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AGRIVOLTAIC SYSTEMS-A REVOLUTION IN SUSTAINABLE ENERGY AND SMART FARMING

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ABSTRACT

The rapid escalation of global atmospheric carbon dioxide (CO_2) levels, has propelled a concurrent rise in surface temperatures. This climatic shift has precipitated widespread ecological disruptions, including biodiversity loss, diminished crop yields, and other catastrophes. Consequently, it is imperative to embrace renewable energy sources. Among renewable energy options, solar energy stands out as a burgeoning sector with zero carbon footprint and abundant availability worldwide. However, traditional photovoltaic (PV) systems necessitate substantial land allocations, posing a challenge amidst escalating global population growth and mounting pressures on agricultural lands essential for ensuring food security. Addressing this nexus, agrivoltaic (AV) systems emerge as a transformative approach, integrating PV electricity generation with agricultural production to enhance land productivity. Agrivoltaics capitalize on the synergy between solar power generation and crop cultivation within a single land unit. By utilizing the interspace and underside of PV arrays for agricultural activities, AV systems not only generate clean energy but also mitigate climate change impacts. Key configurations of AV installations encompass ground-mounted panels, slightly and fully elevated panels, and vertically mounted systems, each tailored to optimize energy yield while fostering agricultural output. The multifaceted benefits of agrivoltaics extend beyond energy production to encompass microclimate moderation, enhanced water use efficiency through reduced evapotranspiration, and augmented income streams via rural employment and year-round agricultural viability. Furthermore, AV systems demonstrate potential in enhancing crop quality and yield under varying shading conditions. Additionally, AV installations foster habitat preservation, support apiculture, and boost native vegetation growth, thereby nurturing ecological resilience. In conclusion, agrivoltaic systems represent a pivotal strategy for bolstering sustainable agriculture, particularly in countries like India, where renewable energy deployment aligns closely with climate and energy imperatives. By enhancing economic returns and enabling decentralized electrification in rural areas, AV systems offer a promising pathway toward climate-smart agriculture.
***Keywords*:** Agrivoltaics, Renewable Energy, Climate Smart Agriculture, Sustainable Development, Sustainable agriculture, Green Energy, Solar energy.

Introduction

Globally, the average atmospheric carbon dioxide (CO_2) concentration has risen significantly, from 285 parts per million (ppm) in 1895 to 419 ppm in 2021 (Chen, 2021). Consequently, it projects an elevation in the worldwide mean surface temperature by approximately 0.97 to 1.21°C (Sangomla, 2022). Substantial damage has already occurred to human habitats due to the escalating global temperature driven by greenhouse gases, leading to biodiversity loss, frequent droughts and floods, reduced agricultural yields, melting of polar glaciers, and rising sea levels (Mora *et al.*, 2018; Yang *et al.*, 2022). Fossil fuels, a prevalent non-renewable energy source, are among the primary contributors to the release of greenhouse gases (GHG). Therefore, the exploration of diverse renewable energy sources is a viable option. Among these, solar energy is the one that generates electricity at the fastest rate without leaving any carbon footprint (REN21, 2021) and it is found abundant across the nation, however it requires extensive land for erecting of photovoltaic systems. Simultaneously, the effects of climate change and an increasing world population pose serious threats to food security, intensifying competition for land. In this context, integration of photovoltaics (PV) with crop cultivation, typically referred to as agrophotovoltaic (APV) or agrivoltaic (AV) systems, is proposed to be a synergistic approach. This method merges renewable energy generation with agricultural production, potentially enhancing land use efficiency around 70 per cent (Weselek *et al.*, 2019).

Climate change and GHG emission

The Intergovernmental Panel on Climate Change (IPCC) cautions about substantial climate fluctuations, noting rapid warming in the Indian Ocean region. Consequently, countries adjacent to that region including India is anticipated to experience intensified heat waves, posing significant threat to the agricultural sector (Masson-Delmotte *et al.*, 2021).

Greenhouse gases (GHG) are one of the main reasons for these changing climatic aberrations. According to Ritchie and Roser (2020), India emitted approximately 2.6 million tonnes of CO_2 in 2019, out of a global total of 36.44 million tonnes. India ranks as the third-largest global emitter of GHGs. The key sectors contributing to GHG emissions include electricity generation, agriculture, manufacturing, construction, and transportation.

National renewable energy scenario

Fossil fuels are integral to power generation across various sectors and industries, yet their use contributes to higher concentrations of greenhouse gases, which subsequently drive significant changes in climate patterns. Concurrently, the global population continues to grow, resulting in a sustained upsurge in energy demand. In response, many nations committed to reducing relying on energy sources derived from fossil fuels and bringing down the release of GHGs following the declaration part of the Paris Climate Agreement (PCA) in 2015. This international accord spurred 196 member countries to intensify their investments in green energy alternatives, encompassing energy from the sun, wind, tidal, biomass, geothermal, and other renewable energy technologies (Elavarasan *et al.*, 2020).

