JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Setting a greener path to agrivoltaics revolution – Indian Context

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ABSTRACT

Agrivoltaics systems (APV), which combine solar panels with farming, have gained attention for addressing food, energy, and water challenges. This study reviews existing research and explores the potential of agrivoltaics in India, especially in West Bengal, due to its strong solar and agricultural capacity. The research highlights economic benefits of APV, including boosting India's GDP and reducing rural-to-urban migration by creating jobs. This paper delves into the role of artificial intelligence and machine learning to optimize agrivoltaics acceptance in society. Agrivoltaics also supports sustainable goals like clean energy, resource conservation, and rural stability. The paper identifies challenges, such as policy gaps, and suggests solutions for large-scale adoption, emphasizing its role in achieving environmental and economic sustainability.

Keywords: *Agrivoltaics, West Bengal, India, Renewable Policy, AIML adoption in agrivoltaics, Reverse migration, SDG*

Introduction: Agrivoltaics has become a common term in academia, green consultancy, environment management and many other sustainability studies and solutions. It is sometimes also known by Agri photovoltaics (APV) or Solar Sharing. The development of the agrivoltaics technology in recent years has been highly dynamic. Today it is prevalent in almost all regions throughout the globe. There are many definitions of APV technology used throughout the world like in Germany [53], in France [54] and in Italy [55]. One such definition portrays a fundamental requirement of APV systems to achieve at least 66% of agricultural reference yield and keep land losses due to mounting structure below 10% for Category I and 15% for Category II (Germany [53]). As per NREL, USA; not all photovoltaic (PV) installations on farms qualify as agrivoltaics. For instance, rooftop PV systems on barns or traditional ground-mounted solar arrays near agricultural land, without directly interacting with vegetation or soil, do not constitute agrivoltaic projects. Similarly, using solar-generated electricity to support farm operations without integrating the PV system into the agricultural environment is not considered agrivoltaics [56]. Hence, any policies related to APV System classification needs to address this issue critically.

Basic performance metrics of Agrivoltaics mentioned in previous researches:

As said earlier, agrivoltaics is using the same land for both electrical energy generation and crop production ensuring combined yield is not less than monocultured land i.e. if the land was used for only agriculture. It is to remember that best possible practices for agriculture or ground mounted photovoltaic systems in silo cannot be adopted simultaneously in agrivoltaics due to shading effect (primarily). Hence for optimization, some performance metrics (not exhaustive in nature) that have been standardized in existing literatures are as followed:

- **Ground coverage ratio**: Ratio between the surface area of the PV modules and the cultivated ground surface PV installation [38] .

- **Land Equivalent Ratio**: It compares the efficacy of using the same land for both crop production and energy generation in an AV system to using the land separately for each purpose [7].

- **Water usage efficiency:** Unit of biomass per unit of water used against the biomass produced in a control zone without the influence of PV [1],[19]

- **Land area occupation ratio**: Ratio between the area of the modules and area of land that they occupy. When modules are tilted, there is a difference between the dimension of the height of the modules and one of their orthogonal projections on the ground [31]

- **Price performance ratio**: Ratio of Cost (annual extra cost for an agrivoltaic implementation compared to the cost of a ground mounted) to benefits (performed benefits which are created by the annual revenues of the preservation of the agriculture land and the revenues of its products [6]. However, social cost benefit analysis of agrivoltaics system is yet to be researched thoroughly.

Chronological Developments and Significant literatures in Agrivoltaics: In this section we would be funnelling down from world view on agrivoltaics to research trends in India in recent times.

❖ **Till 2000s**:

- Research on agrivoltaics systems, though limited before the 2000s, has early roots in the application of solar energy in agricultural contexts. In 1981, Adolf Goetzberger, founder of the Fraunhofer Institute for Solar Energy Systems (ISE) and Armin Zastrow pioneered the concept of what would later be recognized as agrivoltaics [9]. In order to maximize land use and boost agricultural and energy productivity, they proposed growing crops and solar panels on the same plot of land. This idea sparked more research in this field.

❖ **2000-2010**:

- This concept did not gain significant traction until the early 2000s, especially with advancements in photovoltaic technology and the increased interest in sustainable energy solutions. The concept of combining photovoltaic (PV) solar panels with agriculture emerged, primarily in Europe and Japan, as a potential solution to land-use conflicts [22]. Development of agrivoltaics in Japan started in 2004 in Chiba Prefecture initiated by Akira Nagashima who coined the term "solar sharing (synonymous to agrivoltaics)" in 2003 and made its patent free for public use in 2005 [3]. In 2004 Günter Czaloun proposed a photovoltaic tracking system with a rope rack system and the first prototype was built in 2007 on a 0.1 ha area in Austria [57]. In Germany, one of the first practical Agrivoltaics applications can be found in Bavaria, where the electrical engineering company, Guggenmos, has been cultivating different crops since 2008, under a PV system installed at a height of 1.5 m [32]

