pumps are updated with new, energy-efficient pumps under the Program. Farmers must utilise two-thirds of the electricity produced by solar panels, with the remaining energy being traded to the DISCOM at the planned rate of Rs. 7.50 per kWh.[31]
Suryashakti Kisan Yojana (SKY)	Gujarat	The scheme will last for a total of 25 years, divided into 7- and 18-year periods. Under this scheme farmers will receive Rs 7 (Rs 3.5 from GUVNL + Rs 3.5 from the State Govt.) for every unit sold during the first 7 years, and Rs 3.5 for the following 18 years.[32]
PM KUSUM	Rajasthan	The pre-fixed levelized rate of 3.14/kWh was approved by Rajasthan Electricity Regulatory Commission (RERC) for the KUSUM program's Component A for capacities up to 725 MW.[33]
PM KUSUM	Odisha	As part of a 25-year agreement between SECI and the local DISCOM OREDA, solar-agricultural growth is likewise being implemented in Odisha. Under this arrangement, participating farmers earn Rs. 20,000 per acre yearly in addition to using the land for farming.

Mukhyamantri Saur Krushi Vahini Yojana	Maharashtr	The Maharashtra Electricity Regulatory Commission has accepted the long-term, 25-year rate of 3.11/kWh for 100 MW of solar power. Under this scheme, the project is being built by EESL (Energy Efficiency Services Limited) at several areas in Western and North Maharashtra (MSKVY).[34]
PM KUSUM	Haryana	The Commission selected a rate of Rs. 3.11 per kWh. In order to establish a pilot programme, DISCOMS must allocate 135 MW plant and meet a minimum CUF requirement of 15%. The average annual increase in O&M costs is 5.72 percent.[35]

Various liberal policies for agrivoltaic technology by the Government of India and various states have made it beneficial in all aspects. Since the German Chancellor and Indian Prime Minister founded the Indo-German Energy Forum (IGEF) at Hannover Fair in April 2006, strengthening and expanding collaboration between India and Germany in the solar energy industry has been the main objective. They are collaborating closely to improve agri-voltaic in both nations in preparation for upcoming energy changes. Therefore, India has a very high chance of achieving a wide range of objectives with the implementation of more agri-voltaics systems, including fulfilling international commitments, providing employment, ensuring financial constancy, rising sustainable energy production capacity, protecting natural resources, and succeeding in numerous other goals.

Agrivoltaics in Fish Farming and Irrigation in India

Fish farming and irrigation are important parts of agriculture in India because it has a large peasant population. However, traditional farming is not always sustainable, so farmers are increasingly turning to new technologies like agrivoltaics to improve efficiency and profitability. In India, it is a tradition of freshwater fish culture. Being the third-largest producer of fish in the world, India produces 7.96% of global production.[36] Fish farming is mostly practiced in the southern and eastern regions of India because of the huge number of ponds suitable for aquaculture. The availability of water is one of the main issues that Indian fish farmers encounter. Irrigation is also a great concern for farmers, as many zones of the country experience drought conditions for most of the year. Agrivoltaics could provide a solution to both of these problems, as it allows farmers to generate solar power while also providing shade and reducing evaporation from water bodies. In a study on an agrivoltaic system that combined fish farming with photovoltaic panels, it was found that fish production became far better along with improved water quality through the shading of solar panels.[37] The Indian Council of Agricultural Research (ICAR) has shown that agrivoltaic systems can increase crop yields by up to 30% along with generating solar power38. The National Institute of Solar Energy (NISE) found that agrivoltaic systems can help conserve water. The researchers tested an agrivoltaic system that combined solar panels with sugarcane farms, and they found that the panels reduced evaporation by around 30 percent.[39] The Farmers in drought-prone zones may get a significant benefit, as it will help conserve water and reduce the need for irrigation. There are already several agrivoltaic projects underway in India that combine fish farming with solar power. An overview of agrivoltaic projects combining fish farming and solar power in India is shown in Table 3. We are likely to see more and more agrivoltaic projects with a significant impact on the sustainable agriculture of India.