In an effort to reach net zero emissions in 2070, India is now boosting the utilization of renewable energies. The power sector significantly contributes to a country's GDP growth. As of December 2020, India's total electricity production reached 374.65 GW, ranking it third globally. However, coal energy sources accounted approximately 53 per cent of power generation in 2020 (Mahto *et al.*, 2021). To diminish the emissions of GHGs, it is imperative to decrease the reliance on coal-fired power plants. With solar energy in the forefront, India has made significant progress in the adoption of energy from sustainable sources. As of May 2023, India had installed non-fossil fuel capacity exceeding 178.79 gigawatts, marking a remarkable 396% increase over the past 8.5 years, according to the National Investment Promotion and Facilitation Agency (The Economic Times, 2023). India is among the top five nations in the world which has installed solar power capacity of 102.57 GW as of February, 2025 (MNREI, 2025). In this context, we must take advantage of more renewable energy sources, particularly solar energy that can be found abundant across the nation. Furthermore, by 2030, the Indian government hopes to have capacity of 500 gigawatts renewable energy, of which around 300 gigawatts will come from solar energy alone (CEA, 2022). To reach this target successfully, the country needs to leverage revolutions in renewable energy. Solar-powered irrigation pumping systems, as well as solar PV-driven agricultural tools such as sprayers and dusters, along with solar thermal devices for value adding and processing of farm products, represent promising areas for solar energy utilization in the agricultural sector (Santra, 2018).

Agrivoltaics

The growth of solar energy aims to fulfil global energy needs by replacing fossil fuels, yet it necessitates significant land resources. Thus, the continued advancement of solar power hinges on discovering sustainable solutions that harmonize the positive aspects of energy generation, ecological services, and various land uses. Concurrently, climate change impacts and a burgeoning global population pose threats to food security. Land is a primary resource needed for the growth of plants. As a result of climate change, switching of agricultural land to other uses decreased the land availability (Hu *et al.*, 2020) and productivity (Ortiz-Bobea *et al.*, 2021). These elements increase the urgency for expanding farm output from existing agricultural land or transform natural spaces for farming. This dynamic has heightened struggle for land, particularly to regions with constrained land availability or dense populations. In these scenarios, the conflict over land utilization between energy generation and food production is a significant concern.

Solar PV-based power generation tends to get prioritized than agriculture due to the superior efficiency of the process of photovoltaics (~15 per cent) compared to the process of photosynthesis (~3 per cent), especially where regions with ample exposure of sun light but limited land productivity potential (Santra, 2018). However, food production remains essential for human sustenance. Consequently, the innovative concept of agri-photovoltaic systems, which integrates photovoltaics with crop cultivation, offers a potential to harness renewable energy sources and produce food on a single piece of land at the same time (Santra *et al.*, 2017). Agrivoltaic (AV) systems merge cultivation of crops with photovoltaic-based power generation from same piece of land unit which will be a boom in both agriculture and energy sector (Weselek *et al.*, 2019). India stands to benefit by merging its objectives of ensuring food security and advancing its solar mission through the adoption of agrivoltaics to enhance land productivity (Taro Pumps, 2023). The agrivoltaic system is known by various names across different regions. “Agrophotovoltaics (APV)” in the German research context, “Agrivoltaic systems/arrays (AVS/AVA)” in French and U.S. contexts, “Photovoltaic agriculture” in China, “Solar sharing” in Japan, “Photovoltaic or solar greenhouse (PVG)” in specialized setups, and globally as “Agro-PV” or “Agri-PV” or “Agriphotovoltaics” (Toledo and Scognamiglio, 2021).

Agrophotovoltaics (APV) was pioneered by Goetzberger and Zastrow in 1982 to enable solar power generation besides crop cultivation as dual land use (Goetzberger and Zastrow, 1982). Their approach involved elevating solar panels to 2 meters above ground level and optimizing spacing to minimize shading of crops (Weselek *et al.*, 2019). Agrivoltaic (AV) systems encompass the combined allocation of ground-mounted solar installations with agricultural practices such as cropping ("AV-cropping") or livestock husbandry ("AV-animal," e.g., foraging). These integrated systems have demonstrated enhanced land utilization efficiency, water utilization efficiency, and green energy production potential, highlighting the viability and benefits of combining these dual land uses (Walston *et al.*, 2022).

Types of Agrivoltaic systems

Conventional photovoltaic models installed over bare ground whereas PV + crops/ pastures (grazing)/ As per the NSEFI (2023), agrivoltaic installations feature four primary types of plant installations.

A. **Ground-mounted panels:** Installed directly on or close to the ground, with the space between rows of modules designed for agricultural use, accommodating farming machineries. The largest and most advanced example in India right now is the agrivoltaic plant at Cochin airport.

B. **Slightly elevated panels:** Raised structures that partially shade crops grown underneath and between panels. This setup allows for cultivation of shade-tolerant crops, optimizing land use. Examples include installations at the Central Arid Zone Research Institute’s site, Jodhpur and the GIPCL plant, Amrol.

C. **Fully elevated panels:** Installed on raised structures, creating space beneath for farming activities. This configuration facilitates farming and machinery operation across the entire site. Eg: Agrivoltaics site, Parbhani.

D. **Other layouts:** Vertical installations or structures equipped with single and multi-axis trackers for solar panel alignment with sunlight.

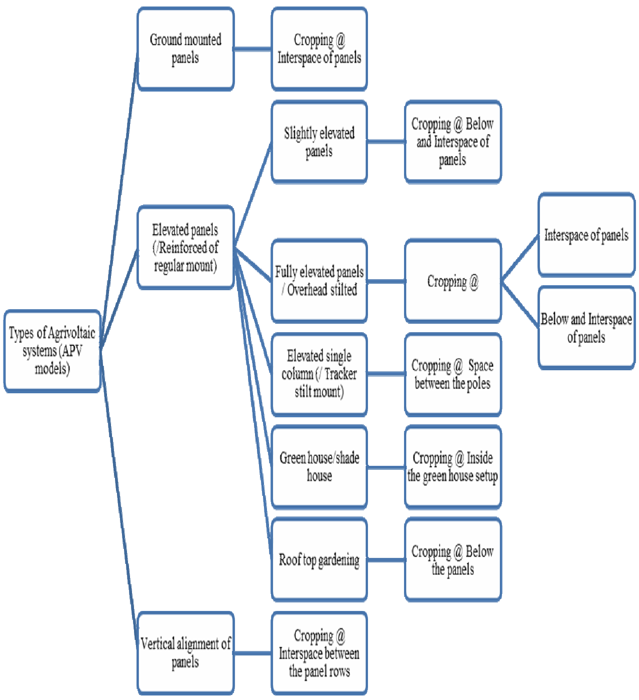

Fig. 1: Types of Agrivoltaic system (APV Models)

