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NISE National Institute of Solar Energy

CENTER OF EXCELLENCE AGRIPV

GUIDELINES

AGRIPV: FOR NET ZERO EMISSION, ENERGY SECURITY, AND ENHANCING FARMER'S INCOME

Centre of Excellence for AgriPV in India
New Delhi

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Responsible:
Bernhard Kreuzberg, Project Director, Innovative Solar project, GIZ India

Authors:
Dr. D. K. Singh, Principal Scientist and Professor & PI, Centre of Excellence for AgriPV in India, ICAR- Indian Agricultural Research Institute, New Delhi-110012

Dr. C. Viswanathan, Joint Director (Research) & Coordinator, Centre of Excellence for AgriPV in India, ICAR- Indian Agricultural Research Institute New Delhi-110012

Dr. Jai Prakash Singh, Deputy Director General, Centre of Excellence for AgriPV in India, National Institute of Solar Energy, Gurugram-122003

Dr. Birinchi Bora, Deputy Director (Tech.), Centre of Excellence for AgriPV in India, National Institute of Solar Energy, Gurugram-122003

Dr. Mamtha Prabhakar, Short-Term Expert (Agriculture), Centre of Excellence for AgriPV in India, New Delhi-110012

Ms. Kajal Meshram, Short-Term Expert (Agriculture), Centre of Excellence for AgriPV in India, New Delhi-110012

Mr. Vinit Yadav, Short-Term Expert (Solar PV), Centre of Excellence for AgriPV in India, New Delhi-110012

Ms. Simranpreet Kaur, Short-Term Expert (Agriculture), Centre of Excellence for AgriPV in India, New Delhi-110012

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Foreword

भा.कृ.अ.प. – भारतीय कृषि अनुसंधान संस्थान, नई दिल्ली–110012 (भारत)
ICAR - INDIAN AGRICULTURAL RESEARCH INSTITUTE
(A DEEMED TO BE UNIVERSITY UNDER SECTION 3 OF UGC ACT, 1956)
NEW DELHI - 110012 (INDIA)

डॉ. सीएच. श्रीनिवास राव
निदेशक एव कुलपति
Dr. CH. SRINIVASA RAO, ***FNA, FNASc, FNAAS***
Director & Vice Chancellor

Phones : +91 11 2584 2367, 2584 3375
Fax : +91 11 2584 6420
E-mail : director@iari.res.in
Website : www.iari.res.in

Foreword

Agriculture has long been the backbone of India's economy. In recent years, agriculture sector is facing challenges from climate change, water & energy crisis and land degradation. As the country moves toward to achieve Sustainable Development Goals (SDGs), there is a growing need to reimagine how agriculture can remain productive, resilient, and environment friendly. Integrating clean energy solutions into farming systems is one such opportunity to achieve the SDGs targets.

Agri-Photo-Voltaics (AgriPV), the integration of solar photovoltaic systems with agricultural is a transformative approach to land use and energy-agriculture synergy. It offers the potential to generate renewable power without compromising agricultural output, delivering energy security to farmers, diversifying income sources, and enabling climate-smart practices. For a nation as land-constrained and agrarian as India, AgriPV holds immense promise in addressing multiple development priorities through a single intervention.

The Indian Council of Agricultural Research (ICAR) and ICAR- Indian Agriculture Research Institute (ICAR- IARI) have been at the forefront of agricultural advancements and farmer welfare in the country. ICAR through its network of institutions, including Indian Agriculture Research Institute (IARI), ICAR-IARI has played a central role in disseminating knowledge, fostering innovation, and driving policy implementation for sustainable agricultural practices. With a strong emphasis on farmer-centric solutions, ICAR- IARI ensures that scientific advancements are translated into tangible benefits for the farming community. In recent years, the institute has also aligned its efforts with India's renewable energy ambitions, actively supporting the integration of solar technologies into agriculture to promote sustainable land use and enhance the economic resilience of farmers.

The Centre of Excellence (CoE) on AgriPV, jointly led by ICAR- IARI and the National Institute of Solar Energy (NISE), under the guidance of the Ministry of New and Renewable Energy (MNRE), represents a significant step in this direction. Envisioned as a national platform for research, innovation, and capacity development, the CoE seeks to develop regionally adapted AgriPV models that optimize crop productivity and solar generation. It will serve as a hub for developing knowledge products, conducting performance assessments, and facilitating stakeholder engagement for scalable AgriPV deployment.

This publication presents practical guidelines and recommendations for implementing AgriPV systems in India. It covers technical design considerations, crop suitability, and approaches to maximize agronomic and energy outcomes. It is intended as a knowledge resource for practitioners, researchers, policymakers, and entrepreneurs working to integrate solar energy within the agricultural ecosystem. I congratulate the CoE Team for bringing out this publication at a time when AgriPv in country is taking off.

We hope that this document will support informed decision-making and inspire collaborative action toward achieving sustainable agriculture and renewable energy goals.

(Ch. Srinivasa Rao)

Foreword

भारत सरकार
नवीन और नवीकरणीय ऊर्जा मंत्रालय
Government of India
MINISTRY OF NEW AND RENEWABLE ENERGY
अटल अक्षय ऊर्जा भवन, लोदी रोड, नई दिल्ली-110003
ATAL AKSHAY URJA BHAWAN, LODHI ROAD, NEW DELHI-110003

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FOREWORD

The global shift toward sustainable energy is no longer optional, it is an urgent necessity. Solar photovoltaic (PV) technology has emerged as one of the most viable and scalable solutions to meet this demand. In the Indian context, where the Government of India has committed to achieving 500 GW of renewable energy capacity by 2030, the role of solar energy becomes more critical.

However, India faces a unique challenge: balancing the need for clean energy expansion with the judicious use of its limited land resources. In this regard, Agri-Photovoltaics (AgriPV), the dual use of agricultural land for both solar energy generation and crop cultivation, presents a promising pathway. AgriPV can significantly enhance land-use efficiency, support energy security, and provide additional income streams for farmers, thereby promoting holistic and sustainable rural development.

The establishment of the centre of excellence (CoE) on AgriPV, jointly led by the ICAR-Indian Agricultural Research Institute (IARI) and the National Institute of Solar Energy (NISE), under the guidance of Ministry of New and Renewable Energy (MNRE), marks a strategic milestone. The CoE is envisioned as a national platform for research, innovation, and capacity building in AgriPV. It will focus on optimizing land utilization, improving energy and agricultural productivity, and developing a comprehensive crop productivity matrix tailored to Indian conditions. Furthermore, the CoE will help shape a robust operational framework and knowledge base to support the widespread and responsible deployment of AgriPV systems across the country.

This report aims to provide guidelines and best practices for the successful implementation of AgriPV systems in India. The report addresses key aspects such as system design, crop selection, and maximizing benefits for both farmers and the solar industry. It serves as a resource for stakeholders seeking to integrate solar energy with agricultural practices effectively. I am sure that it will help to all stakeholders engaged in promotion of AgriPV systems in India.

02/07/2025

Dr. Arun K. Tripathi
Advisor/Scientist 'G'
aktripathi@nic.in

Foreword

राष्ट्रीय सौर ऊर्जा संस्थान
(नवीन एवं नवीकरणीय ऊर्जा मंत्रालय, भारत सरकार का स्वायत संस्थान)
National Institute of Solar Energy
(An Autonomous Institute of Ministry of New and Renewable Energy, Govt. of India)
गुरूग्राम - फरीदाबाद रोड, ग्वाल पहाड़ी, गुरूग्राम - 122 003, हरियाणा, भारत
Gurugram - Faridabad Road, Gwal Pahari, Gurugram -122 003, Haryana, India

डॉ. मोहम्मद रिहान / Dr. Mohammad Rihan
महानिदेशक / Director General

Foreword

India's ambitious clean energy transition is not just a national imperative; it is a global responsibility. With the country targeting 500 GW of non-fossil fuel energy capacity by 2030, solar energy stands at the forefront of this transformation. As a key institute of the Ministry of New and Renewable Energy (MNRE), the National Institute of Solar Energy (NISE) plays a critical role in advancing solar technologies, shaping policy frameworks, and driving innovation to accelerate renewable energy adoption across sectors.

Among the emerging frontiers in solar application is Agri-Photovoltaics (AgriPV), a concept that harmonizes energy generation with agricultural productivity on the same parcel of land. AgriPV exemplifies the kind of integrated, sustainable solutions that India needs to address optimal land utilization, energy access, climate resilience, and farmer income stability. By enabling the dual use of land, AgriPV systems have the potential to transform India's farming landscape into a distributed energy production system, enhancing both rural livelihoods and national energy security.

NISE has been actively working to promote decentralized solar technologies, and AgriPV has become a strategic focus area in this effort. Through applied research, pilot demonstrations, and cross-sectoral collaboration, NISE is bridging the knowledge and policy gaps that currently limit large-scale adoption of AgriPV in India.

The Centre of Excellence on AgriPV, set up by Indian Agricultural Research Institute (IARI) and NISE with support from MNRE, reflects this commitment. The CoE aims to serve as a national platform for developing and validating context-specific AgriPV models that are both technologically efficient and agronomically viable. It is positioned to become a hub for knowledge exchange, innovation, and policy input that will inform future deployments across the country.

This guideline report is a result of the CoE's early efforts and presents a consolidated view of technical insights, design strategies, crop selection criteria, and operational best practices. It offers a practical roadmap for stakeholders, including policymakers, developers, researchers, and farmers, to successfully implement and scale AgriPV systems in India.

We hope this document will not only guide action on the ground but also spark new thinking and partnerships in the quest for a sustainable and solar-powered rural economy.

08.07.25

(Dr. Mohammad Rihan)
Director General, NISE

दूरभाष / Tel. No. : 0124-285 3000, 3056
ईमेल / Email : dgnise.mnre@nise.res.in, mohdrihan@nise.res.in, वेबसाइट/ Website : www.nise.res.in

Preface

Agri-photo-voltaic (AgriPV) also referred to as Agrovoltaic is simultaneous use of cultivable land and electricity production through photovoltaic cells. The AgriPV system enhances the land productivity through production of agriculture commodities and electricity from the same land and helps in reducing carbon emission. AgriPV system can play an important role in achieving energy and food security of the country. Hon'ble Prime Minister of India Shri Narendra Modi ji during COP26 in 2021 has announced the India's commitment to achieve the net zero emission target by 2070 and has set target of 500 GW non-fossil energy capacity by 2030. According to the Ministry of New and Renewable Energy 292 GW is planned from solar photovoltaics.

As of December 2024, India's total renewable energy installed capacity was 209.44 GW. To achieve the target of 292 GW in the remaining 6 years concerted efforts are required. Till now the major part of electricity production from solar energy is coming from the panels installed on the non-cultivable land. Out of total, 60% of land is cultivable with net sown area of nearly 141.01 Mha. The barren land is around 16 Mha. Hence, in order to achieve the net zero emission target and increasing energy demand, solar photovoltaic panel have to reach to agricultural land.

The AgriPV system offers several advantages. However, there will be several challenges in its implementation on a large scale. The AgriPV guideline provides insights on system design, crop selection and maximizing benefits for both farmers and the solar industry.

This CoE AgriPV Guideline is the first comprehensive document developed by the Centre of Excellence at ICAR-IARI to support structured implementation of AgriPV in India. The report aims to enable informed decision-making and promote the sustainable scaling of AgriPV systems aligned with India's renewable energy targets.

Dr. C. Viswanathan, Joint Director (Research) & Coordinator, IARI-ICAR

Dr. Jai Prakash Singh, Deputy Director General, NISE

Dr. D.K. Singh, Principal Scientist & Principal Invigilator, IARI-ICAR

Dr. Birinchi Bora, Deputy Director (Tech.), NISE

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Summary

India is on the path of installing large-scale solar power plant. Access to affordable and sustainable energy, along with food security, is vital for development of the nation. With rising global demand for food, water, and energy, integrated policies are essential. In India, agriculture employs two-thirds of the workforce and contributes 17.66% to GDP. As the third-largest electricity producer and consumer, India is transitioning from fossil fuels to renewables, targeting 500 GW of non-fossil energy by 2030, including 292 GW from solar, to achieve net-zero emissions by 2070. To achieve this target solar panels, had to be taken to agricultural land in such a way that it is used for agriculture and energy production without affecting the crop yield much. Agriphotovoltaic (AgriPV) system in which same land is used for agriculture and energy production has emerged and alternative to fossil fuel-based energy production globally. Centre of Excellence for AgriPV in India has prepared a guideline for installation of AgriPV system in India. The guidelines aim to provide a comprehensive framework for implementing AgriPV system in India. It discusses the conceptual foundation, technical design, policy framework, crop suitability, and learnings from pilot projects, with the objective of supporting farmers, stakeholders, and peers across the public and private sectors.

The AgriPV derived from the terms "agriculture" and "photovoltaics," refers to the co-location of solar photovoltaic systems and crop cultivation, with the goal of producing both food and renewable energy. The dual-use model makes it possible to maximize land productivity while reducing environmental impacts associated with land acquisition and fossil fuel dependency. The system enhances the Land Equivalent Ratio (LER), that compares the combined yield of a dual-use system against a single-use system. An LER greater than 1 indicates higher productivity from the AgriPV system. Apart from enhancing energy output, AgriPV systems offer multiple benefits such as water conservation, protection of crops from climatic extremes, reduction in carbon emissions, and diversification of farmer incomes through integration with livestock, floriculture, beekeeping, and allied activities.

The *Chapter 1* presents concept of AgriPV, as an innovative approach that integrates solar energy generation with agricultural production on the same parcel of land, thereby enhancing land use efficiency, promoting energy access in rural areas, and increasing farmer incomes. The *Chapter 2* includes the definition of AgriPV, benefits, land use patterns in India, challenges, etc.

Chapter 3 presents the description of existing pilot projects across India. Over 22 projects have been deployed across diverse agro-climatic zones, with capacities ranging from 3 kW to 10000 kW. Learnings from these pilots highlight key success factors: optimal panel height, inter-row spacing to allow for mechanization, microclimate management through partial shading, and deployment of advanced monitoring tools like soil sensors and thermal imaging cameras. Challenges identified include shading delays in crop harvests, need for capital investment, and structural adaptations for wind loads and grazing animals.

The *chapter 4* describes the design aspects of an AgriPV systems. Key factors include the height of solar modules, tilt angle, orientation (Typically south-facing in India), row-to-row spacing (Pitch), and the type of photovoltaic technology. Structural considerations such as wind load resistance, soil composition, water drainage, and access for maintenance and farm machinery are also critical.

The *Chapter 5* presents the crops grown in 15 agroclimatic zones of India including cereals, horticultural, sericulture, plantations crops. The choice of crops is influenced by the local agro-climatic zone, light availability (Measured through parameters like DLI and PAR), and the potential to grow shade-tolerant species. Real-time monitoring is essential to assess solar panel performance, soil health, water use, and microclimate effects. Crop growth patterns must be regularly evaluated to mitigate any risk of shading-related yield losses.

The *Chapter 6* describes the potential of AgriPV systems across various agroclimatic zones in India. It highlights the country's strong solar energy prospects, particularly in states with high solar irradiation and approximately 300 days of clear sunshine annually. The chapter also identifies key solar hotspots and examines land characteristics that influence the feasibility and optimization of AgriPV system.

The *Chapter 7* presents case the design combination for AgriPV implementation on a 1-acre land parcel under different scenarios. These scenarios consider crop, solar panel configuration, energy demand, and farm mechanization. Economic viability can be enhanced through government schemes like PM-KUSUM Component A, which supports solar-based decentralized energy generation for farmers, and the Agriculture Infrastructure Fund (AIF), which enables credit.

The *Chapter 8* describes a comprehensive crop matrix for AgriPV systems, proposed based on parameters like Growing Degree Days (GDD), Daily Light Integral (DLI), Light Saturation Point (LSP), and Photosynthetic Photon Flux Density (PPFD). Crops are categorized based on their light requirements. This matrix is aligned with India's 15 agroclimatic zones, offering region-specific crop recommendations. Instrumentation tools such as chlorophyll meters, infrared thermometers, canopy analysers, and automatic weather stations are also highlighted as crucial for precision agriculture in AgriPV environments. Additionally, cultivation under AgriPV has shown potential for expanding it into sericulture and floriculture, diversifying income opportunities further.