❖ **2010 - 2020:**

- **Researches in the World**: The concept of agrivoltaics was first formalized by Dupraz et al [7], who developed a comprehensive model demonstrating the mutual benefits of integrating photovoltaic (PV) panels and crop cultivation. Their work highlighted how shading from PV panels could enhance water-use efficiency, optimize land utilization, and impact crop yield and photosynthesis, introducing agrivoltaics as a sustainable co-location strategy for agriculture and energy production. Building on this, Marrou et al. [19] conducted field experiments in Montpellier, France, confirming the viability of agrivoltaics for crops like lettuce, which exhibited improved water-use efficiency under partial shading. Japan took these concepts to scale in 2015 with one of the first large-scale agrivoltaics projects, supported by the Ministry of Agriculture, Forestry, and Fisheries, which showcased the system's benefits for smallholder farms [11]. In 2017, Germany expanded research efforts through the Fraunhofer Institute for Solar Energy Systems, testing various PV panel configurations and their effects on crop yields and energy generation under European conditions ([33], [2]). In 2018, Barron-Gafford et al. explored agrivoltaics in Arizona's arid environments, demonstrating its potential for water conservation [4]. Collectively, these studies provided critical insights into agrivoltaics' global applications, focusing on water efficiency, land use optimization, and the compatibility of PV systems with diverse crops and climates.

- **Researches in India**: Between 2010 and 2019, research on agrivoltaics in India was limited but offered valuable insights into the potential of this innovative approach. Santra et al. (2017) investigated the integration of photovoltaic systems with farming, demonstrating how it could enhance electricity generation while sustaining agricultural productivity [25]. Mavani et al. (2019) further emphasized the economic advantages of dual land use, combining energy generation with food production exploring advanced technological designs [17]. Kumar et al. (2018) introduced the concept of "floatovoltaics", presenting its ability to enhance water and land management efficiency in semi-arid regions [13]. Thapar et al. (2017) focused on the role of local communities in agrivoltaic projects, advocating for inclusive strategies to accelerate renewable energy adoption while ensuring equitable resource sharing [30]. Despite the limited scope of studies during this period, these findings laid the foundation for further exploration of agrivoltaics in India's agricultural and renewable energy sectors from 2020 onwards.

❖ **Researches in India 2020 onwards:**

- Agrivoltaics research in India has shown remarkable growth, addressing agricultural sustainability, renewable energy integration, and regional climate challenges. Maity et al (2023) has provided has structured view of opportunities and challenges of agrivoltaics in India through SWOT and TOWS matrix representation [44]. Santra et al. (2021) demonstrated the viability of agrivoltaic systems in arid regions, highlighting their potential for water conservation and productivity enhancement [26].

- In subsequent years, researchers expanded the application of agrivoltaics across various crops, technologies and buisess models. Gayathri et al. (2023) provided an indicative list of shade tolerant, shade beneficial and shade susceptible crops for agrivoltaics [41]. Johnson & Manikandan (2023) studied effects of bifacial solar panels on agrivoltaics yield in South India, showcasing the system's ability to enhance land efficiency ratio [42]. Boruah et al.(2023) has presented a method and matrix to segment different zones of India to better optimise design of agrivoltaics system [43]. Center for Study of Science, Technology and Policy (CSTEP) provided a platform for working business models of agrivoltaics [47].

Overall research trend

Research in agrivoltaics is in upward trend. Following review papers mentioned in Table-1 are testament to this fact that post 2020, there has been a high spike in publications on agrivoltaics topics .

TABLE-1

Name of Author of review papers	Published date	Paper considered	Paper reviewed
Widmer et al [36]	2023	135	54
Soto Gomez et al [28]	2024	165	58
Aidana Chalgynbayeva et al [5]	2023	204	121

Most of the research in Agrivoltaics can be classified as below :

(i) Research to optimize Agrivoltaics farm design based on different variables ([2], [40], [18], [37])

(ii) Research to assess microclimatic impact of agrivoltaics ([20], [1])

(iii) Research on Business model viability study and policy intervention approach ([48], [47]

(iv) Research papers on review of agrivoltaics systems ([39], [36], [5], [28],)

(v) Very few researches are on socio-economic acceptance by the farmers or rural community ([14], [27])

Agrivoltaics in Indian Scenario:

India is a country of interest with diverse unique features.

❖ It has 17% of worlds' population but contributes to only 3.3% of World GDP. Only comparable country in terms of population is China (17% of world share) which contributes to 17% of World GDP ([60]).

❖ India is 2^{nd} in agricultural produce ([61] but in the 2024 Global Hunger Index [62], India ranks 105th out of 127 countries and is categorized as having a "serious" level of hunger.