Ground mounted | Slightly elevated panels | Fully elevated panels

Overhead stilted | Elevated single column | Green house/shade house

Roof top gardening | Vertical model

Fig. 2: Photographs of of various agrivoltaic models (Credit: NSEFI, 2023)

Concept, Design and orientation of agrivoltaic system

Unlike standard solar farms where panels are densely packed to maximize land use, agrivoltaic installations feature elevated panels and spacing between PV arrays that allow for crop growth underneath and easy farm operations. Various technological and mechanical modifications could be implemented to mitigate reduced solar radiations caused by panels and minimize drawbacks for crop production. Solar panels used in agrivoltaic systems may employ fixed or sun-tracking mechanisms, such as single-axis or double-axis (Abidin *et al.*, 2021), to optimize power generation. Conventional PV system has 4.6ft ground clearance, 16.6ft inter-row spacing, 19% module efficiency and ground coverage ratio of (GCR% = Module area/plant area) 33% for tracker and 44% for fixed tilt model (Horowitz *et al.*, 2020). In ground-mounted systems, a row spacing of approximately 3-5 meters is considered sufficient to allow adequate light penetration to the crop canopy while ensuring acceptable power production (Weselek *et al.*, 2019). This spacing also facilitates the smooth movement of machinery between the supports. Ground clearance, ground coverage ratio and module efficiency were similar as conventional model and approaches like PV+ grazing/ pollinator habitat have this type of model (Horowitz *et al.*, 2020). The compactness of panels desires to be comparatively lower than traditional ground mounted installations to maintain sufficient light for crops and ensure acceptable agricultural yields.

In elevated systems, the mounting of panels must be tailored to accommodate agricultural machineries and its movements (for cereal crops, at least 4–5 meters clearance is necessary for combined harvesters). The spacing between supporting pillars should be based on planting distances and working widths of machineries. It is inevitable that some areas between the supports will be inaccessible to agricultural machinery, resulting in approximately 2 per cent of land being engaged by the mounting structures (Weselek *et al.*, 2019). In reinforced of regular mount type (fixed), the ground clearance, inter panel spacing, inter row spacing, ground clearance ratio and module efficiency are 8.2ft, 2 ft, 31.2ft, 28% and 19% respectively. Tracker stilt mount type has same configurations as reinforced model but with 32.4ft inter row spacing, 20 per cent ground coverage ratio and 21 per cent module efficiency (Horowitz *et al.*, 2020).

In the vertical mounted type, the design was almost similar to the ground mounted type (space for cultivation and machinery passing) but the panels were oriented in a vertical manner with less than 1 per cent ground coverage ratio, 28.3ft inter row spacing, 6.4ft ground clearance and 21 per cent module efficiency (Horowitz *et al.*, 2020).

Module panels orientated in a landscape had the benefit of a comparatively high shade ratio, which produces a high energy output and portrait orientation models were less expensive to install than landscape orientation models, they were more economically viable (Lee *et al.*, 2023). Agrivoltaics is in its infant stage in India for research and studies. Therefore, there is a lack of appropriate evidence that addresses that ideal type. Based on the region and type of vegetation, the AV type will be recommended.

Status of agrivoltaics in India

The Indian government implemented the Kisan Urja Suraksha Evam Utthan Mahabhiyaan (PM-KUSUM), or Farmer Energy Security and Guarantee Scheme, to meet the growth rates required to meet the 2030 target. The programme seeks to accelerate the construction of distributed photovoltaic installations.

As per the July 2023 report from the National Solar Energy Federation of India (NSEFI), there are currently 22 operational agrivoltaic projects established throughout India. The specified details (which were relevant to agriculture) about the operational 22 agriphotovoltaic projects in India were presented in table 1.

Table 1: Details of operational agriphotovoltaic projects in India (NSEFI, 2023)

Year of commission	State	Plant name & place	Capacity	Mounting	Crops
Ground Mounted Type (Interspace)					
2012	Gujarat	Abellon Energy plant, Aravalli	1 MW	Conventional ground mounted	Watermelon, ginger, chili, turmeric, lady's finger, and bottle gourd
2015	Kerala	Cochin Airport plant	Total - 50MW (Specifically AV not mentioned)	Conventional ground mounted	Prominent crops include tomato, brinjal, broccoli, cabbage, turmeric, ginger, cucumber, cucurbits, yam, long yard bean, and okra. **Periphery Plants:** The edges are adorned with curry leaf trees, drumstick trees, Buddha bamboo, eugenia, and allamanda flowers
2016	Telangana	Mahindra Susten plant, Tandur	400 kW	Conventional ground mounted	Lemon grass, brinjals, lady finger, green chilies, onions
2017	Rajasthan	CAZRI plants in Jodhpur	105 kW	Elevation height – 1.22, 1.9 & 2.6 m	Chickpea, cumin, isabgol, mung bean, moth bean, cluster bean, onion, garlic, chili, cabbage, and Aloe vera
2020	Rajasthan	Fish Pond Agri-PV System, Bhaloji	30 kW	Conventional ground mounted	Fish culture
2022	Maharashtra	Agrivoltaics plant near Parbhani	1.4 MW (Including all types)	Height - 1.25 m & bifacial	Water melon
-Not available-	Maharashtra	GroSolar Agri-PV System, Dhule	1 MW	Conventional ground mounted	Geranium, Guava, Lemongrass
Slightly Elevated Type (Below and Interspace)					
2022	Maharashtra	Agrivoltaics plant near Parbhani	1.4 MW (Including all types)	Height – 1.75 m	Musk melon, coriander, spinach, fenugreek, marigold and basil
-Not available-	Himachal Pradesh	Farmer owned plantat Jahu	250 kW	2.2m height & 2m interspace	Brinjal, chilly, onion, cabbage, and bhindi (for seed)