Constraints

Cost of Solar Panels

Solar-based energy generation has the potential to bring about rural electrification and economic growth when combined with the development of social and economic infrastructure.[40] These renewable energy sources are ideal for rural electrification because of their low maintenance costs.[41] On the other hand, one of the obstacles to widespread adoption of solar-based energy generation is the high capital and installation costs.[42] Loans to end customers and solar system producers have a high interest rate. Additionally, utilities are particularly expensive in India for local manufacturers. As a result, India has higher solar system production costs than other Asian nations. Furthermore, Khare *et al*,2013. acknowledged that some of the issues that keep solar cell costs high include reliance on imported wafers for manufacturing, high capital costs, a lack of technical expertise, and rivalry from nearby countries like China and Taiwan.[43] As a result, convincing farmers to incorporate solar farming into their agricultural land and reap the benefits would be challenging until the price of solar panels was reduced.

Table 3: An overview of Indian Agrivoltaic projects combining fish farming.[36]

Company/Project Name	Location	Description	Technical Data
Arka Microbial Technologies.	Kerala	It has solar panels over its fish ponds, which generate electricity and provide shade for the fish. This has helped to improve the water quality and increase the productivity of the farms.	The solar panels cover 2,000 sq. feet area and generate 1.5 kW of electricity. The ponds of area of 3 acres, can produce up to 15 tons/year
IIT Kharagpur.	West Bengal	The Indian Institute of Technology Kharagpur has set up an agrivoltaic project that combines fish farming with solar power. It uses a PV system to generate electricity and provide shade for the fish ponds.	The project has installed a 120 Wp (watt-peak) solar panel and a battery to power the pond's aerator. The fish ponds of area 4 acres can produce up to 40 tons of fish per year.
Society for Energy, Environment and Develop -ment (SEED).	Tamil Nadu	SEED has set up a project that combines fish farming with solar power. The project uses solar panels to generate electricity and provide shade for the fish ponds.	The plant cover 400 sq. feet area and generate 2 kW of electricity. The fish ponds have a total area of 1.5 acres and can produce up to 15 tons of fish per year.
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).	Telangana	This agrivoltaic project combines fish farming with solar power. The project uses solar panels to generate electricity and provide shade for the fish ponds.	The plant covers 1,500 sq. feet area and generate 1.2 kW of electricity. The fish ponds of 1 acre area can produce up to 10 tons of fish per year.

Solar System Degradation

Natural factors that affect solar systems' output capacity include temperature, wind velocity, dust accumulation, irradiation, humidity, and physical stress.[44] NREL shows that solar systems deteriorate at a rate of 0.5% per year.[45] But alarming findings came from a study of solar panels that are used in India. The panels suffered numerous damages despite being constructed in accordance with International Electrotechnical Commission specifications. The study found that the decline in panel performance ranged from 8% for the best-performing panels to 28% for the lowest-performing panels.[46]

Microclimatic Changes and their Effects on Crop Production

The change in microclimate conditions and its effects on crop cultivation are among the most significant challenges for agricultural activity beneath an APV array. While it is anticipated that the reduction in solar radiation beneath the APV canopy will be the most noticeable alteration, several other microclimate elements may also change. Air temperature is one microclimate characteristic that is directly impacted by sun radiation. In places with strong solar radiation, in particular, the possible effects of air and canopy temperature variations through shade on crop cultivation must be taken into account. Crop production may be negatively impacted by excessive heat. In more sheltered areas, irregularly distributed rainfall might result in decreased water availability, whereas direct water turnouts onto the surface soil after severe rainfall can raise the danger of soil erosion,[47] In addition to these negative effects, the protection provided by the PV panels may also aid in lowering the incidence of fungal illnesses following prolonged rainfall.

Effects on Field Management

The use of APV systems places a number of restrictions on agricultural production and its technical administration. First and foremost, the mounting architecture of APV arrays must be modified to meet the needs of the agricultural equipment being employed. The PV panels must be lifted to an adjusted overhead clearance, allowing conventional farm machinery to pass. A clearance of at least 4-5 m is necessary for cereal farming, in particular, with its big combined harvesters. The space between the pillars must be appropriate for planting distances and machinery working widths in order to prevent the loss of usable land.

Technical Barriers

The lack of solar panels and structures suitable for agri-PV systems is a significant technological impediment. Major module producers do not yet sell modules with the size and efficiency necessary for agrivoltaic systems. Since PV modules are frequently higher up, they should be rather light. Also, the modules and buildings need to be planned so that the crops benefit from ground shadows. Transparent back-sheets in this regard are particularly appropriate for Agri-PV systems, as they provide the opportunity to optimize the transparency of PV panels to be best suitable for different crops. Due to the presence of livestock, agricultural equipment, and people, electrical safety presents a significant difficulty as well. Agri-PV system construction should be built to tolerate a possibly increased wind effect. The dependability and lifetime of PV module components, as well as the system's capacity to produce electricity, may be impacted by the dust that is released as a result of the use of agricultural tools, fertilizers, and other materials in agricultural operations to assure crop production.