Chapter 9 presents way forward for AgriPV system. The policy landscape for AgriPV in India is evolving, with several initiatives already in place. Apart from PM-KUSUM and AIF, other supportive frameworks include the National Solar Mission, Production-Linked Incentive (PLI) scheme for solar manufacturing, and solar parks established for large-scale clean energy generation. The guideline underlines the need for regulatory clarity, especially in defining AgriPV-specific subsidies, land use norms, feed-in tariffs (FiT), and safety regulations. Addressing the yield penalty concerns where crops may experience reduced growth due to shading requires further research and standardization of best practices. The guideline recommends empowering smallholders through cooperative models, joint ventures, and training programs that promote awareness and technical capacity.

AgriPV holds the potential to revolutionize the intersection of agriculture and clean energy in India. By optimizing land use, enhancing energy security, and making agriculture more resilient to climate variability, AgriPV systems can become a cornerstone of sustainable rural development. However, large-scale adoption will depend on the establishment of a strong ecosystem involving research institutions, private developers, financial institutions, and government agencies. The Centre of Excellence (CoE) for AgriPV in India is envisioned as a pivotal body to guide this transition.

In conclusion, the AgriPV Guideline provides a strategic vision and operational roadmap for deploying integrated solar-agriculture systems in India. Through detailed technical design principles, crop compatibility analysis, policy integration, and real-world project insights, the document serves as a reference for scaling up AgriPV in India.

Chapter 1
Introduction

Access to affordable, reliable, and sustainable energy, along with food security is essential for the development of a nation. Rising global populations, urbanization, shifting dietary patterns, and economic growth are intensifying the demand for both food and energy. By 2050, global energy demand is expected to nearly double *(IAEA, 2020)*, while water and food demand is projected to rise by over 50% *(IRENA, 2015)*. To address these growing challenges, there is a need for holistic policy for production and consumption of energy considering their impact on water and food systems.

The agricultural sector in India, which employs two-thirds of the workforce and contributes 17.66% to the GDP *(Statistics Times, 2024)*, plays a crucial role in the economy of the nation. India is the third-largest producer and consumer of electricity, with an installed power capacity of 475,211.80 MW as of March 31, 2025 *(CEA, 2025)*. Electricity demand continues to grow, driven by economic activity, industrialization, and urbanization. Despite a heavy reliance on fossil fuels, India is following ambitious renewable energy goals. Hon'ble Prime Minister of India Shri. Narendra Modi Ji during COP26 in Glasgow, 2021 has announced the India's commitment to achieve the net zero emission target by 2070 and has set target of 500 GW non-fossil energy capacity by 2030. According to the Ministry of New and Renewable Energy 292 GW is planned from solar photovoltaics.

Achieving these goals of renewable energy production presents several challenges, particularly land availability for solar and wind energy production. With 60% of land in India used for agriculture and limited area under barren land, the practice of integrating solar power generation with agricultural practices such as AgriPV offers a viable solution. AgriPV allows the simultaneous cultivation of crops and generation of solar energy on the same land by optimizing land use while reducing environmental impact.

Agriculture accounts for 20% of the electricity consumption in the country *(IEEFA, 2021)*, primarily for irrigation, with some states reaching as high as 50%. Climate change has intensified reliance on groundwater for irrigation, leading to increased energy demand for pumping. Despite the significant growth of agricultural sector in India over the past 75 years, incomes of farmers have not risen proportionally. Many rural households engaged in agriculture continue to be below the poverty line *(National Statistical Office, 2021)*. AgriPV offers a solution by integrating solar energy generation with crop cultivation. However, the dominance of small and marginal landholdings (86.2% of farms being under 2 hectares) *(Agriculture census division, 2019)* must be carefully considered when designing AgriPV systems to ensure broad accessibility and equal benefits.

Although AgriPV has significant potential to drive economic growth in developing country like India. Research in this field is still in its early stages, having only commenced in recent years. The success of AgriPV can be strengthened through extensive field trials and well-defined guidelines that provide clear frameworks for stakeholders. The primary objective of this document is to offer a comprehensive overview of AgriPV, raising awareness among various stakeholders including farmers, research institutions, and newcomers to the field. It is based on insights from existing AgriPV projects in India and other countries, along with reports from countries that have already achieved success in this sector. The key goals and purpose of this document include:

1. Scope and potential of AgriPV in India.
2. Equip farmers and stakeholders with knowledge on designing AgriPV structures and selecting suitable crop combinations for various agro-climate zones in India.
3. Suitable crops for AgriPV systems.
4. Success and challenges in establishing AgriPV systems in India.
5. Create awareness among stakeholders about schemes.

Chapter 2
AgriPV in India

AgriPV, as the name implies, combines agriculture and photovoltaic on the same land. While the concept is clear, its implementation present challenges that require careful consideration. Key considerations include defining AgriPV, land availability and capital investment, design of the system, crop selection and the type of panel to be installed and assessing the impact of solar panels on crop yeild. Integrating solar panels with agricultural land involves balancing agricultural and energy needs. Crop yield optimisation and maximising solar energy production must be carefully managed to benefit both agriculture and energy sectors.

2.1 AgriPV Definition

AgriPV is often referred to as Agrivoltaic. However, **AgriPV** is the most appropriate term as it includes Agriculture and Photovoltaic whereas Agrivoltaic is agriculture and voltaic without photovoltaic. The term "voltaic" refers to the production of electricity through chemical reactions, as seen in voltaic cell which is a basic unit in a battery that converts chemical energy into electrical energy. Whereas, "photovoltaic" refers specifically to the production of electricity through semiconductors. When sunlight, particularly radiation in certain wavelengths, strikes a photovoltaic cell, it excites electrons in a semiconductor, generating an electric current. This is the fundamental principle behind solar energy conversion. Basically, the "PV" in AgriPV refers to Photovoltaic technology, which converts sunlight into electricity using solar cells. Thus, **AgriPV** established the synergy between agricultural practices and photovoltaic technology, making it the most appropriate term.

Different countries have defined AgriPV in different ways, although the underlying concept remains the same. Considering global perspectives and local needs, AgriPV can be defined as:

"The simultaneous production of electricity and crop on the same piece of cultivable land, ensuring the efficient dual use of cultivable land."

This innovative approach not only addresses the growing demand for renewable energy but also ensures the sustainability of agricultural practices, making it a pivotal solution for modern challenges in food and energy security.

2.2 Benefits of AgriPV System

AgriPV enhances land use effieciency through two distinct uses of same piece of land simultaneously i.e use of land for crop production and electricity generation. The benefits of AgriPV can broadly be categorized as:

- **Distinct multiple use:** AgriPV systems enable the cultivation of crops beneath elevated solar panels or between panels in ground-mounted structures. This approach enhances land use efficiency and maximizes productivity by integrating energy generation with agricultural practices. AgriPV system enhances the Land Equivalent Ratio (LER). It is a concept used in agriculture that describes the relative land area required under sole cropping (Monoculture) to produce the same yield as under intercropping (Polyculture) *(Mead and Willey, 2008)*. In AgriPV, LER measures the relative productivity of an

AgriPV system compared to a single-use system. It is calculated by comparing the land area required for a single-use system to achieve the same productivity as an AgriPV system. A LER greater than 1 indicates that the AgriPV system is more productive than the single-use system.

- **Sustainable energy production:** AgriPV harnesses solar energy, a renewable and sustainable resource, to generate electricity. Strategic placement and efficient system design ensure optimized energy production with minimal environmental impact, contributing to cleaner energy solutions.
- **Economic growth and opportunities**: The AgriPV concept provide farmers with an alternative source of income. It offers a dual income source through the sale of electricity and agricultural produce. During off-seasons or adverse climatic conditions, farmers can generate revenue by selling excess electricity to DISCOMs. The innovative nature of AgriPV system attracts youth. Beyond crop cultivation, AgriPV supports activities like fishery, poultry, beekeeping, and animal husbandry enabling an integrated farming system that diversifies income opportunities.
- **Environmental sustainability:** Since the energy generated from AgriPV is renewable, it is environmentally friendly and does not rely on burning of fossil fuels. Additionally, when farmers produce their own energy or utilize it for solar pumps, the dependence on diesel pumps is significantly reduced.

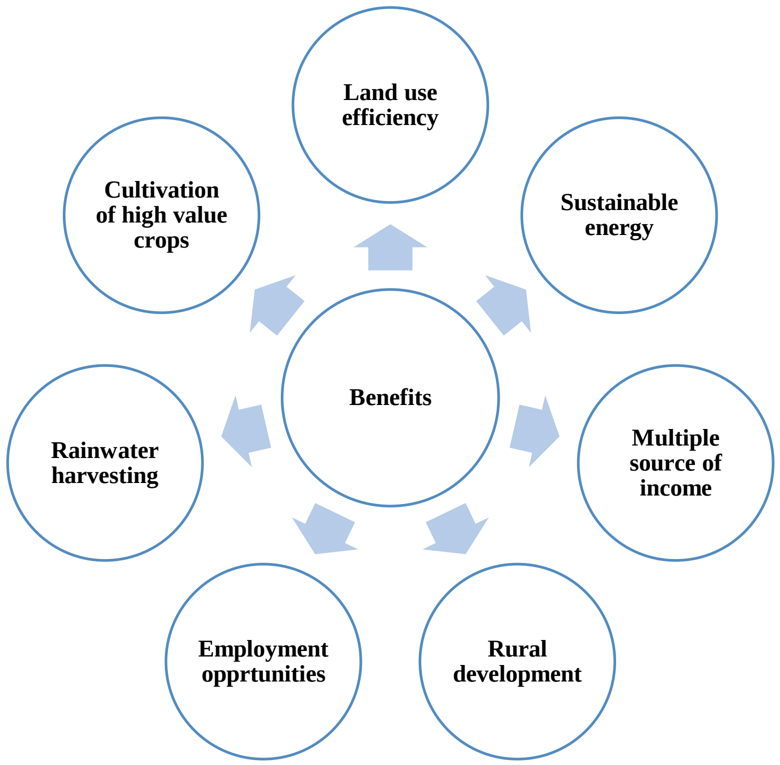

Figure 1: Benefits of AgriPV system

- **Agricultural benefits:** AgriPV helps to reduce crop water usage by minimizing water loss through evapotranspiration. This is especially beneficial for farming in arid and semi-arid regions where water scarcity is a major challenge. The shade provided by solar panels can enhance the growth of certain crops. During the rainy season, rainwater can be harvested and utilized for irrigation, groundwater recharge or cleaning the panels. Also, solar panels offers protection for crops beneath it during harsh weather conditions.

- **Energy for rural development:** AgriPV systems can help rural areas to gain access to reliable renewable energy, reducing dependency on traditional fossil fuels.

2.3 AgriPV in the Indian Context

India, with a population of over 1.4 billion, faces the challenge of meeting its rising food and energy demands while simultaneously reducing greenhouse gas emissions *(Chateau et al., 2023).* To overcome these challenges in energy sector, the country has set an ambitious goal of achieving 500 GW of renewable energy capacity by 2030. Among renewable energy sources, solar energy has significant potential due to abundant availability of solar radiation. However, harnessing solar energy requires significant land area, which poses a challenge in a nation where majority of the land area is dedicated to agriculture. Reserving land solely for solar panels could conflict with agriculture, vital for food security. This is where AgriPV offers a transformative solution. With abundant solar radiation across the country, AgriPV presents a sustainable solution to balance food and energy demands of growing population in India.

2.3.1 Land utilization pattern in India

According to the land clasification (2022-23, *Table 1*), over 58% (170 Mha) of total land area in India is designated for agriculture, with the net sown area accounting for 46% (140 Mha). Among the states, Haryana (90.74%) and Punjab (83.98%) have the highest proportions of agricultural land. In contrast, barren and unculturable land constitutes only 5.40% (16 Mha), while culturable wasteland accounts for approximately 4% (11 Mha) *(Directorate of Economics & Statistics, 2024)*. Given these, relying solely on barren and unculturable land for solar installations may not be sufficient to meet India's renewable energy targets.

Table 1: Land use pattern as per nine-fold classification all India

S. No.	Classification of land	(Thousand Hectares)
	Reporting area for land utilization statistics (1 to 9)	306650
1	Forests	72021
2	Area put to non-agricultural uses	27845
3	Barren & unculturable land	16554
4	Permanent pastures & other grazing lands	10248
5	Land under Misc. tree Crops	2992
6	Culturable Wasteland	11659
7	Fallow Land Other than Current Fallows	11128
8	Current Fallow	13498
9	Net Area Sown	140705
	Agricultural Land (5+6+7+8+9)	179982
	Cultivated Land (8+9)	154203

(Source: Ministry of Agriculture & Farmers Welfare, 2024)

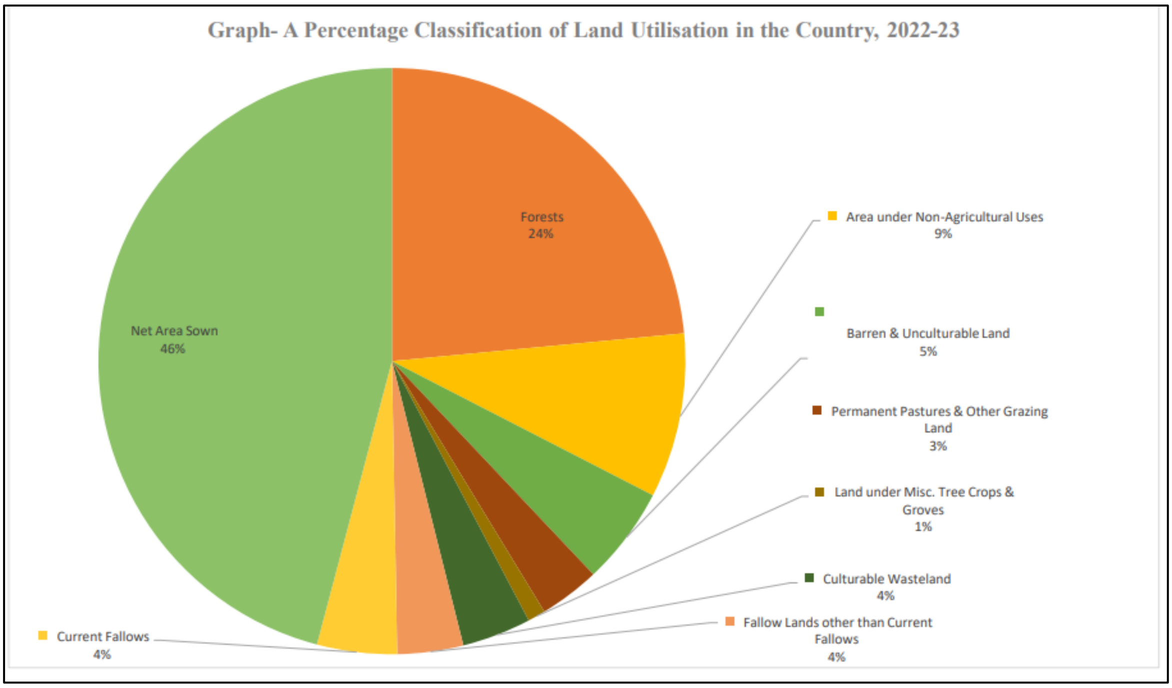

Figure 2: Land utilisation classification (Source: Land use statistics 2022-23, MoAFW)

2.3.2 Land holding pattern in India

The land holding pattern in India will play a significant role in determining the capacity and scale of AgriPV projects. According to the *Agriculture Census 2015-16 (Table 2)*, approximately 68% of Indian farmers are marginal farmers, with an average land holding of just 0.38 hectares. This is followed by small farmers, who contribute 18% of the farming population and hold an average of 1.4 ha of land. Semi-medium farmers account for 10% and have an average land holding of 2.69 ha. Medium farmers represent 4% of the total, with an average land holding of 5.72 ha, and only 1% are classified as large farmers, holding an average of 17.04 ha of land. These landholding patterns could significantly influence the feasibility and scalability of AgriPV installations in India.