Overhead Stilted Type (Interspace)					
2016	Gujarat	GIPCL plant near Amrol	1 MW	1-3 m horizontal mounting height	**Kharif:** Maize, green gram, pigeon pea, cotton, cluster bean, pearl millet, soybean, and groundnut **Rabi:** Wheat, chickpea, mustard, and lucerne, etc. **Summer:** Fodder, sesame, and black gram
2016	Gujarat	GSECL Harsha Abakus plant, Sikka	1 MW (1054kW)	1-3 m horizontal mounting height	Lady finger, cluster bean, coriander, and bottle gourd **Winter:** Cucumber, chili, tomato, and ladyfinger **Summer:** Moong dal
2016	Gujarat	GSECL Harsha Abakus plant, Pandhro	1 MW (1054kW)	1-3 m horizontal mounting height	**Vegetable:** Bottle gourd, coriander, cluster beans, ladyfinger, and brinjal **Pulses:** Sesame, peas, black gram, and green gram
Overhead Stilted Type (Below & Interspace)					
2010	Delhi	Krishi Vigyan Kendra (NHRDF), Ujwa	110 kW	3.5 m elevation height	Root crops, leafy greens, cole crops, capsicum, brinjal, tomato, and okra
2014	Maharashtra	Jain Irrigation plants at Jalgaon	290 kW (Including all types)	>5 m height	Banana (14.4 kW)
				3 m height	Rice (9.6 kW)
				1.7 – 2.5 m	Turmeric, ginger, mint (19.3 kW)
2017	Gujarat	Junagadh Agriculture University, Junagadh	7 kW	Elevation height – 3m	Tomato, capsicum, cotton
2021	Delhi	Sun Master Agri-PV System	2 MW	4.3 m elevation	Eggplant, bottle gourd, cucumbers, potatoes, lettuce, fenugreek, cilantro, lady's finger, spinach, and tomatoes
2022	Telangana	Telangana Agric. University	10 kW	Approx. 3.5 m elevation	Multiple, high growing crops
Elevated Type - Single column					
2014	Maharashtra	Jain Irrigation plants at Jalgaon	290 kW (Including all types)	Dual axis tracking	Cotton and okra (50.4 kW)
2017	Uttar Pradesh	Amity University plant in Noida	10 kW	Elevation height – 4.6 m (15 ft)	Maize, potato, brinjal, mustard
2020	Uttar Pradesh	Dayalbagh Agriculture University, Agra	200 kW	Elevation height – 18 ft	Wheat, carrots, tomatoes, brinjal, gourds, spinach, grams, and cauliflower (crops < 8ft)
Overhead Type - Green house / shade house					
2014	Maharashtra	Jain Irrigation plants at Jalgaon	290 kW (Including all types)	1100 m^2 green house	Banana, raising seedlings (200 kW)
2022	Maharashtra	Agrivoltaics plant near Parbhani	1.4 MW (Including all types)	Overhead 3.75m shadehouse	Muskmelon, mini peppers, field cucumber, melon leaves, coriander, golden turmeric, aromatic ginger, holy basil, fenugreek, spearmint, basil spinach, marigold, rose, garden mums, fragrant tuberose, hibiscus, and cherry tomato
2023	Madhya Pradesh	Indra Solar Farmat Khargapur	400 kW	Polyhouse	Groundnut in *Kharif*, Wheat in *Rabi*, Green gram, red gram and lentils in *Zaid*
Rooftop Gardening Type					
2019	Karnataka	Hinren Agri, Bangalore - PV Rooftop (APVRT) System	3 kW	2.3m elevation height	Lettuce, eggplant, string beans, basil, cilantro, chillies, papaya, lemons, pomegranate, spinach, rosemary, lady's finger, bitter melon, tomatoes, and cauliflower
Vertical Type					
2020	Haryana	NISE Vertical Agrivoltaics Pilot, near Gurgaon	5 kW	Vertical & Bifacial	-Not available-

Location of agrivoltaic system

Agrivoltaic systems suit to almost all regions of the country where the bright sunshine hours per day are enough for power generation. These systems enhance crop production through reduced water loss from evapotranspiration and mitigation of excessive radiation. Moreover, they boost economic viability and facilitate rural electrification (Majumdar and Pasqualetti, 2018). Cultivating crops within solar facilities in such regions not only moderate microclimate conditions like temperature and soil moisture but also enhances irrigation efficiency (Barron-Gafford *et al.*, 2019).

Research has predominantly focused on assessing the feasibility of cultivating shade-tolerant, high-value crops beneath partially shaded panel rows (Walston *et al.*, 2022). Studies in Japan suggest the possibility of commercial production of maize under raised PV panels (Sekiyama and Nagashima, 2019). The uniformity of light and reduction in photosynthetically active radiation (PAR) can vary significantly across different agrivoltaic system configurations (Bellini, 2023). PV systems are most productive in areas with high irradiance, light wind, low humidity, and moderate temperatures, where the conditions can correlate with croplands (Adeh *et al.*, 2019).