Optimization Towards Better Agri-PV Efficiency

Due to the PV modules' configuration, the shading beneath the facility fluctuates during the day based on the sun's altitude. Harvest index and irradiance are highly correlated in cereals like wheat, rice, and maize. Depending on the intensity, duration, and stage of crop development at which the shading is applied, the yield reduction will vary in size. For instance, under severe shading conditions, the yield of rice can decline by up to 73 percent while incoming radiation is reduced by up to 77 percent.[48] Shading levels can be dynamically controlled to further tailor the amount of light that is provided to the crops to meet their demands. In order to change the amount of shadowing inside the greenhouse, PV modules can move around a fixed axis. Currently active different types of solar modules and their tracking angles with shading consequences in Indian Agri-voltaic plants[24] are listed in the below table 4.

Table 4: Shading effects on crops and their managements.[25]

Name of the Project	Type of the APVs	Tracking	Shading	Cultivated Crops	Observations
GIPCL plant near Amrol, Gujarat	Interspaced or overhead stilted hybrid panels with horizontally mounted (1-3m) Mono-facial	5 to 28° tilting manually in every 2 months for different seasons.	Seasonal shading	1. Wheat 2. Groundnut 3. Cotton 4. Soybean 5. Maize 6. Mustard	Manual tilting is required to avoid seasonal shading.

	modules.				
Central Arid Zone Research Institute (CAZRI) plants in Jodhpur, Rajasthan	Interspacial arrays with mono-facial modules having 26° inclination angle	No tracking for fixed module and single axis tracking for others	Shades due to the used PV modules	1. Mungbean 2. Cumin 3. Chickpea 4. Isabgul 5. Onion 6. Garlic 7. Aloe vera and other medicinal plants	Growth of isabgul, medicinal plants and Cumins are highly affected because of the shading
Amity University plant in Noida, UP	Single columned And mono-facial modules with 4.6m elevated poles	No tracking	Minimal shading	1. Brinjal 2. Potatoes 3. Maize 4. Mustard	Crop growth unaffected by shading
Dayalbagh Agriculture University plant in Agra, UP	Mono-facial Semi -transparent glass panels arranged in single column with 18ft elevation, some are arranged in checkerboard pattern	Single axis tracking	Seasonal shading	1. Tomato 2. wheat 3. Spinach 4. Grams 5. Carrot	Manual tilting is required to avoid seasonal shading.

Discussion

Medicinal plants like Aloe vera, Dunal (ashwa-gandha), Vazradanti, etc. can also be grown if the agrivoltaic plant can be designed on degraded lands or rocky scrubs. Solar grazing, where cattle are allowed to graze under solar plants, may be one more use of agrivoltaic in India. The yields of some crops in shaded circumstances require experimental examination. In India, agrivoltaics has the potential to increase agrarian productivity while promoting the use of renewable energy. Agrivoltaic systems can increase crop yield by over 30%, reduce water operations by over 30%, and induce electricity up to 1 MW per hectare of land.[49,50]

Conclusion

Still, the adoption of agrivoltaics in India is in its incipient stage. Lack of a policy framework and land use conflicts need to be addressed. The government of India has taken numerous enterprises to encounter these challenges. Several state governments in India have also launched their own enterprises to promote agrivoltaics. The ICAR has also conducted several studies to demonstrate the benefits of agrivoltaics. With the right programs and policies, agrivoltaics can play a significant role in promoting sustainable agriculture and rural development in India.

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Conflict of Interest

The authors do not have any conflict of interest.

Authors' Contribution

The authors confirm contribution to the paper as follows

Conceptualization, literature review, methodology development: G.M; draft manuscript preparation: G.M, H.G, K.M, N.S, Table, graph and figure creation: H.G, K.M, N.S, Final manuscript editing, coordination among authors, and overall supervision of the review process: G.M; All authors reviewed the paper and approved the final version of the manuscript.

Data Availability Statement

The data supporting this review are derived from various sources and are comprehensively cited within the tables presented in this manuscript. All referenced tables, containing the relevant data points, are available within the main body of the text. Readers are encouraged to consult these tables for detailed information on the sources and data discussed in this review. Additional inquiries regarding specific data points can be directed to the corresponding author.

Ethics Approval Statement

This review paper does not involve any experimentation on human subjects or animals. As such, formal ethics approval was not required for this study.

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