Table 2: land holding pattern of Indian farmers

Land holding group	Land holding size (Ha)	Percentage pf holding to total holding	Average operated area per holding (ha.)
Marginal	< 1	68%	0.38
Small	1 – 2	18%	1.40
Semi-medium	2 – 4	10%	2.69
Medium	4 – 10	4%	5.72
Large	> 10	1%	17.04

(Source: Agriculture census 2015-16, MoAFW, GOI 2019)

2.3.3 Solar energy capacity in India

As of March 31, 2025, India's total installed power generation capacity reached **475,211.80 MW**, as reported by the Central Electricity Authority *(CEA, 2025)*. Of this, **246,935 MW** is derived from fossil fuels, with coal accounting for **215,193 MW**. The installed capacity from non-fossil fuel sources stands at **228,276 MW**, including **105,645 MW** from solar energy, marking a substantial increase from 92.12 GW in October 2024. According to the National Institute of Solar Energy (NISE), India possesses an estimated solar energy potential of approximately 750 GW. Furthermore, the CEA projects that solar capacity is expected to rise to between 270 GW and 293 GW by 2030, representing roughly 58–60% of the country's total non-fossil fuel capacity.

To achieve these ambitious targets, the Government of Indi has initiated several schemes:

1. **National Solar Mission:** Part of the National Action Plan on Climate Change (NAPCC), this mission promotes large-scale solar Deployment, R&D, and investment incentives.
2. **Solar parks:** Aims to facilitate large-scale solar power generation by providing pre-approved land, infrastructure, and financial assistance, targeting 40,000 MW capacity through solar parks across multiple states.
3. **Production-Linked Incentive (PLI) Scheme:** To encourage domestic solar photovoltaic (PV) module manufacturing for reducing import dependency.
4. **Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan (PM-KUSUM) Scheme:** Supports farmers in adopting solar-powered irrigation and decentralized solar projects.

With around 180 million hectares of arable land, India stands to harvest a rich crop of energy from AgriPV. The report Agrivoltaics in India published by the German Corporation for International Cooperation (GIZ) pegs the country's AgriPV potential at 3.1–13.8 TW in a conservative-to-best case scenario.

Physical and geographical location of India and favourable schemes offers numerous opportunities for large scale installation of AgriPV system including:

- Government of India's commitment for green energy.
- Abundant solar insolation across the country.
- Increasing energy demand.
- Land availability.

2.3.4 Challenges

While AgriPV offers several benefits, there are several challenges which need to be addressed. Some of the key challenges are as follows:

- Lack of region-specific studies to evaluate the feasibility and long-term impact of AgriPV in India.
- Lack of infrastructure for power evacuation.
- The capital expenditure required for AgriPV systems is unaffordable for many farmers, especially smallholders.
- There is no clear policies and guidelines specific to AgriPV in India.
- Solar energy generation must happen with minimal or no reduction in agricultural yield to ensure food security.
- Indian agriculture is the home of small and marginal farmers. According to the Agriculture Census, it was reported that India had about 71 million operational landholdings in 1970, and 70 % of them were small and marginal *(Saini & Chowdhury, 2023)*. By 2015-16, these numbers increased to about 146 million and 86.2 %, respectively. Therefore, the future of sustainable agriculture growth and food security in

India will depend on the performance of small and marginal farmers. With 86.2% *(Agriculture Census Division, 2019)* of agricultural households owning less than 2 hectares of land, scattered and small landholdings make large-scale AgriPV deployment challenging.

- Farm size fragmentation remains a major hurdle for AgriPV implementation in India. To ensure the inclusion of small and marginal farmers, policy modifications and targeted initiatives are necessary to facilitate their participation in the AgriPV system.
- Specialized equipment is needed to operate effectively in AgriPV fields. Safety measures must be robust to protect farmers and installations.

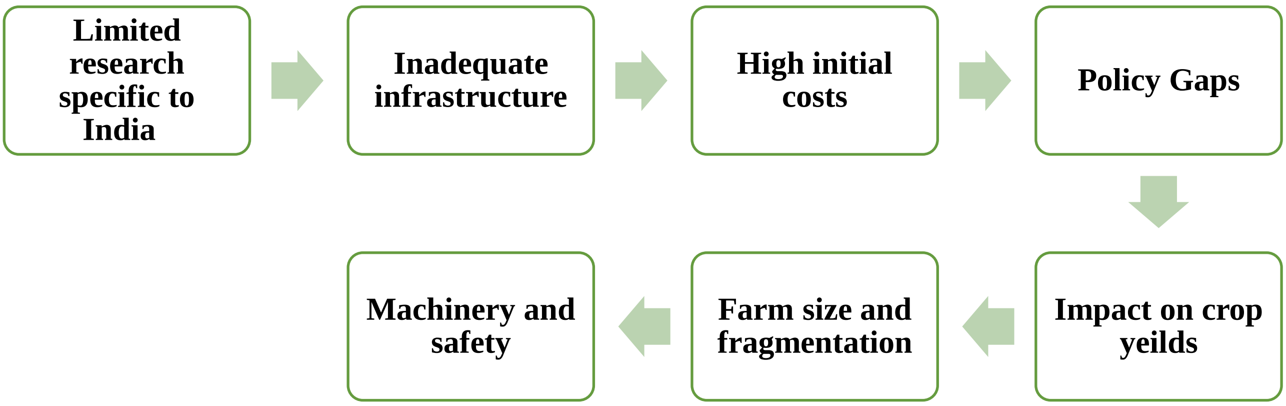

Figure 3: Challenges of AgriPV in India

2.4 Role of AgriPV for Managing Climate Change Impact

AgriPV reduces carbon emissions by decreasing dependence on fossil fuels for energy production. Climate change is mainly attributed to the greenhouse effect. Certain gases create a thick layer and trap long wave radiation from earth leading to global warming. These gases, known as greenhouse gases (GHGs), are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases). In India, coal-fired power plants are the largest contributors to CO_2 emissions. Coal is the main source of electricity generation in the country and contribute to approximately 72% of total CO_2 emissions from fuel combustion *(IEA, 2022)*. Other fossil fuels, such as oil and natural gas, used for power generation also and contribute singnificantly to GHG emissions.

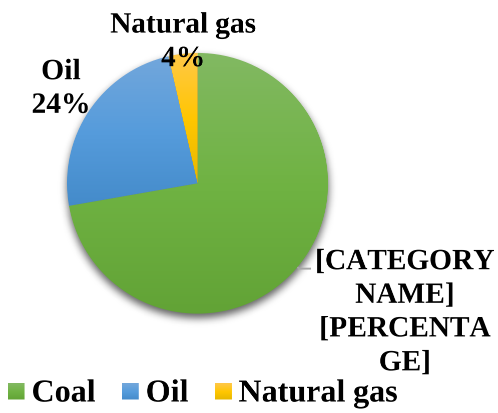

Figure 4: CO_2 emissions by fuel, India, 2022 *(Source: IEA, 2022)*

Globally, energy production is the leading source of greenhouse gas emissions, primarily due to fossil fuel combustion *(EPA, 2024)*. In 2023, energy-related CO_2 emissions increased by 1.1%, adding 410 million tonnes (Mt) and reaching a record high of 37.4 billion tonnes (Gt). Coal emissions alone accounted for over 65% of this rise *(IEA, 2023)*.

2.4.1 Challenges from coal-based energy in India

As discussed earlier, most of the CO_2 emissions in energy sector in India come from burning fossil fuels such as coal, oil, and natural gas used for power generation, transportation, and industrial and agricultural activities. This trend has escalated with increasing electricity demand driven by rapid industrialization, urbanization, and agricultural mechanization. Electricity generation from coal in India increased from 987.68 BU in 2018-19 to 1,043.83 BU in 2022-23, with corresponding CO_2 emissions increasing from 897.28 million metric tonnes to 943.04 million metric tonnes *(Ministry of Power, 2024)*. India's electricity demand increased by 9.09% to 148.83 TWh in September 2024, compared to 136.43 TWh in the same period of 2023. Similarly, electricity generation rose by 9.7% to 149.57 TWh during the same timeframe *(Ministry of Coal, 2024)*.

Coal-fired and lignite-based thermal power plants are significant contributors to greenhouse gas (GHG) emissions, accounting for 2.4% of global GHG emissions, one-third of India's total GHG emissions, and nearly half of the country's fossil fuel-related emissions *(CSE, 2020)*. As coal remains a primary energy source in India, its demand is expected to reach at peak between 2030 and 2035 *(Ministry of Coal, 2022)*, leading to continued CO_2 emissions. This emphasizes the urgent need for renewable energy integration to mitigate climate change impacts. To meet India's 500 GW renewable energy target and address the recurring coal demand-supply gap, the Ministry of Power has identified 81 thermal power units that will transition to renewable energy generation by 2026 *(Ministry of Power, 2022)*.

2.4.2 AgriPV: A sustainable solution

Renewable energy sources, such as solar and wind power, could significantly reduce GHG emissions. AgriPV offers a solution by combining agricultural production with solar energy generation. Replacing diesel-powered water pumps with solar-powered can cut GHG emissions. Goal of the nation to achieve net-zero emissions by 2070 and meeting 50% of its electricity needs from renewable sources by 2030 is a step forward in managing climate change. According to the United Nations, net-zero emission involves reducing carbon emissions to a level where the remaining emissions can be absorbed by natural and technological carbon removal methods, leaving no net addition to the atmosphere.

A Study in Baden-Württemberg region of Germany by *Sponagel et al*. (2024) reveals that deploying AgriPV systems on 1–5% of arable and grassland could reduce GHG emissions by 1.2–5.9 million metric tons of CO_2 equivalent. According to *Gomez-Casanovas et al*., (2023), the use of AgriPV system for renewable energy has the potential to help mitigate climate change as we shift away from fossil combustion.

2.4.3 Environmental considerations for solar panel production

While solar energy generation emits no GHGs during operation, the production process of solar panles has environmental implications:

- Solar panel manufacturing relies on fossil fuels and mining of precious metals, contributing to emissions and resource depletion.

- Production involves energy-intensive materials such as glass and metals, with associated environmental impacts.
- The fabrication process uses caustic chemicals, consumes significant water and electricity, and generates waste.

However, studies by the National Renewable Energy Laboratory (NREL) show that solar panel production emits 18 times less carbon than coal-based power generation, highlighting its advantages as a cleaner energy source.

2.5 Classification of AgriPV Systems

Diverse climate, agricultural practices, and land use patterns in India necessitate a customed approach to implement AgriPV systems. A clear classification of AgriPV types is essential to guide policymakers, researchers, industry and other stakeholders in selecting the most suitable systems for different regions. Understanding the various types of AgriPV systems - based on installation type, panel arrangement, agricultural activity and interaction level - enables stakeholders to assess their feasibility, benefits and challenges.

2.5.1 Classification based on the type of installation

- **Open field systems:** In open agricultural fields, PV panels are installed to permit traditional farming activities beneath or between the rows of panels.
- **Greenhouse systems:** PV panels are integrated into the structure or roof of greenhouses, generating energy while allowing enough light for the plants inside.
- **Floating systems:** Photovoltaic (PV) panels are installed on floating platforms on the water bodies, providing shade and help reduce water evaporation.

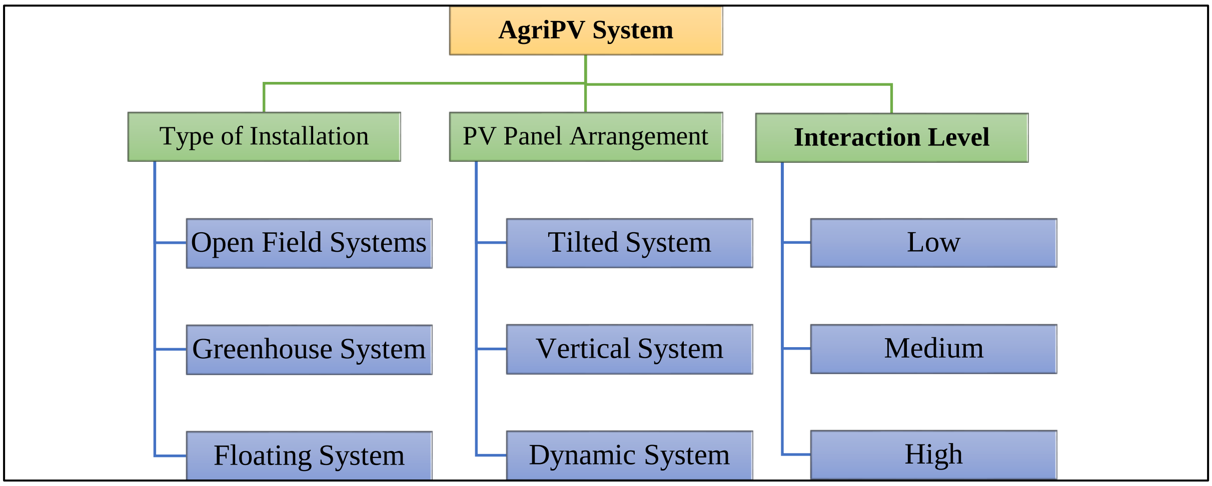

Figure 5: Classification of the AgriPV system

2.5.2 Classification based on PV panel arrangement

- **Tilted Systems:** PV panels are installed horizontally at a certain height above ground with tilt angle with respect to ground surface, facilitating farming activities underneath.
- **Horizontal Systems:** Vertically mounted PV panels optimize land use and reduce shading, making them suitable for crops requiring full sunlight.
- **Dynamic Systems:** PV panels that can be adjusted in angle and orientation enhance solar capture and manage shading for diverse crops.

2.5.3 Classification based on interaction level

- **Low interaction:** Solar panels and agricultural activities remain mostly independent, with minimal interaction between them.
- **Medium interaction:** There is moderate interaction, where panels influence agricultural practices, such as using shade-tolerant crops or modified irrigation systems.
- **High interaction:** Solar and agricultural systems are designed to complement and optimize the performance of each system.

(a): GIPCL AgriPV plant, Amrol, Gujarat

(b): Sahyadri farms AgriPV plant Nashik, Maharashtra

Figure 6: Orientation of panels (a) & (b)

Chapter 3
Existing AgriPV Projects in India

There are about 22 operational AgriPV pilot projects various states in India. The capacity of these project ranges from 3 to 10000 kW, and multiple crops are grown on the same field. India has great potential to utilise AgriPV systems in different areas either on productive land or on unproductive land. Approximately 60% of area in India is available for agricultural activities. However, crop yields may be impacted if agricultural land is completely converted to AgriPV *(Yadav et al., 2024)*.

Table 3 presents the list of AgriPV project installed in various states of India.