Agrivoltaic systems on Ecosystem Service

Walston *et al.* (2022) indicated four major ecosystem services of agrivoltaic system. They were 1) Energy and economy: These systems generate power, directly contributing energy production and the economy. 2) Agricultural production: Agricultural activities such as crop cultivation and livestock rearing can coexist on lands where agrivoltaic systems are installed. 3) Biodiversity: Integrating natural habitats within agrivoltaics can enhance plant and animal biodiversity. 4) Supporting and regulating services: Innovative management practices can also enhance supporting and regulating services such as net primary production, carbon sequestration, and water and soil conservation.

Conventional PV models installed over bare ground whereas APV have similar configuration as conventional PV models but they were accommodated with various agriculture components which will depends on the model. There are three agrivoltaic types based on agriculture ecosystem services. They were

- AV-cropping systems: Integrating solar energy infrastructure with crop cultivation.
- AV-animal systems: Combining solar energy infrastructure with animal husbandry and grazing practices.
- AV-habitat systems: Integrating solar energy infrastructure with habitat restoration efforts (like pollinators).

(A) Energy generation

Photovoltaic systems, including agrivoltaic systems, are renowned for their low-carbon energy production during operation, making solar facilities as carbon-free power source (Walston *et al.*, 2022). While global data on total power production via agrivoltaic platforms is limited, current projections indicates that AV-cropping systems alone could generate over 2.8 GW globally, covering approximately 21,000 acres (8,500 hectares) of land up to 2022 (Gorjian *et al.*, 2022; Heath *et al.,* 2022; Walston *et al.*, 2022).

Temperature variations influence the operational efficiency of solar PV panels. The effectiveness of solar panels can drop by 0.6 per cent for each degree Celsius that the temperature rises above 25 degrees (Barron-Gafford *et al.*, 2019). Agrivoltaic systems offer a crop/ native habitat vegetation which may develop more humid microclimates beneath panels during hot summer months, thereby enhancing panel longevity and performance (Barron-Gafford *et al.*, 2019). Moreover, advancements such as the use of bifacial PV modules in agrivoltaic systems, leverage increased reflections from underlying crops to boost power generation synergistically (Rodriguez-Gallegos *et al.*, 2020).

The electrical output and economic returns can be boosted through raising of panel’s density, which concurrently reduces the amount of sunlight available for crops (Dupraz *et al.*, 2011). When PV modules are in solar-tracking mode, they automatically align with the sun's position to maximize energy production and improve ground-level solar radiation in comparison to stationary PV modules (Valle *et al.*, 2017). Module density has a greater impact on the radiation level underneath an agrivoltaic array than does module mobility (Weselek *et al.*, 2019). Specific agrivoltaic configurations may optimize solar PV panel efficiency. Water flow through PV panel frames as a heat exchanger improved panel efficiency (Li *et al.*, 2022).

(B) Crop production

Owing to the arrangement of PV modules, shade will vary throughout the entire day depending upon the solar radiation and position. Lower module densities are predicted to allow crop-accessible radiation range from 60 per cent to 85 per cent in contrast to open-field situations (Weselek *et al.*, 2019). Up to 73 per cent of incoming radiation was able to reach the crop surface when PV module density was reduced and panel row spacing was set at 3.2 meters (Marrou *et al.*, 2013c).

Reduced light availability is the primary impact of PV systems on crop cultivation and it potentially result in yield losses in many crops. As the technology is in its emerging stage, the scientific literature on the impacts of shading from AV panels on crops remains relatively sparse. The degree of yield reduction is contingent upon the shade's concentration and duration, crop's growth stage coinciding with shading, and the technical design of the agrivoltaic system. For instance, severe shading conditions can lead to up to a 73 per cent drop in yield of rice, accompanied by a decrease in incoming radiation by 77 per cent (Weselek *et al.*, 2019). According to Homma *et al.* (2016), there was a 20 per cent decrease in rice yields for every 20 per cent decrease in sun radiation.

While excessive heat may benefit some crops, such as potatoes, by increasing yields, it generally leads to reduced marketable yields (Kim *et al.*, 2017). More shading may be effective by promoting stability of yield in arid areas where the high sun irradiation and significant water losses were predominant (Amaducci *et al.*, 2018). The impact of agrivoltaic panel shading patterns and microclimatic conditions on crop production varies between seasons and depends on the type crop (Marrou *et al.*, 2013c).

In semi-arid conditions, moderate shading (25–36 per cent decrease in full sunlight) can increase fruit yield and plant height of tomatoes. Higher levels of shading, which account for 50–75 per cent of direct sunshine, have negative impacts and reduce fruit yields. Sweet peppers showed similar results, with moderate shade (a 12 to 26 per cent reduction in full sunshine) enhancing production and plant heights (Rylski and Spigelman, 1986).

Forages and leafy crops may advantage from reduced radiation, leading to increased leaf surface and overall biomass. Additionally, raising maize beneath agrivoltaic panels in dry conditions has been found to reduce soil evaporation and increase average yields, potentially stabilizing yields during dry situations (Amaducci *et al.*, 2018). Shading has an impact on the quality of harvestable product in addition to yield. Shading also reduces the incidence of sunscald in tomatoes and sweet peppers compared to full-sun conditions, highlighting its role in protecting crops from excessive solar radiation and heat. Similarly, coffee (Jezeer *et al.*, 2018), spice crops like pepper and cardamom, traditionally adapted to shaded environments potentially might thrive in agrivoltaic setups as well.