❖ Although India shares 6.5% of world energy generation (3rd after China and USA), and 5th largest economy of world; in 2023, India's per capita GDP stood at $2,485, which is only 18.91% of the global average of $13,138.33, and the per capita electricity consumption in India was 1,331 kWh, representing only 6.22% of the global average of 21,394 kWh. (calculated from Statista and World bank open data)

❖ **Dark face of agrarian economy in India**: India has 45% workforce employed in agriculture or allied sector [63] but the GVA from primary sector is only 16-20% of India's GDP. India's rural population increased 2.5 times than 1960 but China's rural population has decreased from 1960 level (calculated from world bank data) whereas China's crop production per acreage is thrice than India. According to the National Crime Reporting Bureau (NCRB,64) data in 2019, 10281 farmers had committed suicide for different reasons and about 15,000 farmers killed themselves annually on average in the last ten years alone, which is equivalent to 48 farmers killing themselves every day.. The picture has not changed much in 2022 i.e. Post COVID (Figure-1). Total no of farmer suicide has increased by approx 10% from 2019 level. The trend is nearly similar except two stark observations (Figure-2):

(i) Persons engaged in farming sector i.e. who are not directly doing the farming activity has committed more suicide in 2022 than 2019.

(ii) There is significant increase in suicide incidence in Rajasthan. Hence, the highly conducive observation (high solar power generation and low suicide numbers) for the state of Rajasthan is losing its outlier position.