Table 3: Existing pilot projects in India in different agro-climatic zones

Project Name & Installed Capacity DC	State, City	Type of AgriPV Plant	Crops Cultivated
Zone: 1 - Western Himalayan Region			
Sandhwani Solar Power Plant - farmer owned, 250 kW	Himachal Pradesh, Jahu	Elevated Structure	Eggplant, Cabbage, Onion, Chilly, Turmeric
Zone: 5 - Upper Gangetic Plain Region			
Amity University Noida, 10 kW	Uttar Pradesh, Noida	Single column	Maize, Potato, Brinjal, Mustard
Dayal Bagh University Agra Plant, 200 kW	Uttar Pradesh, Agra	Single Column	Grams, Brinjal, Tomato, Wheat, Spinach, Cauliflower, Carrot, Gourds
Zone: 6 - Trans Gangetic Plain Region			
National Institute of Solar Energy, 100 kW	New Delhi, Gwal Pahari	Interspace	Flowers, Tomato, Chilli, Kufri lima potato
National Institute of Solar Energy, 5 kW	New Delhi, Gwal Pahari	Vertical Installation	-
Krishi Vigyan Kendra (NHRDF), 110 kW	Delhi, Ujwa	Elevated Structure	Okra, Tomato, Brinjal, Capsicum, Leafy vegetables, Root vegetables, Cole crops planned
Sunmaster AgriPV System, 2 MW	Delhi, Najafgarh	Elevated Structure	Brinjals, Lettuce, Spinach, Lady Finger, Potatoes, Tomatoes, Bottle Guard, Fenugreek, Coriander, Cucumber, Mango Turmeric, Pomegranate

Zone: 8 - Central plateau and Hills Region			
Indra Solar Farm, **2 MW**	Madhya Pradesh, Tikamgarh	Elevated Polyhouse Structure	Wheat, Lentils, Green and red gram, Peanuts
Jeevan Solar Farm **2 MW**	Madhya Pradesh, Sagar	Elevated structure with monofacial and bifacial	Wheat, Sorghum, Green Gram, Brinjal, Corn, Chili, Tomato, Cauliflower, Brocolli, Bell pepper, Onion, Strawberry, Lettuce, etc.
CAZRI Jodhpur Plant,	Rajasthan, Jodhpur	Interspace	Mungbean, Mothbean
100 kW			Cluster bean, Isabgol, Cumin, Chickpea, Aloevera, Sonamukhi, Sankhpuspi, Chilli, Cabbage, Onion, Garlic
Fishpond Agri-PV System, 30 kW	Rajasthan, Bhaloji	-	Fish
Zone: 9 - Western plateau and Hills Region			
Jain Irrigation Banana Pilot Project, **14.4 kW**	Maharashtra, Jalgaon	Overhead Tilted	Banana, Maize
Jain Irrigation Rice Pilot Project, 9.6 kW	Maharashtra, Jalgaon	Overhead Tilted	Rice
Jain Irrigation Okra/Cotton Pilot Project, 50.4 kW	Maharashtra, Jalgaon	Overhead Tilted	Cotton, Okra
Jain Irrigation Turmeric/Ginger/Mint Pilot Project, 19.3 kW	Maharashtra, Jalgaon	Overhead Tilted	Turmeric, Ginger, Mint
Jain Irrigation Greenhouse Pilot Project, 200 kW	Maharashtra, Jalgaon	Greenhouse	Banana
AgriPV System in Manwath Near Parbhani, 1 MW	Maharashtra, Parbhani	Interspace	Cherry Tomato, Capsicum, Cucumber, Betel Leaves, Turmeric, Ginger, Basil, Spinach, Methi, Coriander, Mint, Rose, Chrysanthemum, Tuberose, Hibiscus, Marigold, Muskmelon, Fenugreek, Marigold, Basil, Water melon

Gro Solar AgriPV System, 10 MW	Maharashtra, Dhule	Interspace	Geranium, Guava, Lemongrass
Agrivoltaics Plant Nashik, 500 KW	Maharashtra, Nashik	Elevated with Single Axis Tracking	Grapes, Oranges, Raspberry, Tomato, Strawberry
Zone: 10 - Southern plateau and Hills Region			
Mahindra Susten Tandur Plant, **400 kW**	Telangana, Tandur	Interspace	Lemon grass, Annatto dye, Brinjal, Lady finger, Green chilies, Onions
Agritech Innovation Pilot 2.0, 10 kW	Telengana, Hyderabad	Elevated Structure	-
Hinren AgriPV Rooftop System, **3 kW**	Karnataka, Bangalore	Rooftop Elevated Structure	Cauliflower, Tomato Ladies finger, Chilly, Pomegranate, Lemmon, Spinach, Rosemary, Bitter gourd, Brinjal, Beans, Basil, Coriander, Papaya, Lettuce
Zone: 12 - West coast plains and Ghat Region			
Cochin Airport Plant, **4 MW**	Kerala, Cochin	Interspace	Yam, Long yard bean, Drumstick, Mountai, Ginger, Turmeric, Cabbage, Cauliflower, Snake gourd, Bitter gourd, Bottle gourd, Ash ground, Blode cucumber, Eggplant, Tomato, Pumpkin, Okra
Zone: 13 Gujarat Plains and Hills Region			
GIPCL Amrol Plant, **1 MW**	Gujarat, Amrol	Interspace/ Overhead Hybrid	Groundnut, Soybean, Pearl millet, Cotton, Green gram, Pigeonpea, Maize, Cluster bean, Chickpea, Wheat, Mustard, Lucerne, Sesame, Fodder, Black gram
GIPCL Vastan Plant	Gujarat, Vastan	Interspace	n.a.
GSECL STPS Solar (Harsha Abakus), **1.05 MW**	Gujarat, Jamnagar, Sikka	Interspace	Bottle gourd, Coriander, Cluster beans, Tomato,

			Cucumber, Zucchini,
			Chili, Moong Dal, Ladyfinger
GSECL Panandhro	Gujarat, Panandharo	Interspace	Brinjal, Coriander, Cluster beans, Ladyfinger, Bottle gourd, Green gram,
(Harsha Abakus),			Sesame, Split black gram, Zucchini, Peas
1 MW			
Junagadh Agriculture University Plant,	Gujarat, Junagadh	Overhead tilted	Tomato, Capsicum, Cotton
7 KW			
Abellon Energy Plant,	Gujarat, Aravalli	Interspace	Bottle gourd, Ginger, Lady finger, Watermelon, Turmeric, Chilli
3 MW ~ 1 MW AgriPV			

(Source: Pulpika et. al., 2023)

3.1 Learnings From Site Visits

The Centre of Excellence (COE) team visited to several AgriPV projects across India *(Table 4)* to gain insights about the projects and crops cultivated.

Table 4: Review of the AgriPV sites visited by COE team

Sr. No	Site Name	Description	Crops cultivated	Best performing crop under AgriPV system	Crops under cultivation during visit
1	AgriPV plant, GIPCL, Amrol, Gujarat **(1.0 MW)**	Interspace/ Overhead Hybrid	Groundnut, Soybean, Pearl millet, Cotton, Green Gram, Pigeon pea, Maize, Cluster bean, Chickpea, Wheat, Mustard, Lucerne, Sesame, Fodder crop, Black gram	Turmeric, Wheat	Turmeric and Sorghum
2	Agrivoltaic plant (Renew Solar energy), Manwath, Parbhani, MH **(1.4 MW)**	Monofacial and bifacial panels, 3.75 m Shade-house, 1.75m Bifacial, 1.25 m Bifacial, 1.75m Monofacial.	Ginger, Turmeric, Soybean, Onion, Cabbage, Zucchini, Linseed, Chickpea, Pigeon-pea, Rice, Fodder crop (Napier, Dhaincha), Chrysanthemums, Watermelons, Rose, Soybean, Kidney beans	Turmeric, Banana, Cabbage, Pigeon Pea, Leafy Vegetables	Turmeric, Zucchini, Banana, Pigeon Pea, Onion, Ginger.

3	AgriPV plant, Jain Irrigation, Jalgaon, MH **(30.32 kW)**	Monofacial and bifacial (East-west) panels with a transparent rear glass or back sheet allow light to pass through.	Turmeric, Banana, Leafy vegetables	Turmeric, Leafy vegetables	Turmeric
4	Gro Solar Energy AgriPV plant, Dhule, MH **(10.0 MW)**	Below and interspace cultivation, monofacial panel orientation	Lemon grass, Moringa, Natal Plum (Karvanda), Onion, Spring onion, Red Gram, Okra, Ginger, Pigeon-pea, Gram, Watermelon,	Lemon grass,	Lemon grass, Moringa, Natal Plum (Karvanda)
5.	Sahyadri Farms, Nasik, MH **(250.0 kW)**	Movable panel at 120˚, East -west orientation, Height – 3.75 m,	Grapes, citrus, etc.	So far, only two crops have been tested, and the grapes have not been harvested yet, making it difficult to determine best performing crop.	Grapes, citrus
6	Sun Master AgriPV plant, Najafgarh **(2.0 MW)**	Elevated structure	Millet, Jowar, Bajra, Leafy vegetables		Tomato, Cauliflower, Lemon, Chilli, Carrot, Cabbage, Spinach, Okra, Bottle Guard, Turmeric
7	Indra Solar Farms, Khare Energy Pvt. Ltd., Tikamgarh **(2.0 MW)**	Elevated structure with monofacial and bifacial	Wheat, Sorghum, Green Gram, Brinjal, Corn, Chilli and Goat farming	Wheat	Wheat
8	Jivan solar Farms, Sagar **(2.0 MW)**	Elevated structure with monofacial and bifacial	Wheat, Sorghum, Green Gram, Brinjal, Corn, Chili, Tomato, Cauliflower, Brocolli, Bell pepper, Onion, Strawberry, Lettuce, etc.	Wheat, Sorghum, , Brinjal, Chili, Tomato, Cauliflower, Brocolli, Onion, Strawberry, Lettuce	Wheat, Chili, Tomato, Cauliflower, Brocolli, Bell pepper, Onion, Strawberry, Lettuce, Cherry Tomato, Cucumber

The site visits provided valuable insights into the integration of solar power with agriculture. The successful growth of crops, such as leafy vegetables under shaded conditions, highlights the potential of AgriPV system. The use of advanced sensors for monitoring moisture content and solar radiation demonstrates the importance of precision agriculture in improving efficiency. Despite challenges such as land levelling and drainage, the positive outcomes observed at the Manwath AgriPV site for crops like banana, leafy vegetables, cabbage, and turmeric gives a big hope. The implementation of automated cleaning systems and the beneficial effects of diffused sunlight on crop growth emphasize the effectiveness of AgriPV systems. This was evident at both the Manwath AgriPV site and the Jain Irrigation AgriPV site.

Successful cultivation of high-value crops such as lemon grass for oil extraction and moringa for powder production are done at Gro Solar Energy AgriPV site, Dhule further supports the economic sustainability of these systems. Overall, the site visits underscore the potential of AgriPV systems to enhance agricultural productivity, promote sustainable energy solutions, and contribute to the economic well-being of farming communities.

The GIPCL AgriPV plant in Amrol, Vadodara, established in 2016, has 1 MW capacity across 2.3 hectares, with 1.3 hectares dedicated to crop cultivation. The installation consists of 3,240 solar panels (310 W each), spaced at intervals of 25, 130, and 150 mm to allow efficient land use. A 10-meter crop width ensures unobstructed tractor movement (45 HP), while panels are mounted at a height of 2.5 meters. The site was well maintained, and crops especially turmeric and wheat have performed well. However, shading effects cause a harvest delay of 10–15 days, with yields reduction varying by 5–10%.

The COE team visited the Sagar AgriPV plant, commissioned on February 1, 2025, under the PM KUSUM-A scheme. This 16-acre AgriPV project in Sagar, featuring elevated solar panels at 12 feet, facilitating the cultivation of over 13 different crops, including horticultural and agricultural varieties. The project integrates vermicomposting and organic farming beneath the panels, emphasizing sustainability. By optimizing land use, enhancing farm income, and strengthening rural energy security, this pilot shows AgriPV as a scalable and climate-resilient solution for agriculture and renewable energy integration.

The visit to India's largest AgriPV plant under the PM-KUSUM-Component A scheme, developed by Khare Energy Pvt. Ltd. in Tikamgarh, Madhya Pradesh, spanning 16 acres (14 acre for agriculture, 2 acre for solar), the provided performance, particularly of wheat, with yields ranging from 18 to 30 quintals against the state average of 28 quintals. Partial shading from elevated panels enhanced soil moisture, reduced irrigation and enables multiple summer crop cycles, improving land-use efficiency by 20%. The 16 different crops, including cabbage, watermelon, tomato, and strawberries were cultivated. It also supports local livelihoods through employment, solar O&M training for farm workers, and hands-on learning for students. The project exemplifies the integration of clean energy, sustainable agriculture, and community empowerment.

Chapter 4
Solar PV Design for AgriPV System

AgriPV systems are inherently multifaceted, as they integrate both energy generation and agricultural activity within the same land area. The design parameters must be carefully balanced to optimise both, as maximizing electricity generation can sometimes create less favourable conditions for crop growth and vice versa. For instance, excessive shading from solar panels may reduce photosynthetic efficiency, affecting crop yields, while inadequate spacing between panels or insufficient ground clearance can hinder traditional farming activities such as mechanized harvesting.

To ensure optimal performance, it is crucial to establish design parameters that harmonize photovoltaic efficiency with agricultural viability. A well-designed AgriPV system should enhance land-use efficiency while maintaining a balanced trade-off between energy generation and sustainable agricultural practices.

This chapter presents the key design considerations essential for the effective integration of solar PV technology with agricultural practices. It covers aspects such as real-time monitoring systems to optimize performance, innovative mounting structures tailored to enhance dual land use, and the role of trackers in maximizing energy output. Additionally, it addresses electrical safety protocols and testing standards to ensure system reliability, and guidelines for supporting uninterrupted agricultural activities.

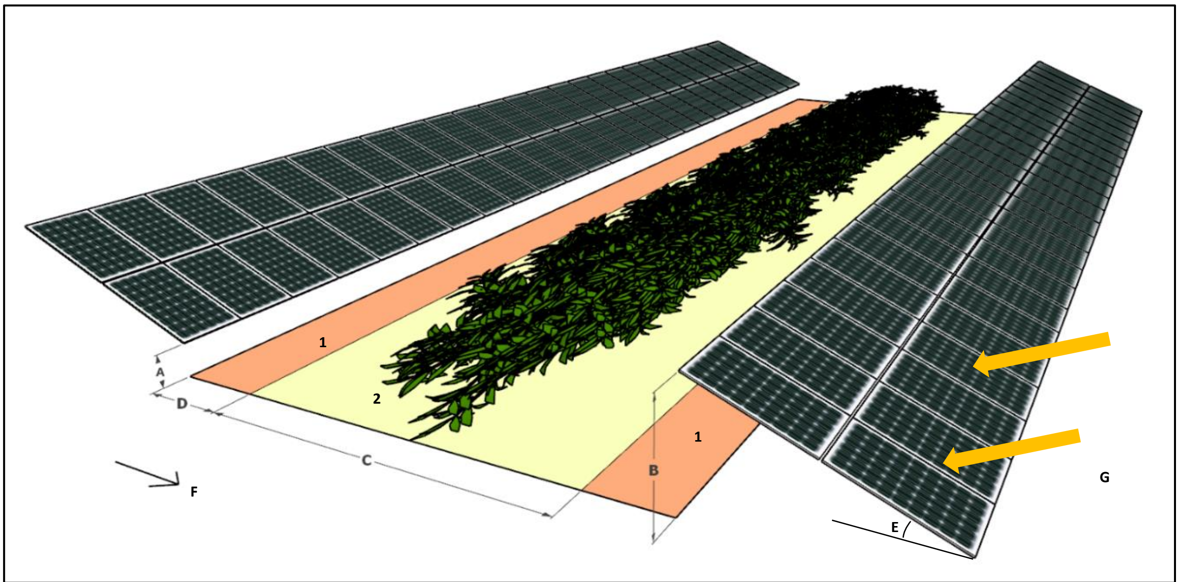

Figure 7: Key design parameters of AgriPV systems

Key design parameters:
A, B: Height of the Solar Modules from the ground, Front and
C: Width of the cultivation region
D: Safety margin between crops and Solar PV system
E: Tilt angle of the Solar PV module
F: Facing Direction of the Solar PV Modules
G: Solar Irradiation
H: Safety Margin Area
I: Agronomic Area

Table 5 : Key design parameters of AgriPV system

Parameter	Key considerations
A, B: Height of solar modules (Front & back)	Determined by the optimal tilt angle for maximizing solar irradiation. The height of the crops needs to be considered to ensure sufficient clearance and avoid shading effects.
C: Width of cultivation region	Depends on shadow-free distance throughout the year, ensuring uninterrupted agricultural operations. Should accommodate tractor and cultivator width for ease of movement. Also, beneath the solar module area is considered as cultivation region for low heighted and underground crops.
D: Safety margin between crops & solar PV system	Required walkway space for O&M team movement, solar panel cleaning, and regular maintenance. Prevents accidental damage to crops or PV panels.
E: Tilt angle of solar PV module	Based on the site's latitude and longitude to optimize solar generation. Solar PV simulation and analysis are required to finalize the tilt angle.
F: Facing direction of solar PV modules	In the Northern Hemisphere, modules should face south, while in the Southern Hemisphere, they should face north. Solar energy generation analysis determines the ideal facing direction.
1: Safety margin area	Allocated for safe movement during O&M activities and cleaning processes, ensuring system longevity.
2: Agronomic area	The primary cultivation area where major crops are grown. Selection of crops is planned for both open-field and shaded areas beneath the solar panels.