According to Lee *et al.* (2023), approximately 20% drop in crop output has been documented in AV type agriculture. However, the land equivalent ratio (LER) of an AV system is normally 1.2 to 1.5, which is more than 1. Land equivalent ratio of an AV system will be estimated with the sum of crop and energy yield ratios. $LER = (FM_{AVS}/FM_C) + (E_{AVS}/E_C)$. For AV and conventional systems, FM and E stood for crop fresh biomass and electricity yield, respectively. The type of crop will determine how an AV system affects agricultural yield, and the type of AV model and module installation density will determine electricity yield. In addition to this he also stated that the shading ratio (SR= Area of PV modules/Area of farmland in the system) of the system is affected by the insolation to the crop, which varies according to the type of AV model and module density. The shading ratio of the majority of the present functioning models falls between 20 and 40 percent (Amaducci *et al.*, 2018; Weselek *et al.*, 2019; Abidin *et al.*, 2021; Mamun *et al.*, 2022) due to variations in the tilting angles of PV modules.

(C) Microclimate alteration and water use efficiency

The most noticeable change under agrivoltaic panels is the reduction in solar radiation, which alters several microclimate factors. In hot regions, this reduction can create a suitable microclimate for crop cultivation by reducing irradiation by approximately 30 per cent (Weselek *et al.*, 2019). Under agrivoltaic panels, soil temperatures tend to decrease while air temperatures may be higher, and crop temperatures for crops like durum wheat, lettuce, and cucumber also decrease during the daytime (Marrou *et al.*, 2013b). Adeh *et al.* (2018) noted higher soil moisture retention beneath ground-mounted PV system panels. Furthermore, Marrou *et al.* (2013a) observed decreased evaporation and transpiration as a result of reduced solar radiation, which led to decreased evapotranspiration under panels. Improved water use efficiency and water conservation (328 per cent) were reported under agrivoltaics systems due to the presence of the photovoltaic panels that functioned as an obstacle against moisture loss from land (Adeh *et al.*, 2018) and plant (Walston *et al.*, 2022). When light intensity dropped to 50 to 70 per cent of the direct sunlight, water balance in AV systems was enhanced by ten to thirty per cent (Marrou *et al.*, 2013a). Integrating tilting-angle solar panels into farming practices reduced water irrigation needs by 20 per cent in lettuce cultivation (Abidin *et al.*, 2021). Citrus crops grown under shade nets showed increased water use efficiency (WUE) with reduced solar irradiation (Medina *et al.*, 2002). Rainwater collected via harvesting systems integrated with panels was stored in farm reservoirs for irrigation, thereby replenishing groundwater levels. Furthermore, recycled water from solar panel cleansing can be used to irrigate crops.

(D) Animal husbandry

Some agrivoltaic setups proved that solar energy projects and animal husbandry, such as livestock grazing, may coexist harmoniously. Conventional PV type with pasture grass ground cover model usually opted for this ecosystem service. Vertical type of agrivoltaic system can also act as a fence to the farm. Livestock species especially sheep are well-suited for solar setups due to their gentle nature and comparatively smaller than larger livestock species. Productivity and growth of lambs under panel system were found to be similar to lambs reared in open pastureland conditions (Andrew *et al.*, 2021) highlighting the potential for agrivoltaic systems to enhance land productivity by integrating livestock grazing with solar energy development.

(E) Habitat development

Changes in land use, such as intensified agriculture, have reduced available land for supporting apiaries, resulting in declines in both the quantity and quality of honey production. Utilizing agrivoltaic systems as sites for apiaries could offer multiple advantages for both agriculture and apiculture ecosystem by enhancing honey yields (Dolezal *et al.*, 2021). This includes structure as convention PV including fixed and tracking designs but with pollinator attractive vegetation instead of bare ground below the panels. For instance, integrating honeybee hives into existing solar parks of United Kingdom could have provided £5.9 million worth of pollination services to surrounding agricultural production in 2017 (Armstrong *et al.*, 2021). Therefore, agrivoltaic systems present the opportunity to cultivate agricultural crops alongside apiaries, such as flower crops, on the same land, potentially improving profitability and providing habitat for pollinators.

Recent studies suggest that partial shade from panels in some regions can enhance native vegetation development and the diversity of beneficial insects (Graham *et al.*, 2021). This approach may contribute to the conservation of native insect populations by establishing habitats that support solar-pollinator interactions (Walston *et al.*, 2018).

(F) Income generation

Projections indicate that solar PV jobs could grow to 22.2 million by 2050 (Ram *et al.*, 2020). This model will positively impact the rural economy by generating employment, revenues through taxes and diversifying the sources of incomes for landowners and farmers. These developments provide employment opportunities within the local community, involving roles in panel maintenance and farming activities (Chauhan, 2018). This helps locals generate revenue throughout the year. Continuous access to electricity can foster the development of small businesses and manufacturing ventures in rural areas, offering regular employment opportunities. Additionally, agrivoltaics can serve as a source of supplementary income, potentially reducing dependence on livestock and thereby mitigating excessive methane emissions.

Agrivoltaics as climate smart approach

The threat posed by climate change to agriculture and the world's food supply continues to escalate (Ortiz-Bobea *et al.*, 2021). Drastic decline in productivity of major crops of India is mainly due to climate change effects and it is worsening further with time. Depending on the region and expected climate, the reduction in yields for rice, wheat, sorghum, barley, and corn might be as high as 35, 20, 50, and 60 per cent, respectively (Chauhan, 2022). It is ironic that conventional farming techniques, which account for roughly one-third of GHG emissions, are also highly energy-intensive as well as contribute to climate change (Gilbert, 2012). Currently, 19–29 per cent of greenhouse gas (GHG) emissions result from agriculture (Chauhan, 2022). To address these challenges, a range of agricultural practices aimed at ensuring food security amidst climate change are collectively termed "climate-smart agriculture" (CSA). This approach brings together climate considerations onto the development and adoption of ecologically sound farming practices, aiming to enhance agriculture's resilience to climate variability and mitigate its role in the global warming catastrophe.