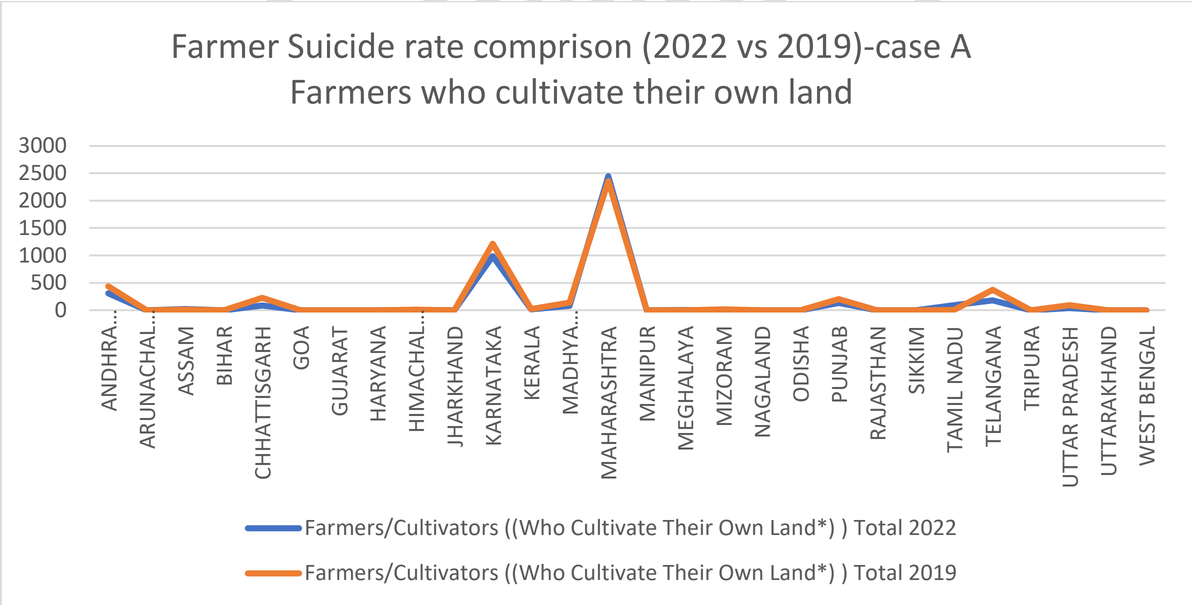


FIGURE-1

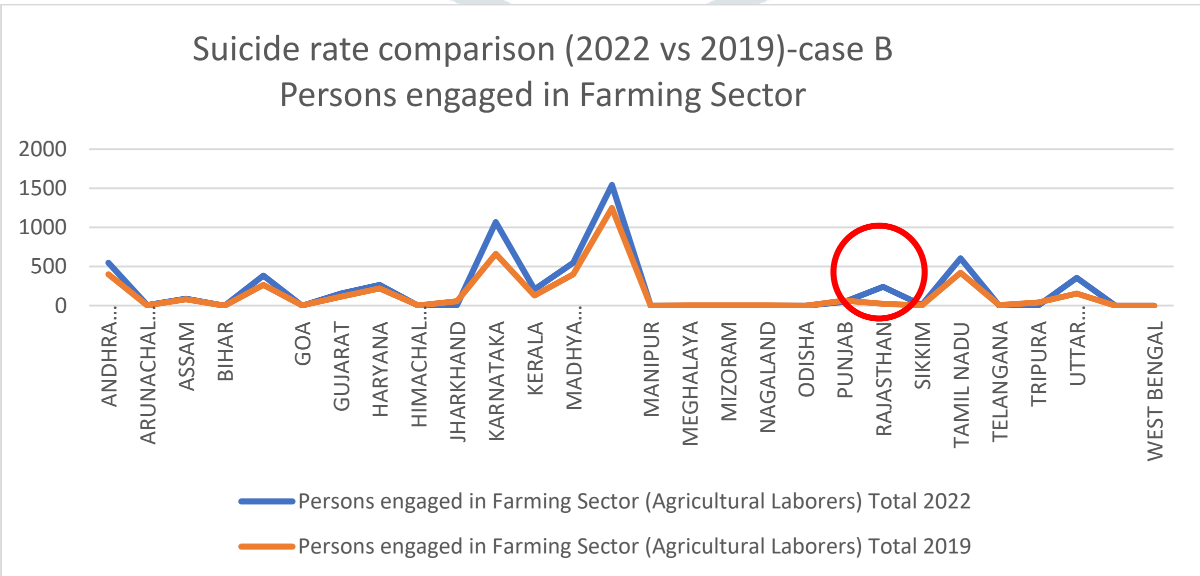


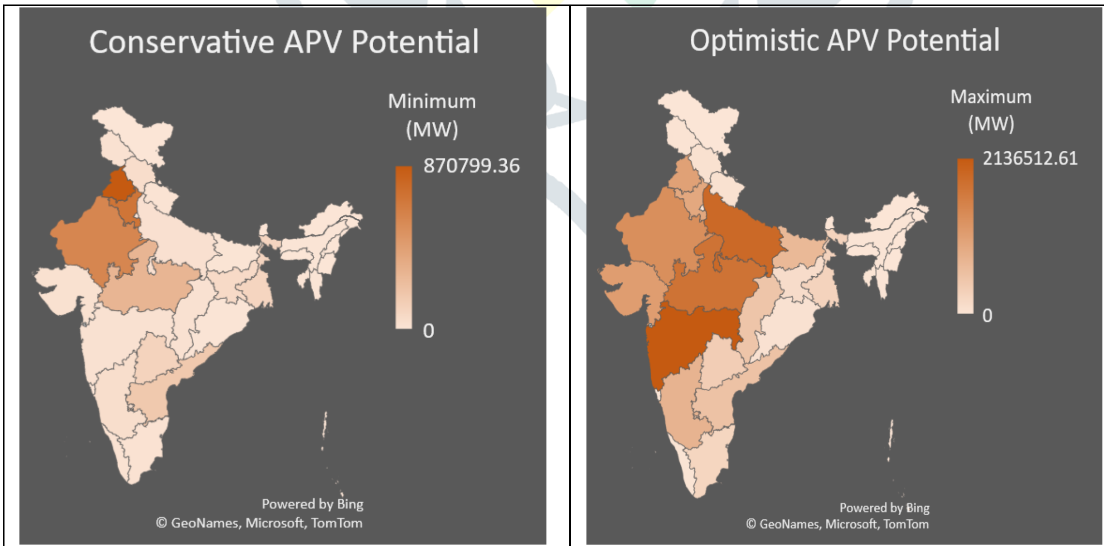
FIGURE-2

❖ **India's agriculture; Land-Energy-Food trifecta**: As in 2019-20, India's total land area was 328.75 million Hectare. Total cropped area was almost 70% i.e. 211.36 million Hectare of which 50% area (approx.100 Million Hectare) is not irrigated and entirely dependent on localised water resources or rainwater. India's total cropped land can be categorised in mainly cereal, pulses, food grain, vegetables, oil seeds tobacco and other crops [65]. Also as per NITI Ayog data [66], agricultural land decrease has been documented with increase in food production requirement which means in near future, Land use efficiency needs to be increased to cater the needs of increasing population from perspective of both food and energy. In 2021-22, India's total electricity consumption for agricultural purposes was 228.45 billion unit which is 20 % of national consumption [65]. This data highly correlates with contribution of agriculture to national GDP. India has already achieved generation of 116 Billion Unit of electricity from Solar Only in 2023-24 (NISE website) which is approx. 50% of overall requirement of Agri-sector on 2022 level. India's total electricity generation capacity has touched 452.69 GW with renewable energy-based power generation capacity has increased to 203.18 GW as of October 2024, accounting for more than 46.3 percent of the country's total installed capacity. India's ambitious solar installation target is detailed below in Table-2 [67].