4.1 Objectives of AgriPV System

The integration of solar panels and crop cultivation in AgriPV systems enhances land productivity and farmers' income. The vegetation beneath solar panels helps maintain a cooler ambient temperature, improving the efficiency of PV modules while reducing soil moisture loss and irrigation needs. Simultaneously, solar panels create a controlled microclimate, shielding crops from extreme heat and harsh weather, which supports better growth and higher yields.

Figure 8: Objectives of AgriPV system

4.2 Design Consideration for Solar PV System on Agricultural Land

Several essential factors must be taken into account for the successful installation of an AgriPV system. These factors include the agroclimatic zone, which influences crop selection and solar efficiency, and the effect of microclimate on the crop due to panel shading, which influences plant growth. Adequate drainage system and flood risk management are crucial to prevent waterlogging and soil erosion. Furthermore, the tilt and orientation of solar panels should be aligned with the land parcel's topography to maximize sunlight capture. Lastly, adherence to regulatory and policy frameworks is vital for seamless grid integration and long-term project sustainability.

The objective of an AgriPV system is to integrate solar power generation with crop cultivation on the same land, to enhance farmers' income. Various factors influence system performance and quality. Based on their significance, these factors have been classified and given below.

Understanding and considering all key design factors influencing AgriPV project performance is essential, as these factors vary based on location and system configuration. Each site requires a tailored approach, necessitating collaboration between farmers and solar PV system developers to ensure optimal outcomes.

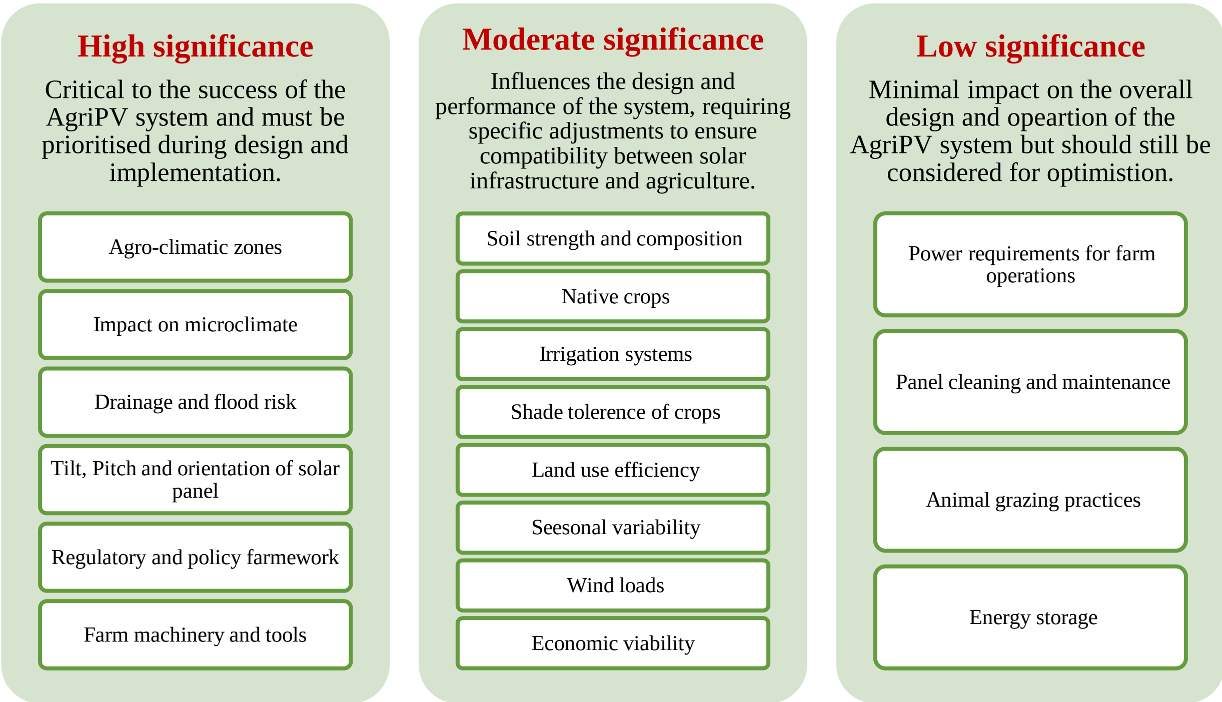

Figure 9: Key design factors affecting the AgriPV systems based on their significance

4.2.1 Agroclimatic zone

India's diverse agroclimatic zones play a crucial role in determining the feasibility and optimization of AgriPV systems. The country is classified into 15 agroclimatic zones based on climatic conditions, soil types, and crop suitability, which directly impact solar energy generation and agricultural productivity. Parameters such as solar irradiance, temperature variations, humidity, and rainfall influence key factors for design of AgriPV systems along with the tilt angle of solar panels, row-to-row spacing (Pitch), and selection of photovoltaic technology. For instance, in high-radiation regions like Rajasthan and Gujarat, steeper tilt angles and wider spacing may be needed to balance solar power generation with crop shading, whereas in high-humidity regions like the Western Ghats, corrosion-resistant materials and proper ventilation strategies is critical.

Moreover, the agroclimatic zone dictates the selection of crops that can grow well under partial shading conditions, irrigation strategies, and fertilizer management practices. India's 15 agroclimatic zones, ranging from arid deserts to humid tropics, demand tailored system designs that account for variations in temperature, rainfall, and solar irradiation. Adapting to these zones ensures optimal energy production while safeguarding the local agricultural ecosystem. Such considerations allow for designing systems resilient to diverse weather patterns, such as monsoons or droughts.

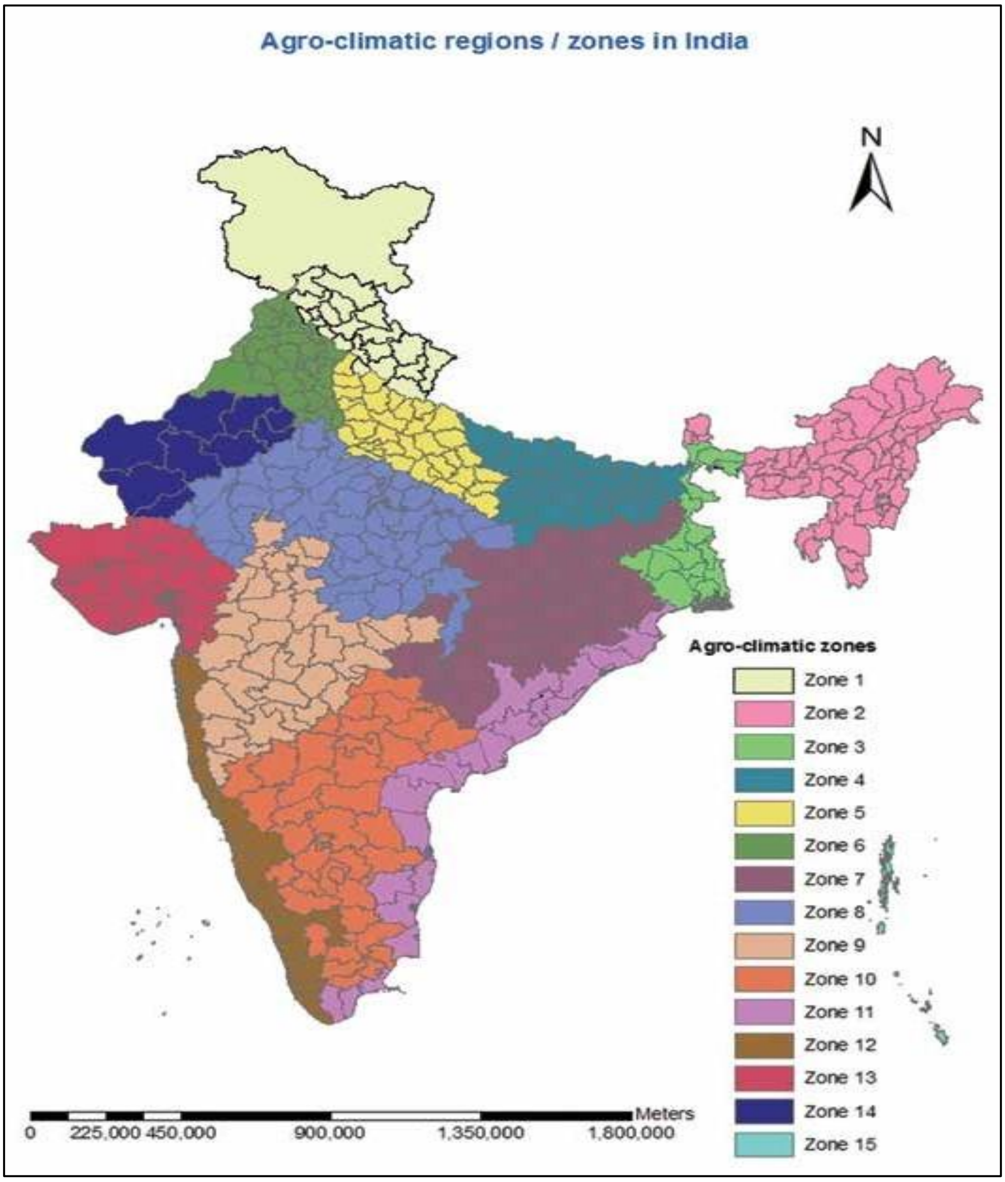

Figure 10: Agro-climatic zones in India

Table 6: Agro-climatic zones in India

Zone	Agro-climatic regions/zones	States represented
1	Western Himalayan region	Himachal Pradesh, Jammu & Kashmir, Uttarakhand
2	Eastern Himalayan region	Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, West Bengal

3	Lower Gangetic plain region	West Bengal
4	Middle Gangetic plain region	Uttar Pradesh, Bihar
5	Upper Gangetic plain region	Uttar Pradesh
6	Trans Gangetic plain region	Chandigarh, Delhi, Haryana, Punjab, Rajasthan
7	Eastern plateau and hills region	Chhattisgarh, Jharkhand, Madhya Pradesh, Maharashtra, Odisha, West Bengal
8	Central plateau and hills region	Madhya Pradesh, Rajasthan, Uttar Pradesh
9	Western plateau and hills region	Madhya Pradesh, Maharashtra
10	Southern plateau and hills region	Andhra Pradesh, Karnataka, Tamil Nadu
11	East coast plains and hills region	Andhra Pradesh, Odisha, Puducherry, Tamil Nadu
12	West coast plains and ghat region	Goa, Karnataka, Kerala, Maharashtra, Tamil Nadu
13	Gujarat plains and hills region	Gujarat, Dadra & Nagar Haveli, Daman & Diu
14	Western dry region	Rajasthan
15	Island region	Andaman & Nicobar Islands, Lakshadweep

4.2.2 Impact of AgriPV on microclimate

The integration of solar PV panels in agricultural fields significantly alters the microclimate beneath them, affecting key environmental parameters such as temperature, humidity, and soil moisture. The shading effect of solar panels reduces direct solar radiation, leading to lower soil and air temperatures compared to open-field conditions. This modification can be beneficial in hot and arid regions, where excessive heat can cause soil moisture loss and heat stress in crops. However, in colder climates, reduced sunlight penetration may slow down the growth rate of certain crops, making it necessary to select plant species that can thrive under modified light conditions. Understanding these microclimatic variations is essential for optimizing crop productivity and ensuring the efficient operation of AgriPV systems.

Heat distribution across the soil surface is largely influenced by the design of the PV mounting structure, including panel height, tilt angle, and spacing between rows. A well-optimized mounting system ensures adequate airflow and prevents excessive heat accumulation, which could otherwise lead to soil drying and increased water evaporation. The balance between shading and sunlight exposure also affects soil temperature regulation, which in turn impacts seed germination, root development, and nutrient absorption by crops. Since soil temperature and moisture retention capacity vary across different agroclimatic zones, AgriPV projects must incorporate region-specific design strategies to maintain optimal growing conditions.

Water management plays a crucial role in AgriPV systems, as changes in microclimate directly influence evapotranspiration rates and soil moisture retention. Reduced sunlight exposure can lower the rate of evaporation, thereby conserving water and making irrigation more efficient. Additionally, rainwater harvesting techniques and soil mulching can be integrated to enhance water conservation in AgriPV fields.

Given these dynamic interactions, careful consideration of the crop microclimate is vital during the planning and design phase of an AgriPV project. The selection of crops must align with the altered environmental conditions, with a preference for species that can adapt to reduced light and fluctuating temperature levels. Similarly, cultivation cycles may need adjustments to synchronize with seasonal variations and solar panel shading patterns.

4.2.3 Drainage and flood risk

Proper water drainage and flood risk assessment are crucial when installing solar PV systems on agricultural land to ensure long-term system reliability and crop protection. Uneven land surfaces and inadequate drainage planning can lead to waterlogging, which may damage crops, reduce soil fertility, and impact the structural integrity of PV mounting systems. To mitigate these risks, land levelling should be completed before installation, and the height of solar panels and electrical components must be designed considering the worst-case flood scenarios. Elevated mounting structures and properly sealed electrical systems will help safeguard the infrastructure from water damage, ensuring uninterrupted operation even in extreme weather conditions.

In regions prone to heavy rainfall, efficient drainage planning is essential to prevent excess water accumulation in cultivable areas. Implementing well-designed water channels, trenches, or underground drainage systems can help divert water away from both the PV system and the crops, maintaining optimal soil conditions. Additionally, integrating rainwater harvesting techniques can turn excess rainfall into a resource for irrigation, enhancing the overall sustainability of the AgriPV system.

4.2.4 Solar panel tilt, pitch and orientation

The selection of an optimum tilt angle and orientation for solar panels is a critical design factor in AgriPV systems, as it directly influences both solar energy generation and agricultural activities beneath the panels. The tilt angle determines how effectively the solar PV system captures sunlight throughout the year, while the orientation ensures maximum exposure to solar radiation. In India, which lies in the Northern Hemisphere, solar panels are typically oriented towards the south to maximize solar energy absorption. Conversely, in the Southern Hemisphere, a north-facing orientation is preferred. The tilt angle varies based on the agroclimatic zone, ensuring optimal electricity generation while maintaining a balance with agricultural needs. Optimum tilt angle section can be selected from the below table based on the agroclimatic zone and state.

Table 7: Recommended tilt angle for argo climatic zone

Zone	States Covered	Latitude and Longitude (Degree)	Recommended Tilt angle (Degree)
1	Jammu and Kashmir, Himachal Pradesh and Uttarakhand	Lat: 27° E to 37° E Lon: 73° N to 8° N	20° to 30°
2	Sikkim, Darjeeling (West Bengal), Assam Hills, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura and Meghalaya	Lat: 22° E to 29° E Lon: 84° N to 98° N	20° to 25°

3	Eastern Bihar, West Bengal, and Assam valley	Lat: 22° E to 28° E Lon: 87° N to 95° N	20° to 25°
4	Eastern Uttar Pradesh and Bihar (except Chotanagpur plateau)	Lat: 24° E to 28° E Lon: 82° N to 88° N	20° to 25°
5	Central and western parts of Uttar Pradesh.	Lat: 25° E to 30° E Lon: 73° N to 81° N	20° to 25°
6	Punjab, Haryana, Delhi, Chandigarh and Ganganagar district of Rajasthan	Lat: 28° E to 32° E Lon: 77° N to 82° N	20° to 25°
7	Chotanagpur plateau Rajmahal hills, Chhattisgarh plains and Dandakaranya.	Lat: 18° E to 25° E Lon: 80° N to 88° N	15° to 20°
8	Bundelkhand, Bhander plateau, Baghelkhand, Malwa plateau and Vindhyachal hills.	Lat: 22° E to 28° E Lon: 72° N to 83° N	20° to 25°
9	Southern part of the Malwa plateau and Deccan plateau (Maharashtra)	Lat: 17° E to 25° E Lon: 73° N to 80° N	15° to 20°
10	Southern Maharashtra, Karnataka, western Andhra Pradesh and northern Tamil Nadu.	Lat: 10° E to 20° E Lon: 74° N to 82° N	10° to 20°
11	Coromandel and Northern Circar coasts, coasts of Andhra Pradesh and Orissa.	Lat: 9° E to 22° E Lon: 76° N to 88° N	10° to 20°
12	Malabar and Konkan coasts and the Sahyadris	Lat: 8° E to 21° E Lon: 72° N to 77° N	10° to 20°
13	Kathiawar and fertile valleys of the Mahi and Sabarmati rivers	Lat: 21° E to 26° E Lon: 68° N to 74° N	15° to 25°
14	Western Rajasthan west of the Aravallis	Lat: 25° E to 27° E Lon: 69° N to 76° N	20° to 25°
15	Andaman- Nicobar and Lakshadweep	Lat: 10° E to 16° E Lon: 70° N to 95° N	10° to 15°

(Source: GIZ Agrivoltaic Analytical Study Report, 2023)

Beyond energy optimization, the tilt angle and row-to-row spacing (pitch) of the PV arrays must align with the operational requirements of the agricultural land. For instance, in farms where mechanized equipment such as tractors is used, adequate spacing should be provided between rows to allow smooth passage. If the pitch is too narrow, it may obstruct farm operations, making it difficult for farmers to carry out essential activities such as plowing, sowing, and harvesting. Therefore, AgriPV systems must consider both solar performance and farm machinery compatibility when designing the layout of the PV system.