Three primary goals are pursued by climate-smart agriculture (CSA) (Lipper *et al.*, 2014; World Bank, 2023).

- **Increased productivity** - Aimed at boosting agricultural output to raise farmers' income, ensure food security, and foster rural economic growth.
- **Enhanced resilience -** Targeting farm systems to withstand climate-related challenges such as natural disasters, pests, diseases, and other disruptions.

- **Reduced emissions -** Developing agricultural technologies to mitigate greenhouse gas emissions and promote environmental sustainability.

In order to meet the decarbonization objectives in response to the impact of climate change and increasing power needs, substantial advances in green energy like solar, which ranks among the lowest emitting sources of GHGs among all electricity generation types (Walston *et al.*, 2022). The life-cycle emissions of solar facilities, according to analysis of their GHG emissions, are 10–50 times lower compared to those of fossil fuel-based power (Bosmans *et al.*, 2021). Over 99 per cent of solar PV facilities have life-cycle emissions below 100 g CO_2 eq kWh^{-1} (Bosmans *et al.*, 2021).

Agrivoltaic technology have the potential to simultaneously boost farm productivity in dry areas through lower greenhouse gas emissions and increased energy and water efficiencies, thereby minimizing the adverse correlations between agriculture and climate change. Through carbon sequestration by vegetation, the establishment of AV-habitat systems can counteract these quite large GHG emissions, enhancing the quality of the air. It has been estimated that an agrivoltaic system can mitigate about 598.6 tonnes of CO_2 emissions per hectare annually. Additionally, agrivoltaics can contribute to increased electricity generation, reducing reliance on coal-based power plants. Campana *et al.* (2017) underscored the opportunity of photovoltaic hydro-pumping systems to enhance grassland output simultaneously reducing the effects of climate change and desertification.

Similarly, solar PV pumping systems integrated into agrivoltaic systems reduce CO_2 emissions that would otherwise be emitted by diesel-based pumps (Santra, 2018). Therefore, leveraging solar energy in agriculture through agrivoltaic systems or solar-based pumping systems for irrigating of crops, or employing solar thermal-based value addition and processing of farm produce, promotes climate-smart agriculture.

In arid regions, agrivoltaic panels can synergistically improve crop production by mitigating water loss and extreme conditions like drought and heat (Marrou *et al.*, 2013a; Ravi *et al.*, 2016). Synergies in grape and fruit farming can be attained by deploying PV panels to directly shielding crops from unfavourable weather conditions (Weselek *et al.*, 2019).

Moreover, adopting agrivoltaic systems improves microclimates in agricultural fields, reduces water loss from the soil by means of evapotranspiration, minimizes top soil erosion, optimizes rainwater usage through harvesting and recycling, and eventually decreases the chance of failure of crops when unpredictable precipitation patterns. By providing shade from solar panels, native vegetation may be able to flourish in optimum microclimates, improving soil stability, carbon sequestration and reducing water runoff and erosion (Walston *et al.*, 2022).

The rainwater harvesting capabilities of agriphotovoltaic systems can provide water for cleaning purposes and supplemental irrigation, further enhancing their utility in sustainable agriculture practices. Overall, agrivoltaic systems represent a promising approach to minimizing the negative consequences of global warming while simultaneously supporting sustainable energy as well as agricultural practices.

Economics of agrivoltaic system

Generally, the cost for installation of 1 MW plant in 2 ha area is about Rs. 5 crores (Santra, 2018). In ICAR-CAZRI, Jodhpur, 105 kW agrivoltaics system was installed at total cost of Rs. 62 lakhs. Revenue from marketing of power generated from this AV system is estimated at around Rs. 7.6 lakhs per year. Factoring in discount and interest rates, the breakeven period for the system is projected to be around 8-9 years, with a system lifespan of 25 years (Santra, 2018). Furthermore, the Government of India supports farmers through the PM-KUSUM scheme and facilitates electricity procurement from agrivoltaic systems at advantageous standard rates for up to 25 years.

All agrivoltaic models require higher capital investment and installation costs compared to conventional structures. Horowitz *et al.* (2020) compared the installation cost of different PV systems like typical fixed PV, fixed PV+ grazing/pollinator, tracker PV + grazing/ pollinator, vertical mount type, PV + crops in tracker stilt mount and also PV + crops (reinforced regular mount) system. According to them, all of the above systems have the same module cost, inverter cost and found minor variations in miscellaneous costs, however, there is a huge cost difference in structural, electrical and labour costs for installation, which were the influencing factors of cost of various models especially tracker types of models, vertical models and reinforced models. The structural cost of tracker, trackers stilt, vertical and reinforced models were 55, 264, 91 and 167 per cent higher than the conventional PV models, respectively. The structural cost of the above models requires the elevation of up to 8.2 ft above the ground with heavy-duty materials, which made those models' initial costs expensive. The sensitivity analysis also supported the same that the increase in panel ground clearance and inter-panel spacing increases the system installation cost. The electrical cost was similar for all models with a maximum variation of 12.5 per cent, except the reinforced model, which is 58 per cent higher than the conventional. Installation cost (labour and equipment) was 22-50, 39, and 78 per cent higher for tracker, vertical, and reinforced models, respectively. These factors make the tracker, vertical, tracker stilt and reinforced model's overall installation cost 13-16, 20, 37 and 52 per cent higher than the typical fixed PV model, respectively. Increasing the system's power capacity (higher MW) gradually reduces the installation cost of all models.