TABLE-2 (Solar Target of India)

Year	Peak energy demand (in GW)	Total installed capacity (in GW)	Renewable Power (in GW)	Solar Power (in GW)	% share of Solar of overall installed capacity
2024	250	453	203	92	20.31
2030	463	1000	500	280	28.00
2047	708	2053	NA	1200	58.45
2070	NA	NA	NA	5600	NA

But increased requirement of green energy and agricultural produce, both require significant land and agrivoltaics has the potential to reduce the competition and integrate the food and energy on the same land. From following visual representation (Figure-3), it can be seen that most of the potential lies in western part of India. The maximum Agri-photovoltai (APV) potential is projected as 13803 GW i.e. approx. 20-30% of available cropped land may be required to reach full potential of APV.



Minimum 3156 GW	Maximum 13803 GW

FIGURE-3, Visual representation made by author from data available in STAAI-CSTEP website [68].

It can be seen from above that India is looking for a solution to

(i) Increase per capita farmers income

(ii) Increase agriculture production efficiency

(iii) Reduce farmer suicide rate

(iv) Increase Solar energy share

(v) Increase agricultural electicity consumption

The following major benefits of Agrivoltaics can significantly contribute towards addressing above socio-economic issues ([28], [49])

- Rural Electrification
- Increase in combined farm yield
- Income generation through sale of solar energy
- Water conservation
- Pesticide reduction
- Employment Generation

Growth of Agrivoltaics in India:

In India, oganisations like Indian Agrovoltaic Alliance, the National Solar Energy Federation of India (NSEFI) supported by the Indo-German Energy Forum (IGEF) , Central Arid Zone Research Institute - Indian Council of Agricultural Research (ICAR- CAZRI)are doing extensive researches on focused adoption of agrivoltaics. Researches in the area tried to establish design parameters for agrivoltaic power plants across various geo-climatic regions and soil types in India which will help in appropriate crops/ plants selection and necessary policy formation like plant physiology, root penetration, growth pattern, sunlight requirement (Photosynthetically Active Radiation) and Daily Light Integral (DLI) values, plant life, and sowing and harvesting seasons [43].

Despite the researches, practical installation of agrivoltaics is still in its nascent stage and has not yet crossed the proof of concept barrier to a a full commercial scale. 21 nos installed and 3 nos ongoing projects have been documented so far. Abellon Energy put the oldest of these sites into service in Gujrat in 2012. Since then, various players have contributed to the development of India's agrivoltaics sector. Different agrivoltaics projects are visualised in Indian Map as below ([23]).

Mahto R. (2021) shown that most of the projects are done in the arid zone of India (North Western and Western Inia) ([16]). Very few researches are executed in eastern part of India. Superimposing solar potential of India on NCRB 2019 data shows an interesting result that States with higher farmer suicide cases are also found to be ideal for agrivoltaics.

The Government launched PM-KUSUM scheme in March, 2019 with objective of reducing diesel consumption of the farm sector, providing water and energy security to farmers, increasing the income of farmers, and curbing environmental pollution. The Scheme has three components targeted to achieve solar power capacity addition of 34.8 GW by 31.03.2026. The component wise progress upto Nov-2023 is detailed below in Table-3 [69]

TABLE-3 (KUSUM PROGRESS)

Component	Units	Target	Achievement (as of 30.11.2023)	in %
Component A: Setting up of Decentralized Ground/Stilt Mounted Solar Power Plants	Megawatts (MW)	10,000 MW	141.33 MW	**1.41%**
Component B: Installation of Stand-alone Solar Pumps	Number of pumps	14 Lakh	2,78,114	**19.87%**
Component C: Solarisation of Grid-Connected Agriculture Pumps	Number of pumps	35 Lakh	4,594	**0.13%**

It can be seen from above that, although the academic push and technical feasibility has been established, but diffusion of this innovative idea is not taking place in the farmer community as envisaged. A Bass diffusion model study with social survey to assess the coefficient of innovation and the coefficient of limitation in the Indian Farmer community may help in realistic projection of Agrivoltaics growth in India.

Identified Research Gaps:

- **For West Bengal**

(i) New Pilot project in West Bengal as there are no such well documented study in West Bengal

(ii) Zone of acceptance for villages of West Bengal to provide own land for solar PV installation.

(iii) Shortcomings in Solar Policy of West Bengal to promote agrivoltaics

- **For overall India**

(iv) Finding farmers' motivation, acceptance in society and the economic factors for the scalability of agrivoltaic systems

(v) Adoption of agrivoltaics with integrated farming system

(vi) Predictive model for Level of additional income through agrivoltaics that attenuates rural migration and estimate the increment of National Income, HDI, Human Happiness Index and public good.

(vii) Application of AI/ML in Agrivoltaics design

In next section, this paper tries to outline the course of future researches to address these gaps.