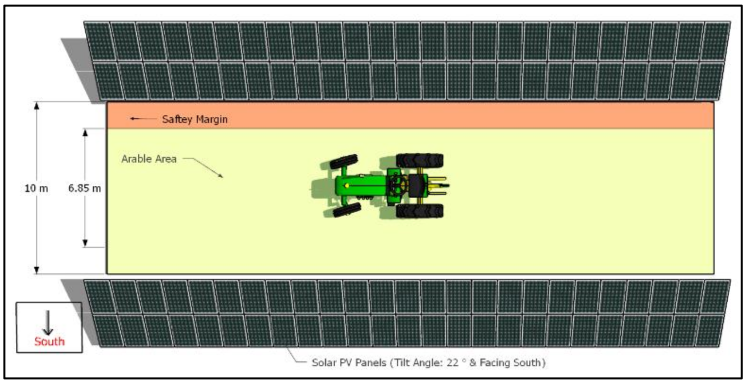

Figure 11: Shadow analysis for 21 December, tilt, 22°, row to row distance: 10 meters

The shadow analysis for December 21, highlights the importance of selecting an optimal pitch for solar PV arrays in an AgriPV system. With a 10-meter spacing, nearly half of the area falls under the shadow zone during this critical period, which can significantly impact both solar generation and crop growth. However, increasing the pitch beyond the necessary limit may reduce the overall solar plant capacity within the available land, affecting energy output.

To ensure a balance between agricultural operations and solar efficiency, the pitch must be optimized considering key factors such as tractor movement, crop requirements, and solar PV system sizing. Proper planning helps in maintaining adequate sunlight for crops while preventing excessive land occupation by the PV system.

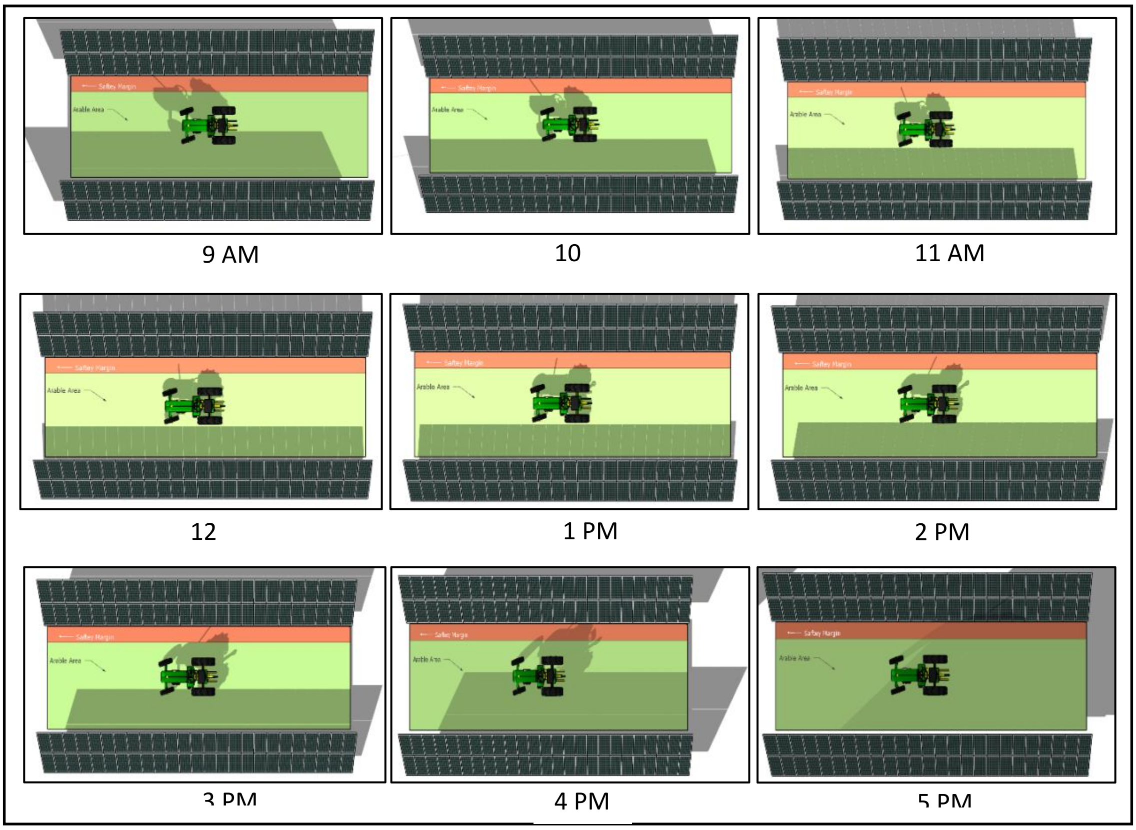

Figure 12: Shadow analysis of ground mounted system on 21 December

Another key aspect of tilt angle selection is its impact on the microclimate and crop yield. A higher tilt angle can create more shading beneath the panels, reducing soil evaporation and preserving moisture, which can be beneficial in arid and semi-arid regions. However, excessive shading in regions with lower solar radiation can hinder crop growth, making it essential to strike the right balance between shading and sunlight exposure. Adjustable tilt mechanisms can also be considered in certain cases to optimize energy generation while ensuring adequate light penetration for crops during different seasons.

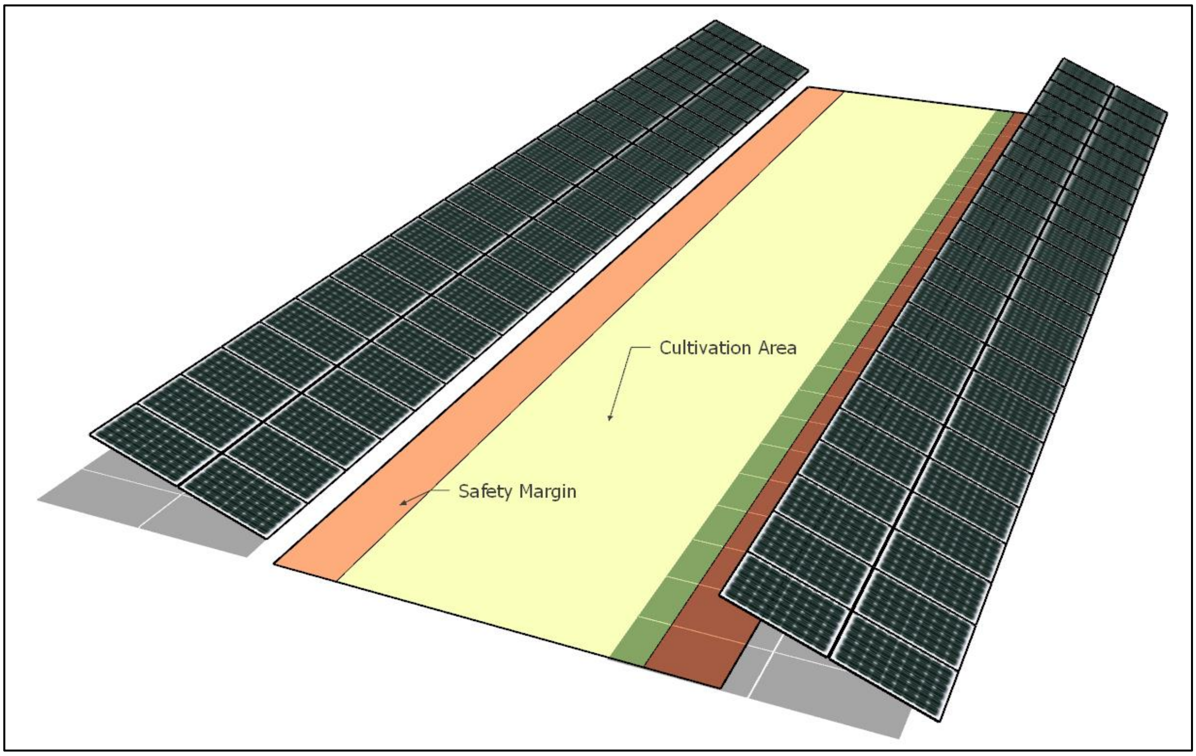

Figure 13: Consideration of safety margin for solar PV system maintenance

"**Safety margin**" in AgriPV systems refers to the minimum spatial clearance maintained between the solar PV structure and the cultivation land to ensure safe operation, ease of maintenance, and uninterrupted agricultural activities.

Maintaining a safety margin prevents physical damage to crops and solar structures, facilitates smooth farming operations, and reduces risks such as electrical hazards or shading inconsistencies, ensuring the long-term efficiency and safety of the AgriPV setup.

4.2.5 Regulatory and policy framework

Compliance with local and national policies, including land use and renewable energy incentives, is critical for project approval and sustainability. Policies promoting dual land use and AgriPV adoption, such as subsidies and tax benefits, should be leveraged.

4.2.6 Soil strength and composition

Soil strength and composition play a crucial role in determining the stability of solar PV mounting structures and the suitability of land for agriculture in an AgriPV system. Durable soil ensures structural integrity under varying loads, while its composition influences drainage, crop selection, and overall farm productivity. Sandy soils may require deeper foundations to prevent shifting, whereas clayey soils demand effective water management to avoid waterlogging. Therefore, comprehensive soil testing, including agricultural compatibility and soil quality assessments, is essential during the design phase to optimize both solar installation and farming operations.

4.2.7 Land use efficiency

AgriPV systems must balance solar panel density with agricultural land use to maximize productivity. Proper spacing, dual-use arrangements, and innovative designs like vertical panels enhance land-use efficiency, supporting India's dual goals of renewable energy and food security. Land utilization has been discussed in more detail for several cases and AgriPV system designs in chapter 7.

4.2.8 Wind load

In high-wind regions, particularly coastal and cyclone-prone areas, AgriPV structures must be reinforced to withstand extreme wind pressures. The design should incorporate aerodynamic profiles and robust anchoring to enhance stability and operational continuity.

The structural design must account for the maximum recorded wind speeds in the region, including data from the most recent cyclones near the project site. This ensures that the system can endure severe weather conditions without compromising safety.

All AgriPV structures must be designed to withstand site-specific wind loads and should be validated and approved by a qualified structural engineer. Compliance with national and international safety standards is mandatory to ensure long-term reliability and resilience.

4.2.9 Mechanisation

The layout of solar panels should ensure accessibility for farming operations such as plowing, planting, and harvesting. Designs must accommodate equipment like tractors, ensuring compatibility with the scale and type of agriculture practiced in the region while avoiding obstructions.

4.2.10 Panel cleaning and maintenace

Access for cleaning and routine maintenance is essential, especially in dusty or polluted regions. Automated cleaning systems or easy access designs enhance performance and reduce operational costs, maintaining high energy efficiency.

4.2.11 Animal grazing

Regions with grazing livestock require robust designs that prevent damage to infrastructure while allowing animals to graze. Elevated panels or fenced enclosures ensure the coexistence of livestock farming and energy generation, benefiting both sectors.

4.2.12 Energy storage or grid connectivity

Depending on regional energy needs and grid availability, AgriPV systems may incorporate energy storage solutions like batteries or direct grid connectivity. This ensures reliable energy supply for both agricultural and commercial operations.

4.2.13 Economic viability

Financial feasibility, including initial investment, operational costs, and revenue streams, determines project success. Models tailored to Indian contexts, such as farmer-owned or lease-based systems, ensure profitability and adoption at scale.

4.2.14 Power requirements for farm opeartions

Integrating the energy demands of irrigation pumps, storage units, and processing plants with solar PV systems ensures seamless power supply for farming activities. This reduces dependency on external power sources and enhances overall farm efficiency.

4.3 Realtime Monitoring for AgriPV System

Monitoring plays a critical role in ensuring the long-term success of an AgriPV system by assessing its overall performance in both energy generation and agricultural productivity. Since AgriPV systems integrate solar PV infrastructure with active farming, continuous monitoring is essential to verify the sustainability of agricultural activities beneath the panels, evaluate the system's impact on the environment, and optimize its efficiency. A well-structured monitoring framework not only helps in maintaining compliance with regulatory requirements but also enables data-driven improvements to maximize the dual benefits of energy production and crop cultivation over the system's lifespan.

To achieve this, key performance indicators should be regularly tracked across multiple aspects of the system. Monitoring crop performance helps assess the impact of shading and microclimatic conditions on yield, while soil fertility analysis ensures that land remains productive over time. The efficiency and output of the solar PV system must also be continuously evaluated to maintain energy generation levels. Additionally, microclimate conditions, including temperature, humidity, and wind patterns, need to be observed to understand their effects on both crops and solar panel efficiency. Lastly, water management strategies should be monitored to ensure optimal irrigation and assess water-saving benefits achieved through panel-induced shading. Establishing a robust monitoring mechanism enables AgriPV systems to deliver maximum economic and environmental benefits while ensuring long-term viability. These key performance areas must be monitored to ensure best practices and optimal system performance.

- Water management and savings
- Agricultural productivity
- Soil fertility of cultivable and uncultivable land area
- Microclimate conditions
- Solar PV system performance

A description on each area and the methods is given in following section.

4.3.1 Water management and savings

Effective water management is crucial in AgriPV systems to optimize both agricultural productivity and solar panel efficiency. The dual land use in AgriPV projects requires careful planning to balance water availability for crops while also maintaining solar panel performance by regular cleaning.

It is highly anticipated that the shading effect created by solar panels in AgriPV systems can lead to significant water savings by reducing direct sunlight exposure on the soil. This helps in lowering evaporation rates, retaining soil moisture for longer periods, and moderating the microclimate under the panels and reducing water stress. The combined benefits make AgriPV systems suitable particularly for arid and semi-arid regions. Additionally, cooler temperatures under the panels reduces the need for irrigation to combat heat stress in crops. The cooling also enhances the efficiency of solar modules by maintaining temperatures. To maximize water efficiency, AgriPV systems should integrate advanced irrigation technologies such as drip irrigation or automated soil moisture sensors based irrigation.

4.3.2 Agricultural productivity

Ensuring agricultural productivity is a critical aspect of AgriPV systems. Effective monitoring of agricultural output helps evaluate the system's impact on cultivation and ensures that the dual-use approach remains beneficial for both energy generation and food production. Key areas of focus for monitoring agricultural productivity include crop yield, plant growth and soil fertility.

Comparing crop yield under AgriPV system with neighbouring open-field provides insights into the system's efficiency. By benchmarking productivity against traditional farming practices, it is possible to establish whether AgriPV enhances or maintains agricultural output. The goal should be to ensure that the presence of solar panels does not impact food production much.

4.3.3 Soil health, fertility and land area

Another important aspect of monitoring is assessing soil health and fertility under the AgriPV system. The shading effect from solar panels can influence soil moisture retention and microbial activity, which in turn affects crop growth. Measuring soil nutrient levels, organic matter content, and pH ensures that the soil remains suitable for continuous farming. If necessary, corrective measures such as soil amendments can be used to maintain soil productivity.

The long-term operation of solar panels, typically spanning 25 to 30 years, has a direct impact on soil fertility, both in actively cultivated and uncultivated areas. Continuous monitoring is essential to ensure that the soil remains productive for agriculture.