Advantages of agrivoltaic system

Increased land productivity, by up to 70 percent due to combined energy and crop production, has been demonstrated (Weselek *et al.*, 2019). Moreover, agrivoltaic systems contribute to reduced GHG emissions, with carbon emissions from solar units being 10 to 53 times lesser than traditional power generation methods (Tawalbeh *et al.*, 2020). These systems also show potential for enhancing yield and quality, particularly in shade-tolerant crops, and increasing water use efficiency through strategies such as reduced evapotranspiration and rain harvesting.

In arid regions, agrivoltaic systems have shown promise in improving crop production by providing additional shading and enhancing water productivity (Weselek *et al.*, 2019). Furthermore, co-locating agrivoltaic systems with grape farming has been reported to increase revenue significantly, up to 15 times compared to traditional farming practices (Malu *et al.*, 2017). Beyond agricultural benefits, agrivoltaic systems contribute to rural electrification and generate job opportunities for the locals (Chauhan, 2018).

Disadvantages of agrivoltaic system

High capital and installation costs, coupled with a lack of technical skills in maintaining and repairing, are the significant obstacles for the wide spread adoption of this solar-based energy systems. Additionally, there is a lack of social awareness and absence of a universal model suitable for all regions and crops.

Cleaning elevated panels poses logistical challenges, and the degradation rate of solar systems whereby systems may produce less than 90 percent of their initial electricity output after 20 to 25 years underscores durability concerns (Jordan and Kurtz, 2013). Moreover, solar cells contain toxic chemicals like lead, cadmium, and selenium, which can harm human health and the environment if not properly disposed of. This challenge extends to other components of solar systems, including batteries and inverters, which also require appropriate disposal methods. Addressing these multifaceted challenges is crucial for sustainable and responsible expansion of solar energy technologies in India and beyond.

Challenges and research gaps

Agrivoltaic systems offer a positive strategy in enhancing land utility and contributing to sustainability targets of energy, food, and environmental security. However, as these multifunctional landscapes emerge, significant challenges and gaps in information must be addressed. Agrivoltaic systems, which integrate farming and power generation on the single land unit, often represent a compromise compared to their individual outputs if each land use were pursued separately (Mamun *et al.*, 2022) which can lead to trade-offs such as reduced crop yields due to shading or decreased energy production efficiency from spacing constraints between PV arrays. Challenges such as reliance on imported wafers for solar cell manufacturing and gaps in technical expertise contribute to high costs in solar cell production (Khare *et al.*, 2013).

Research is essential to assess the feasibility of agrivoltaic systems with taller crops like corn, soybeans, and wheat, which require more sunlight (Barron-Gafford *et al.*, 2019). This exploration includes studying technological and economic possibility of raising panels or adjusting panel's spacing to grow these crops, which may incur additional costs and affect electricity pricing (Schindele *et al.*, 2020). Furthermore, there is a need for research that expands beyond insect communities to explore interactions between solar installations and wildlife, including birds, mammals, and other vertebrates (Walston *et al.*, 2022).

Strategies to improve agrivoltaics in India

Agrivoltaic systems are currently in its budding stage and needs technical advancements. Initiatives such as promoting local production of solar panels in India could lead to reduced panel costs. The viability of combining agrivoltaic technology with taller, commercial grain crops requires further research. Increasing awareness about solar technology, encouraging APV applications (as SMART program incentives in United States) and implementing training programs in rural India by educational institutions would equip local populations with skills for maintaining and operating solar plants. Government support in the form of subsidies, financial assistance, and insurance for purchasing and installing renewable energy options is crucial. Enhancing the power generation capacity of panels across fluctuating lighting conditions and developing policies for proper disposal and increased recycling of e-waste are very essential. Investing in e-waste recycling could create employment opportunities locally. Implementing dynamic PV modules with tracking ability can optimize incident radiation on crop canopies, promoting crop production efficiency and increasing electricity and yield (Valle *et al.*, 2017). Moreover, utilizing panels that allow more photosynthetically active radiation (PAR) to reach crops could further optimize agricultural output.

Conclusion

"Agrivoltaics: A path to sustainable, decentralized, and resilient agriculture." Many farmers and people employed in the farming sector struggle financially due to dependence on unreliable farming techniques and a lack of awareness about advancements in technology. In countries like India, the development of renewable energies currently forms one of the key components of a sustainable climate and energy policy. Sustainability goals, combined with the limited agricultural land area in these countries, have led to an ethical conflict about land use for food or bioenergy production. This could be alleviated by the implementation of agrivoltaics. Agrivoltaics enhance the economic value of farming, doubles the farmers income and can contribute to decentralized, off-grid electrification in developing and rural areas, thus further improving agricultural productivity. India's agrivoltaic ecosystem is slowly maturing from a R&D stage into the commercial market. As only very few studies address the impact of this technology on crop yields and quality, further investigations incorporating different climatic conditions, crop species and varieties are indispensable for the evaluation of its applicability in prospective agricultural systems. Further developments and reduction in cost may lead to easy acceptance of agrivoltaic systems among people. However, agrivoltaic can be an important component of future agricultural systems, addressing some of the major current and prospective societal and environmental challenges, such as climate change, global energy demand, food security and land use. Agri-voltaic systems have immense potential in Indian agriculture by providing food, energy, and water security, as well as may be a promising alternative for climate smart agriculture in the near future.

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