Importance of exploring West Bengal in Indian Agrivoltaic Atlas:

West Bengal is a novel state which has not shown significant active participation in agrivoltaics. Although STAAI data[68] projects 94 GW of APV potential (conservative) in the state, commensurate research work or policy incentive seems lacking which is evident from Table-4.

TABLE-4 (Solar Power Status of West Bengal)

Item	Unit	WB	India	% share
Solar Potential	MW	6260	748990	8.36%
Installed Capacity	MW	310.47	90762	3.4%
Solar Units generated	MU	168.32	115975	1.45%

In view of the fact that, there are no documented pilot project of agrivoltaics in Eastern & North-Eastern India. West Bengal, being a high cropping intensity state of India with minimal farmer suicide rate, can be explored as an epicentre of agrivoltaics advocacy and implementation. The average income of farmers is low compared to national average and it may help in creating positive sentiment about agrivoltaics through solar revenue generation. The solar feed in Tariff in West Bengal is 3.20/- at present and irrigation electricity tariff ranges from 3.5 to 8/- as per WBSEDCL tariff order (70). Hence, there is potential of monetary saving for the farmers. Also if we superimpose NCRB data with State wise GVA contribution data in Agriculture sector [65]**,** it can be seen all of high Agri-GVA contributor states have high farmer suicide count except west Bengal where farmers income is far less than the states where higher suicide rates are seen [71]**.**60% of geographical area of West Bengal is agricultural land with cropping intensity of approx. 190% i.e. same land is cropped twice in a year on an average. It produces about 13% of the country's paddy, 24% of its potatoes, and an impressive 74% of jute and mesta. The state also leads in fish production (15%), vegetables (16%), fruits (4%), lentils (6%), rapeseed and mustard (7%), spices (4%), and flowers (12%) [29]**.** According to Gonocruz, R. A., et al. (2021), agrivoltaics can be successfully implemented for rice fields [10]. Photovoltaics with fish farming has also been successfully explored and showed promising results [21]. Hence further research on horticulture & tea under agrivoltaics may explore new avenue of income generation for marginalised section of West Bengal.

Adoption of of AI & ML in optimizing Agrivoltaics design:

"*Attention is all you need*"; a paper by GOOGLE generated all the attention towards artificial intelligence (AI). All the efforts are being made to reduce uncertainty from future predictions. With adoption of artificial intelligence (AI) , machine learnings (ML) and large language models, future big data predictive models will help in narrowing down agrivoltaics system uncertainty in a particular area. Application of AI in Game theory or linear programming will help to identify optimum strategy between energy yield and crop yield. The available national and district level multiagency data sets can be superimposed, extracted and filtered easily with help of AIML. Some of the notable works going on in this area are as bellow:

(i) Photosynthetically active radiation decomposition models for agrivoltaics systems applications which was recently published in Solar Energy [45]

(ii) Agrivoltaics systems to optimise land use for electric energy production [2] [24]

(iii) Predictive modelling on crop and energy yield [12], application of fuzzy logic in modelling [34]

(iv) A group of scientists in Sweden has developed a techno-economic optimization model for designing agrivoltaics system based on climatological data with figures on expected solar power generation, shading distribution, water for irrigation, and agricultural yield [72].

(v) USA has developed INSPIRE data portal which provides design parameters based on agricultural inputs [59].

In an agrarian demography like India, such integration of AI with sustainable technology like agrivoltaics can bring significant certainty in farmers' income and bring down stress and anxiety related diseases & suicides in rural India. Some of the big data sources are tabled below:

TABLE-5 (Big Data Sources related to Agrivoltaics in India)

Category	Data Source	Website URL	Data Available
Solar Energy	National Institute of Solar Energy (NISE)	https://nise.res.in	Solar irradiance data, solar PV deployment, solar energy performance metrics
Agriculture	Ministry of Agriculture & Farmers Welfare	https://desagri.gov.in/	Crop yield data, production statistics, land use details, price data
Agriculture	Indian Council of Agricultural Research (ICAR)	https://icar.org.in	Crop science research data, agro-tech adoption, soil health records
Weather	India Meteorological Department (IMD)	https://mausam.imd.gov.in	Real-time weather data, historical weather data, forecasts
Groundwater	Bhuvan Geo-Platform (ISRO)	https://bhuvan.nrsc.gov.in	Groundwater mapping, land use patterns, soil moisture data
Climate & Environment	National Remote Sensing Centre (NRSC)	https://nrsc.gov.in	Remote sensing data for climate, vegetation index, groundwater changes, weather patterns
For other data: https://iced.niti.gov.in/iced-manual (Portals)			

Development of an interactive user interface platform which can provide answers to the questions of farmers can only be done through artificial intelligence and deep learning models. Ministry of Statistics and Programme Implementation (MOSPI), NITI Ayog needs to create sophisticated large data banks using IOT in agricultural sector which would be backbone of the user interface. A detailed study based on INSPIRE DATA has been carried out and five primary themes have been identified for success of agrivoltaics in USA [15]. India also needs such data repository and findings from social acceptance studies to achieve success in agrivoltaics.