For **cultivable land**, soil fertility must be assessed periodically to track changes in organic matter content, nutrient availability, pH, and microbial activity. The shading effect of solar panels can influence soil temperature and moisture retention, which may impact nutrient cycling. Regular soil testing and monitoring of crop health indicators will help to determine if any corrective measures, such as organic amendments or controlled fertilization, are required to maintain optimal soil conditions.

For **uncultivable land**, AgriPV presents an opportunity to restore and reintegrate unused or degraded agricultural land into active farming. The increased profitability of AgriPV systems can encourage landowners to bring previously abandoned land back into cultivation. It is crucial to monitor cases where land that has remained fallow measures is being re-cultivated under AgriPV system.

Periodic reporting, should document the changes in soil health and fertility over time. This data will help ensure that AgriPV systems not only support clean energy generation but also promote proper land use and improves soil quality for future agricultural activities.

4.3.4 Microclimate

Monitoring environmental conditions is crucial for the optimal performance of solar systems and agricultural activities under AgriPV projects. Key parameters such as solar irradiance, ambient temperature, wind speed, and humidity directly impact the efficiency of solar panels and the growth of crops. Solar irradiance determines the energy generation potential, while ambient temperature and wind speed influence the cooling and operational stability of the panels. Regular monitoring of these conditions ensures that the system operates within design limits, preventing overheating, structural damage, or energy losses.

Parameters like soil moisture, rainfall, temperature and humidity play a critical role in crop production. Excessive moisture or poor drainage can lead to waterlogging, whereas inadequate irrigation can stress plants and reduce productivity.

Additionally, temperature fluctuations and microclimatic changes induced by the AgriPV setup need to be tracked to mitigate risks like frost damage or excessive heat stress on crops. Real-time monitoring of these conditions allows for proactive interventions. These can be monitored using temperature, relative humidity and air speed sensors together with radiation measurement sensors positioned underneath the photovoltaic modules.

The placement and type of the sensors that can be used are :

(1) External ambient

(2) Behind the solar PV module – Temperature sensor, humidity sensor, air velocity sensors, irradiation sensor

4.3.5 Solar PV system productivity

Monitoring the performance and productivity of the solar PV system is very important for maintaining productivity of AgriPV systems. Since AgriPV systems integrate agricultural activities with solar power generation, multiple factors, including crop growth, environmental conditions, and structural stability must be continuously monitored. Proper monitoring helps in early detection of issues for taking corrective measures.

Key factor influencing PV system performance is the interaction between crop growth and solar panels. During installation, the system is designed considering the standard crop height, with a safety margin to prevent shadowing on the panels. However, in operation, variations in crop height and unexpected plant growth can result in partial shading of the PV modules. Localized heating, known as the hot spot effect, can negatively impacts module efficiency and may cause long-term degradation. Regular inspections should be conducted to check for shading issues, and thermal imaging should be performed if there is a noticeable reduction in energy output.

Real-time energy generation monitoring is essential to detect fluctuations in system performance. Daily generation data should be analysed to identify any unexpected declines in output, which could indicate panel soiling, wiring issues, inverter failures, or environmental impacts. Any steep or abnormal changes in generation should be properly corrected.

Another crucial aspect of monitoring is the involvement of farmers and on-ground personnel in routine checks. Since they are present at, they can provide valuable information about the structural integrity of the solar mounting system, cabling status, fencing conditions, and grounding system health. Farmers and ground workers should be provided adequate training on different components of AgriPV system so that they are effectively monitor the system.

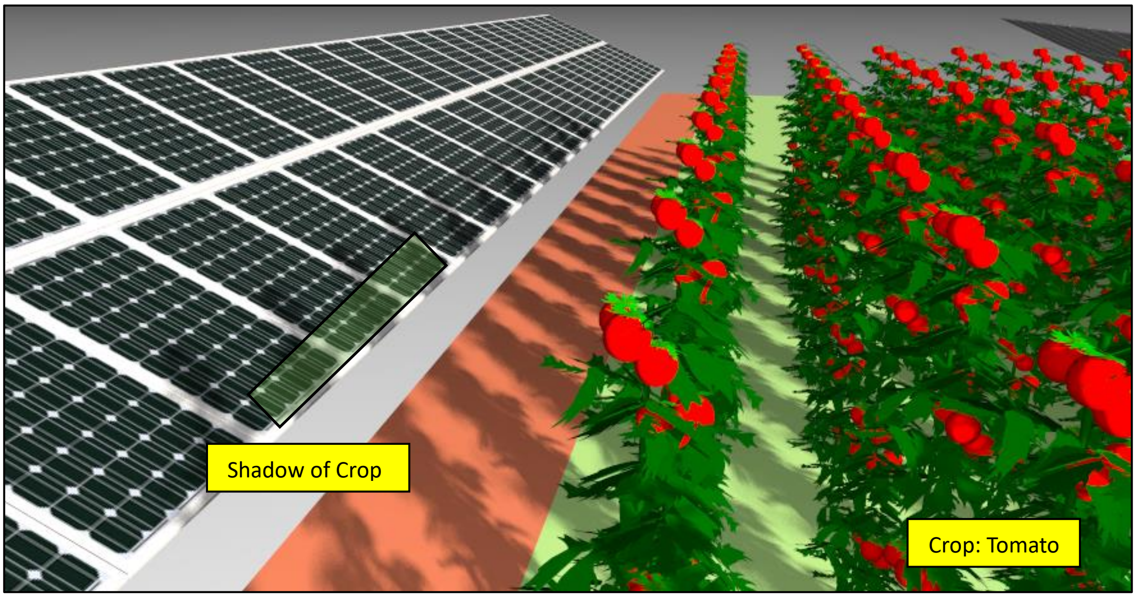

Figure 14: Shadow effect on panel because of the height of the tomato crop

To maintain the system's health, it is recommended that structured inspection protocols and reporting mechanisms be developed. Regular technical assessments by trained personnel should complement daily visual inspections by farmers, ensuring that all critical components, including inverters, transformers, and energy storage systems, are functioning efficiently. By implementing a comprehensive monitoring strategy, AgriPV systems can sustain optimal performance, balancing energy generation with agricultural productivity.

4.4 Structural Integrity

The structural integrity of mounting systems in AgriPV systems is a critical factor that directly impacts both the longevity of the solar infrastructure and the sustainability of agricultural activities beneath it. Unlike traditional ground-mounted solar installations, AgriPV structures must be designed to accommodate diverse farming practices while ensuring durability under various environmental conditions. The design should consider crop-specific requirements, allowing adequate sunlight penetration while minimizing shading effects that could hinder plant growth. Additionally, the structural framework should be robust enough to support the weight of solar panels over an extended operational life, typically 25-30 years, without compromising mechanical stability.

Key considerations in AgriPV mounting system design include wind resistance, weight distribution, and soil adaptability. Given that solar farms are often installed in open landscapes, structures must withstand high wind loads, particularly in regions prone to storms or cyclones. The foundation design should be tailored to the soil characteristics of the site, ensuring adequate anchoring to prevent tilting, shifting, or structural failure over time. Material selection plays a crucial role in longevity—corrosion-resistant coatings and galvanized steel or aluminium components are preferred to withstand exposure to fertilizers, pesticides, and irrigation water.

Another essential aspect is the structural adaptability to farming operations. The mounting system should allow sufficient clearance for agricultural machinery, irrigation setups, and manual labour while maintaining structural stability. Overhead panel arrangements, vertical bifacial setups, and adjustable tilts are some innovative solutions used worldwide to optimize space utilization and solar efficiency without impeding farming activities. Furthermore, the structure should be resilient to vibrations or mechanical stress caused by routine agricultural operations such as plowing, harvesting, or irrigation system movements.

A well-designed AgriPV mounting structure ensures that the system remains functional throughout its lifespan with minimal maintenance costs and operational disruptions. Proper engineering and regular structural assessments help prevent early degradation, safeguard investments, and support sustainable co-existence of solar energy generation with agricultural productivity. Some examples are shown to understand the design of the structure in various locations:

(A) (B) (C)

(A) Jain Irrigation, Maharashtra, India: Overhead Structure - Bifacial Solar PV Panels.
(B) GIPCL, Gujarat, India: Interspacing between subsequent MONO Solar PV Panels.
(C) Manwath, Maharashtra, India: Elevated Structure - Bifacial Solar PV Panels

Figure 15: Existing AgriPV installations A, B, C

(D) (E) (F)

(D) Sahyadri Farms, Maharashtra, India: Elevated Structure - Bifacial Solar PV - Single Axis Tracking (From East to West);
(E) Colorado State University's Educational Centre (ARDEC), United States – Translucent Solar PV Panels
(F) Volnohorsk, Ukraine: Bifacial Glass-Glass Solar PV – Single Axis Tracking - Reflected surface

Fig. 16: Existing AgriPV installations D, E, F

(G) (H) (I)

(G) Donaueschingen, Germany: Vertical - Bifacial Solar PV.
(H) China – Lightweight Aluminium Structure – Bifacial Solar PV – Foundation - Ground Screw
(I) Heggelbach Pilot, Germany: - Elevated Tracking – Bifacial Solar PV

Figure 17: Existing AgriPV installations G, H, I

4.5 Advancement in Solar Panel Technology

AgriPV systems are being implemented across multiple locations in India, utilizing different structural configurations to optimize both solar energy generation and agricultural production. These systems are designed to ensure that crops receive adequate sunlight while maximizing the efficiency of solar panels. Two key design - bifacial solar panel technology and inter-panel spacing—play a crucial role in enhancing both energy output and agricultural yield.

Bifacial solar panels, used in several AgriPV installations, enable energy generation from both the front and rear sides by capturing reflected sunlight from the ground. This enhances the overall efficiency of the system while allowing for better land utilization. Additionally, maintaining interspacing between subsequent panels helps ensure that adequate sunlight reaches the soil, promoting uninterrupted photosynthesis and optimal crop growth. Balance between energy production and agricultural needs is essential for sustainable AgriPV operations.

AgriPV systems worldwide are adopting advanced solar technologies to enhance both energy generation and agricultural productivity. The integration of bifacial solar PV panels, often combined with single-axis tracking, allows for optimized sunlight capture throughout the day. This tracking mechanism ensures that panels follow the sun's movement, increasing overall energy yield while still maintaining sufficient space for agricultural activities. **Translucent solar panels** are being deployed to regulate the amount of sunlight reaching the crops, making them ideal for shade-tolerant plants and controlled farming environments. These design innovation contributes to more efficient land use by balancing energy production with crop growth.

Furthermore, the use of **glass-glass bifacial panels** with reflective surfaces enhances rear-side generation, leading to improved energy efficiency. Strategic panel interspacing ensures adequate sunlight penetration to the soil, supporting optimal photosynthesis and uninterrupted agricultural productivity. These technological advancements, coupled with thoughtful structural designs, demonstrate how AgriPV systems can be designed to diverse climatic and agronomic conditions.

One of the key considerations in structural design is stability against environmental factors like wind loads, heavy rainfall, and seismic activity. AgriPV structures are typically taller than conventional solar PV systems to allow farming equipment and machinery to operate underneath. This added height increases wind exposure, making structural stability a critical requirement. Designs must adhere to national building codes and international standards to ensure robustness under such conditions. For instance, single axis tracking systems, which dynamically adjust the panel tilt, require additional structural reinforcements to withstand dynamic loads and maintain optimal performance.

Availability of sunlight beneath is another vital aspect for the AgriPV structures. The design must strike a balance between providing adequate shading to protect crops from excessive heat and ensuring sufficient sunlight reaches the crops for healthy growth. Shadow-free portions and the patterns of light availability must be carefully analysed during the planning and installation phases. Prolonged shading can lead to slower crop growth and delayed harvesting times compared to open fields, as observed during site visits conducted by the Center of Excellence (COE). Properly spaced structures, height adjustments, and innovative designs like bifacial panels or dynamic trackers can mitigate these challenges, promoting better light distribution.

Structural designs must also support a microclimate conducive to plant growth. Higher and vertical structures help improve air circulation and reduce excessive humidity beneath the panels, minimizing the risk of fungal growth and pests. Additionally, the system must be designed for easy access for maintenance and cleaning, which are essential for both solar panels and farming activities.

4.6 Tracking System for AgriPV

The incorporation of tracker systems in AgriPV systems can significantly enhance both energy generation and agricultural productivity. Tracker systems enable solar panels to follow the sun’s path, optimizing the capture of solar radiation throughout the day. This dynamic adjustment reduces shading on agricultural areas and creates a more favourable microclimate for crop growth beneath the panels.

4.6.1 Types of tracker system

Single-axis trackers: These trackers rotate solar panels along a single axis, typically oriented either horizontally or vertically. Single-axis trackers are cost-effective and can increase energy generation compared to fixed systems while maintaining compatibility with certain crop layouts.

Seasonal tilt systems: These systems offer manual or semi-automatic adjustments to the panel angle based on seasonal changes. They are a low-cost alternative for improving energy efficiency while keeping the shading effect predictable for farmers.

Dual-axis trackers: Dual-axis trackers allow for precise adjustments in both horizontal and vertical directions, maximizing solar exposure across seasons. Although more expensive, they are highly effective for regions with variable sunlight and can support crops with higher sunlight requirements by minimizing shading.

4.6.2 Benefits of tracker system

Tracker systems in AgriPV offer significant benefits by optimizing energy generation and enhancing agricultural productivity. By dynamically adjusting the angle of solar panels to follow the sun's path, trackers can increase solar energy output by up to 23% compared to fixed systems *(Barron-Gafford et al., 2019)*. They create a more favourable microclimate for crops by reducing shading stress and allowing better sunlight penetration during critical growth periods. Additionally, trackers improve land-use efficiency by accommodating diverse crop patterns and irrigation setups.

4.7 Safety

Standard Operating Procedures (SOPs) are essential for AgriPV installations to ensure safety and compliance during installation and operation. These procedures should include safe electrical connections, proper cable routing, and robust earthing systems. Adherence to national safety standards and local guidelines reduces risks and ensures the system's performance aligns with best practices.

Table 8: Standard operating procedures to ensure electrical safety

Standard Operating Procedures	Description
Pre-installation inspection	Assess site for hazards, including uneven terrain, proximity to water sources, and potential interference points.
Proper grounding and earthing	Install and test an effective earthing system to prevent electric shocks and equipment damage.
Cable management	Use UV-resistant, weatherproof conduits for cable routing and avoid loose or exposed wiring.
Signage installation	Place warning signs near high-voltage equipment, transformers, and inverters to alert workers and visitors.
Farmer orientation	Conduct a safety briefing for farmers to explain the placement of electrical equipment and safety measures.
Isolation mechanism check	Ensure functional isolators are installed to disconnect the PV system during maintenance or emergencies.
Surge protection system	Install surge protection devices to shield equipment from voltage spikes caused by lightning or faults.
Periodic earthing testing	Check the resistance of the earthing system and ensure it meets safety standards.
Emergency response plan	Develop and train workers and farmers on procedures for handling electrical accidents or system failures.
Routine maintenance checks	Inspect and clean all electrical components, including inverters and panels, for dust, wear, or corrosion.