Impact of Agrivoltaics on GDP of India:

India's Gross Domestic Product (GDP) for 2023, at current prices, reached approximately ₹295.35 lakh crore (about $3.55 trillion). This marks an expansion of 9.6% from the previous fiscal year [73]. The country's economic growth has been primarily fuelled by significant contributions from private consumption and gross fixed capital formation. Sector wise share from 1950 to 2020 is tabled below [50.][74].

TABLE-6

SECTORAL COMPOSITION OF INDIA'S GDP OVER THE YEARS (in %)

Sectors		**1950**	**1960**	**1970**	**1980**	**1990**	**2000**	**2010**	**2020**
Primary	Agriculture	55	45	42	37	30	22	16	20
Secondary	Industry	15	20	22	23	23	25	30	26
Tertiary	Services	30	35	36	40	47	53	54	55

It can be calculated from worldbank open data [73] that the GDP of the agriculture, forestry and fishing sector has increase approx. 9 times at constant 2015 US dollar level whereas rural population of India has increased by approx. 2.5 times from 1960 to 2023. It reflects that although the GDP share of agriculture sector decreased over the year, but the absolute value addition has increased through better resource utilisation albeit it has not followed the expected growth rate as China. Adoption of agrivoltaics can boost the share of primary sectors on an equal footing with other sectors through following benefits but there is very limited research on quantifying agrivoltaics' contribution towards GDP calculation as on date.

- Boost to Agricultural Productivity
- Increased Renewable Energy Production
- Job Creation and Economic Activity
- Reduced Import of Energy Resources
- Mitigating Climate Change Costs
- Encouragement of Technological Innovation

As per GIZ report 2024 [48], the estimated projection of capacity addition in agrivoltaics by 2040 in India is 20 GW (moderate). Assuming that farmers will be more comfortable in providing the land in exchange of certain fixed lease or rent rather than developing the entire agrivoltaics system in a BOOM model (build, own, operate and maintain), there will be at-least two direct income generation and a few indirect income generations in rural economy However, after building of confidence, it is expected that the younger generation in rural sector will come forward to 'start-up agrivoltaics business' with full support and participation of the local community, leading to maturity of many rural entrepreneurs within a few decades in India.

- Direct Income generation:

(i) Land rent per MW: estimated as 3 lakh per year with escalation for 25 years [48]

(ii) Installation and O&M work can generate local income if rural youth or women workforce can be upskilled and employed.

- Indirect Income Generation:

(i) Savings in water charges

(ii) Higher yield in certain crops

(iii) Eco-Tourism and Educational Tourism

(iv) Revenue from Carbon Credits

(v) Integration with Animal Husbandry and Apiculture etc

To have a positive impact on GDP, India's expenditure on technology import for agrivoltaics should not exceed the domestic investment. Policy to incentivize inhouse manufacturing and technology development will be essential in future times which requires investment in R&D.

Impact of Agrivoltaics on Reverse migration:

Search of hope generally leads to migration. Search of hope may come from aspiration or dejection. Hence, the storyline of rural to urban migration in all over world more or less give us similar picture- A group of people leaving their birthplace in search of a better tomorrow. There may be various opinion regarding the perception of "better tomorrow"; consequently, rural-to-urban migration in India is a complex, multi-dimensional process driven by a variety of economic, environmental, and social factors. The main reason behind such migration is the economic gap between rural and urban areas. Urban regions offer more job opportunities, higher salaries, and an improved quality of life compared to rural settings [51]. According to the National Statistical Office (NSO) of the Government of India, employment opportunities and marriage are identified as the two primary factors influencing migration patterns. [58]

Although migration has fuelled urban growth but has also strained infrastructure, housing, healthcare, and sanitation systems. Additionally, rural migrants face socio-economic challenges, including difficulties adopting to urban environments due to skill mismatches, limited access to safety nets, and social stigmatization [52].

The adoption of agrivoltaics, which allows for the dual use of agricultural land for farming and solar energy production, has potential to encourage reverse migration from urban to rural areas. By providing an additional revenue stream through solar energy while maintaining or even enhancing crop yields, agrivoltaics addresses key economic barriers that often push rural inhabitants to urban areas for better income opportunities. Studies, such as those by [4] and [25], highlight agrivoltaics' capacity to improve rural incomes, especially in semi-arid and arid climates where traditional agriculture alone might struggle to be profitable.

There is a conservative potential of 3156 GW of agrivoltaics in India [68]. Considering employment generation potential of agrivoltaics in India, if 1 MW of agrivoltaics installation can employ 4 people with justified remuneration, that will translate into approx. 1.3 crore people not choosing to migrate from rural to urban due to economic pressure. However, suitable skilling up is needed to ensure rural employment instead of creating another migratory labour force. Also, if we think of expected land lease amount to be paid by the agrivoltaics developer over 25 years of lifecycle, it will be to the tune of approx. 3 Lac Crore Indian rupees ([48]) which is 10% of India's GDP in 2023.

A relational study between benefit of agrivoltaics and perceptions of rural people on its impact on their livelihood can shade more light into this topic.

Broader Perspectives: Impact of Agrivoltaics on SDGs

In this segment, the author wishes to take conceptual liberty in making opinionated proposition on the path for future agrivoltaics deployment. It is a known fact that with the aim of taking forward the success of Millennium Development Goals; the United Nations (UN) General Assembly, in its 70th Session held on 25th September 2015, adopted the document titled "Transforming our World: The 2030 Agenda for Sustainable Development" consisting of 17 Sustainable Development Goals (SDGs,75). These goals cover the spectrum of good living and ethical living to the farthest level possible as of now. Hence, deployment of agrivoltaics should not only be commercially viable but also emotionally acceptable, ecologically sustainable with some level of positive externalities for other living beings. According to author, the possible impacts of agrivoltaics on SDG goals are tabled below. For remaining goals and relevant indexes, the impact is considered not significant. The view is purely subjective.

TABLE-7

Expected contribution of Agrivoltaics to SDG goals

SDG goals	Possible Means	Contribution	Precautionary Issues
Goal 1. End poverty in all its forms everywhere	Income generation of rural population	Moderate	
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Increase Land efficiency ratio, uplift social status of agricultural employment integrating technology	**High**	Focus shift from agriculture to solar due to more profit and industrialisation of farm lands
Goal 5. Achieve gender equality and empower all women and girls	Rural energy access and income generation	Moderate	
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all	Decentralized green energy	**High**	Hazardous E-waste generation [46]
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Rural employment and green income generation	Moderate	
Goal 13. Take urgent action to combat climate change and its impacts	Reducing carbon foot print		Impact of photovoltaics waste on climate [8]
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	Low usage of pesticides, conversion of fallow lands to agricultural lands		

To bring in the positive impacts, we have to break the policy barriers that stunted the growth of agrivoltaics throughout the world and specially in India. Detailed barrier analysis has been done in GIZ 2024 [48] report which deals with barriers like lack of policies in land usage categorization, unavailability of standards etc. Policies that can be thought of:

(i) Agriculture should always get priority over Photo-voltaic: SDG goal 2

(ii) Agrivoltaics deployment should not be a push strategy, but a pull strategy: SDG Goal 8

(iii) Procedure for Change of land type post commissioning of agrivoltaics should be verified and approved critically: SDG Goal 9

(iv) Based on the percentage of rural employment in workforce, the agrivoltaics installer may get commensurate tax holidays: SDG Goal 5

(v) Students of net positive solar villages may be offered scholarship in higher education: SDG Goal 4

Conclusion and way forward:

India is passing through a challenging situation for availability of food and energy to the largest population of the world as the per capita availability of land for agricultural use, already being lowest among larger economies of the world, is decreasing in one hand, and the import of fossil fuels, already costing as much as India's trade deficit, are increasing. Agrivoltaics has the potential to provide amicable solution to the both, however, no two locations in India would be found to be most suitable for the same system design. This paper suggests that by optimising crop yield and energy generation, agrivoltaics in conjunction with AI and ML have the potential to completely transform Indian agriculture. Site-specific solutions will be made possible through the use of AI- driven predictive models and data from sources such as NISE and ICAR.

On regional level, West Bengal state presents a wealth of viable agrivoltaic opportunities not only in conventional food grain cropping but also in industries like horticulture and fish farming. Large-scale adoption could be propelled by focused policy support, social acceptance of new technology in conventional farming and farmer-centric business models, which can enhance regional economic growth, rural employability, and energy security.

This paper also identified the broader perspectives of agrivoltaics, such as, its impact on SDGs, which can be both positive and negative. The uncontrolled and unscientific application of agrivoltaics can, therefor, further deteriorate the situation, instead of giving solution to the above problems.

Precautionary issues mentioned in the paper need to be addressed. Appropriate economic and financial modelling based on data from the field and use of advance software with AI would be the need of the hour to get the necessary outcome.

- **Conflicts of Interest:** The authors declare no conflict of interest.
- **Author Contributions:** Each author contributed equally to this paper. All authors have read and agreed to the published version of the manuscript.

- **Funding:** This research received no external funding.

- **Institutional Review Board Statement:** Not applicable.
- **Informed Consent Statement:** Not applicable.
- **Data Availability Statement:** Not applicable.

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