Farmers involvement during installation is critical to address potential disruptions to agricultural activities. Their participation ensure changes to land use or farming practices are well understood and minimized. Clear electrical signboards at strategic locations are mandatory to enhance awareness and prevent accidents. Fundamental signage widely used in AgriPV and serve as key references for ensuring compliance with industry protocols and guidelines are given below:

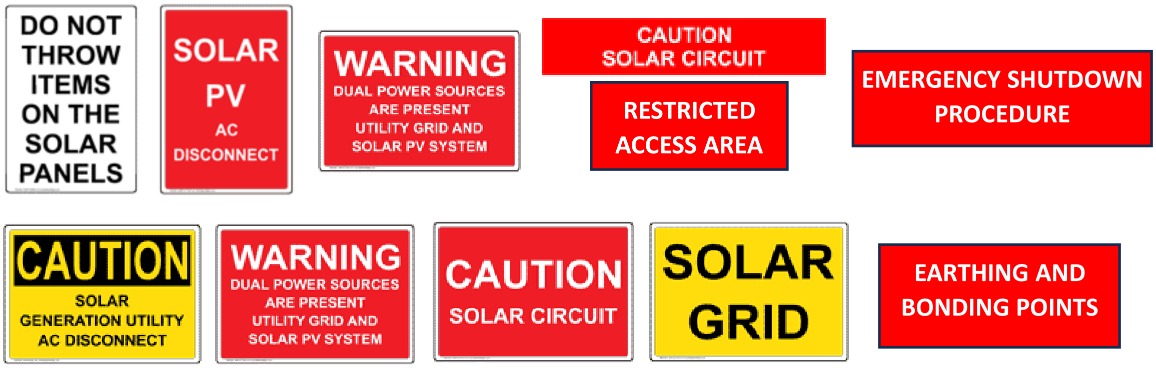

Figure 18: Standard signage in solar PV system setup

Signage in local language: Few examples are given below:

Figure 19: Example of local language signage

Regular maintenance is vital to uphold electrical safety. Daily inspections of earthing systems, cable integrity, and connections help mitigate potential hazards. Proactive measures, including periodic checks for wear and tear, ensure the system remains safe and efficient, benefiting both solar energy generation and farming operations

4.8 Testing Standards for AgriPV System

Testing standards are essential to verify the quality, durability, and efficiency of AgriPV systems. They provide a framework to evaluate components such as solar panels, mounting structures, and electrical systems under various operating conditions. By adhering to these standards, AgriPV systems can ensure reliable energy production and sustained agricultural productivity, even in challenging environmental scenarios. Testing also helps identify potential issues early, reducing the risk of system failures and increasing the overall lifespan of the setup.

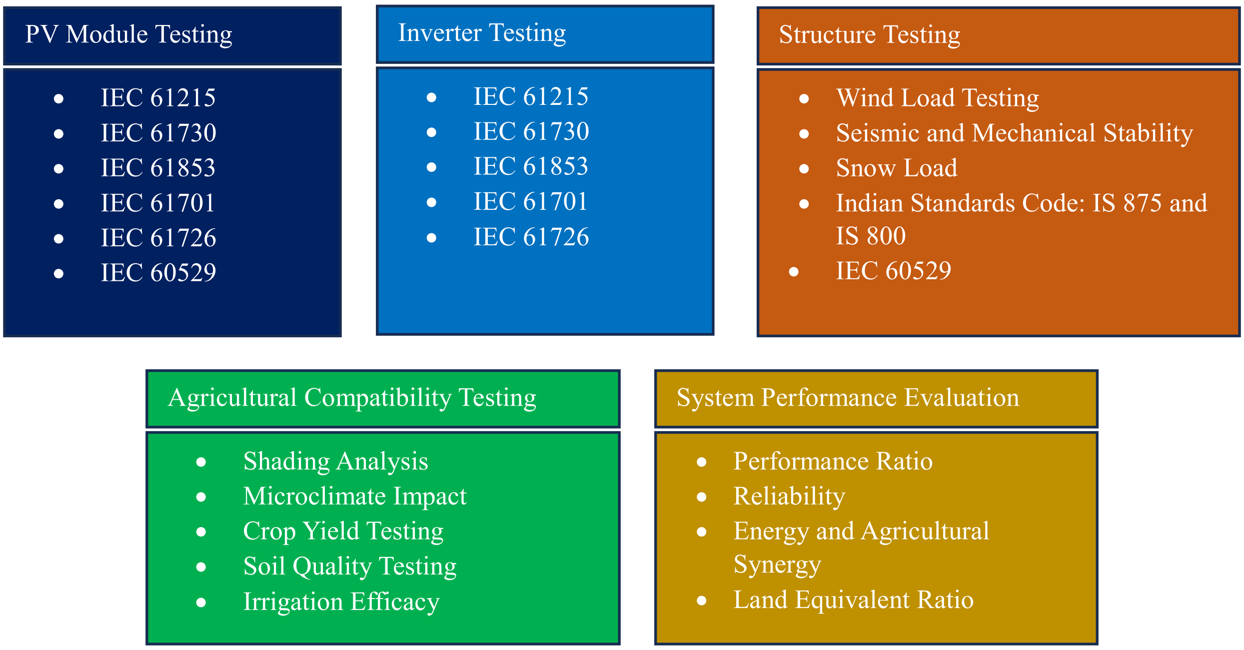

Figure 20: Recommended testing standards for AgriPV system

4.9 Performance of AgriPV System

The Land Equivalent Ratio (LER) is used for evaluating the efficiency of AgriPV systems by comparing combined yields of solar energy and agriculture against their respective standalone yields. It provides insights into how effectively land resources are utilized, ensuring dual-use optimization. Incorporating land loss (LL) adjustments makes LER a more precise tool for assessing overall system performance *(Ghaffarpour et al., 2024).*

$$\textit{Land Equivalent Ratio} = [\left(\frac{\textit{Yield solar from AgriPV}}{\textit{Yield solar ref}}\right) + \left(\frac{\textit{Yield agricuture from AgriPV}}{\textit{Yield agriculture ref}}\right)]\ x\ (\mathbf{1} - \boldsymbol{LL})$$

LL = Land Loss (LL = 0 for fruit overhead systems) *(Singh, 2024)*

Adopting robust testing standards enhances the safety of AgriPV installations for both farmers and system operators. These standards help mitigate risks such as electrical hazards, structural instability, and environmental impacts. By ensuring compliance with established benchmarks, stakeholders—including farmers, developers, and regulators—can trust in the system's performance and safety.

Table 9: Performance of the energy and crop integration for different land equivalent ratio (LER) (Zahrawi and Aly, 2024)

LER=1	The AgriPV and the normal condition are showing the same results.
LER>1	AgriPV is showing better results than normal conditions.
LER <1	The normal conditions are showing better results than AgriPV.

4.10 Business Models for AgriPV System

Development of business model is essential for implementation of AgriPV system in India. These models should emphasize maintaining and enhancing agricultural productivity while integrating solar power generation to provide additional income streams. Some business models are presented below:

1. Farmer-Owned

Farmers retain full ownership of both land and solar infrastructure. They continue agricultural activities while benefiting from energy production, either for self-consumption or through grid sales. This model works well for farmers with access to financing options such as subsidies or loans

2. Community-Owned

A group of farmers or a Farmer Producer Organization (FPO) collectively invests in and manages AgriPV systems. Profits from energy generation are shared among members, supporting their farming and economic growth. It is ideal for small and marginal farmers who can benefit from pooled resources

3. Land-Sharing

Farmers lease their land to developers for solar infrastructure installation while continuing agricultural activities. This model maximizes land efficiency and provides income from both farming and energy production. It suits areas where optimizing land use is crucial

4. Joint Venture Model

This model involves a partnership between farmers and developers. Farmers provide land, while developers manage solar operations and investment. Profits from both agriculture and energy are shared, creating mutual benefits for both parties

5. CSR-Funded

In this model, private companies use their CSR funds to set up AgriPV systems on farmers' lands. Farmers retain the right to farm while benefiting from improved infrastructure and energy generation. This model supports sustainable agriculture without imposing financial burdens

6. Lease-Based Model

Farmers lease land to developers who install and manage the AgriPV system. They earn a fixed lease income while continuing to farm. This low-risk option provides financial security and ensures agricultural productivity

7. PPA-Based

In this model, developers install AgriPV systems on leased or farmer-owned land, and the generated energy is sold through Power Purchase Agreements (PPA). This arrangement allows farmers to continue farming while generating income from land lease or energy production.

8. Government-Backed

Government agencies provide financial support, such as subsidies or tax incentives, to promote AgriPV adoption. This ensures the financial viability of projects. Then AgriPV projects are built on Government / private sector owned land, while farmers continue farming under a supportive regulatory framework.

Table 10: Business models for AgriPV systems in India

Sr. No.	Business Model	Owner of the Land	Investment by	Revenue Beneficiary	Farming by
1	Farmer-Owned Model	Farmer	Farmer	Farmer (dual income)	Farmer
2	Community-Owned Model eg. FPO Owned	Community	Community Funds / NGOs	Community Members	Community Farmers
3	Land Sharing Model	Farmer	Developer	Farmer and Developer	Farmer
4	Joint Venture Model	Farmer/Shared Ownership	Farmer and Developer	Farmer and Developer	Farmer
5	Corporate Social Responsibilities - CSR Model	Farmer	Corporate CSR Funds	Farmer	Farmer
6	Lease-Based Model	Farmer	Developer	Farmer (lease income)	Developer / Farmer
7	Power Purchase Agreement	Farmer / Developer	Developer / Investor	Developer / Investor	Farmer
8	Government / Utility -Backed Model	Government / Utility / Public Sector	Government / Utility / Public Sector	Government / Utility and Farmers (lease income)	Farmer / Contractors

Chapter 5
Cultivation under AgriPV

Cultivating crops under AgriPV requires careful planning as agriculture remains the primary focus, and solar panels come second. The goal is to maintain crop production with little to no yield loss due to shading from the panels. When designing AgriPV systems in India, the country's diverse climate and soil conditions must be considered. Likewise, crop selection must begin with identifying regionally suitable species, followed by choosing those adaptable to partial sahding. For new AgriPV setups, panel spacing should be planned based on the light requirement of the chosen crops, whereas in existing PV installations, crop selection must depend on the available sunlight under the panels.

National and international studies suggest that most field crops can grow under AgriPV but with some yield reduction. However, vegetable crops, leafy greens, berries, and flowers are generally more suitable. With advancements in technology, transparent solar panels that allow more sunlight to pass through are now available, reducing the shading effect and making more crops viable for cultivation.

Several factors must be taken into account while selecting crops for AgriPV systems:

- **Crop compatibility**: Not all crops might be suitable for AgriPV cultivation. The selection of crops should consider their specific light, water, and temperature requirements.
- **Spacing**: To ensure that adequate light reaches the crops, proper spacing and positioning of the solar panels should be considered, particularly for crops that require indirect sunlight.
- **Maintenance and management**: Crops under AgriPV systems need regular monitoring to ensure optimal growth. Proper management of the solar infrastructure and crop health is essential to achieve sustainable yield.
- **Local and climatic conditions**: Crop selection for AgriPV must account for climate suitability, soil quality, sunlight availability, weather resilience, and water resources to ensure sustainable growth.

Figure 21, shows the agroclimatic zones of India, classified based on rainfall, temperature, soil type, and major crops. This information is important for creating AgriPV guidelines suitable to each region. The diverse climatic conditions across regions necessitate customized AgriPV designs. For example, high-rainfall areas such as the Eastern Himalayas and coastal regions may require elevated PV structures to prtotect panels from waterlogging, while arid zones like Rajasthan and Gujarat benefit from designs that enhance water conservation. Soil type also affects system needs. Fertile alluvial soils in the Indo-Gangetic plains support many crops, while lateritic and red soils in Karnataka and Odisha require better water management. By selecting suitable crops and implementing effective resource management strategies, cultivation under solar panels can be made successful and sustainable.

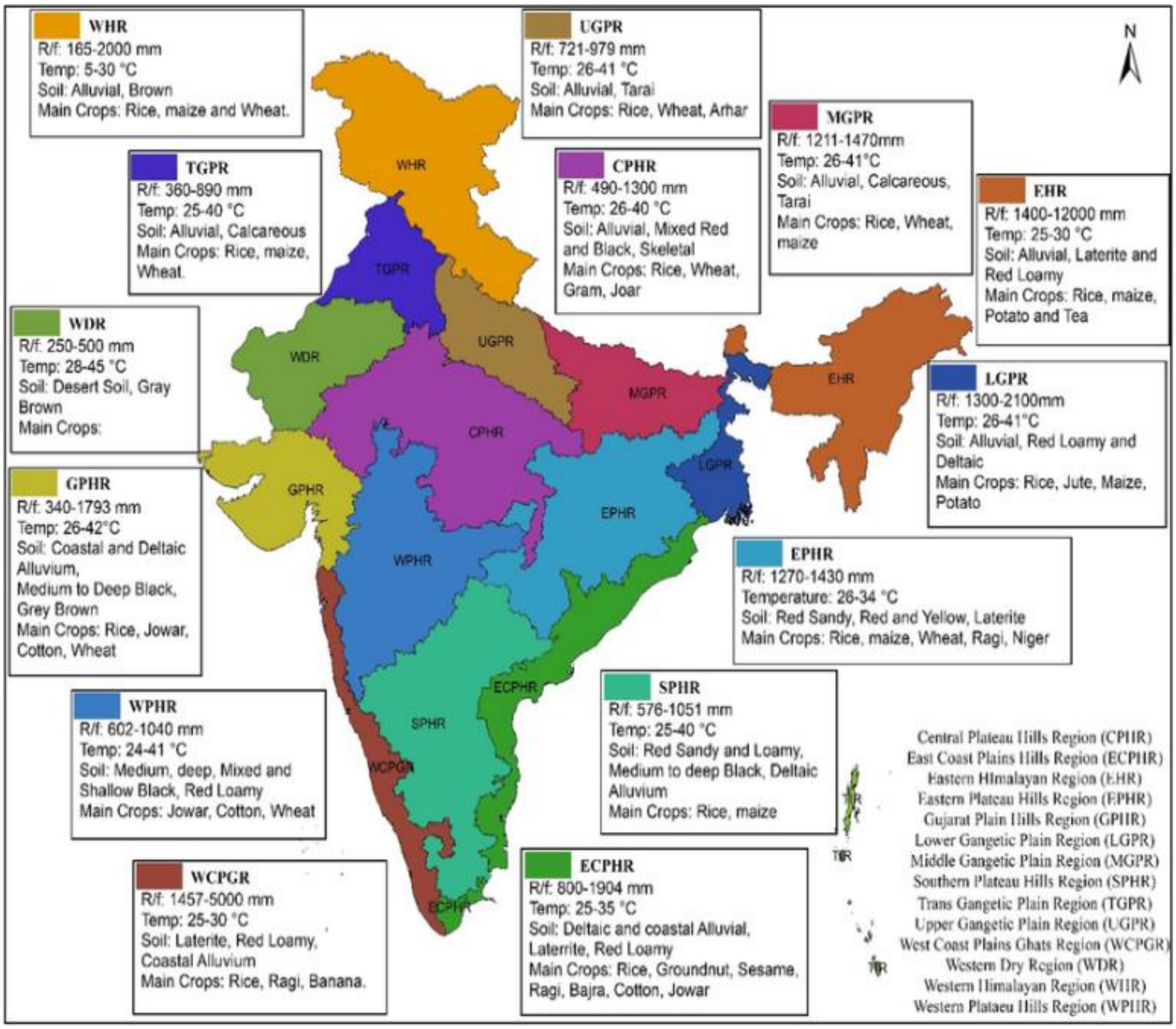

Figure 21: Characterises of different agroclimatic zones in India (Source: Mall et al., 2021)

The various crops grown in India can be categorized into different groups, as outlined below *(Figure 22)*. A detailed explanation of each category, along with the crops included, is provided in the following sections.

Cereal crops	**Horticultural crops**
Rice	**Fruits**
Wheat	**Vegetables**
Sorghum	**Spices and medicinal crops**
Millets	**Flowers**
Maize	**Ornamental plants**
	Plantation crops

Figure 22: Types of crops

5.1 Cereal Crops

Cereal crops are cultivated in large area in India. Major cereals produced in India include rice (both Basmati and non-Basmati), wheat, paddy, sorghum, millets, barley, and maize. FAO estimates that maize, wheat and rice together account for more than three-fourths of all grain production worldwide.

Rice

Wheat

Sorghum

Millets

Maize

Figure 23: Cereal crops

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According to the third advance estimate for the year 2023-24 by the Ministry of Agriculture of India, the production of major cereals such as rice, wheat, maize, and bajra was 136.7 million tonnes, 112.92 million tonnes, 35.67 million tonnes, and 10.66 million tonnes, respectively. India is the world's largest producer of millets, accounting for 38.40% of global production. The country also ranks as the second-largest producer of rice (25.27% of global production) and wheat (13.33% of global production), and the fifth-largest producer of maize (2.9% of global production) *(FAO, 2023)*.

Also, cereal grains such as wheat, maize, and paddy are major staple foods for the majority of the world's population. By 2050, cereal production will need to increase by 70-100% to feed the estimated global population of 9.8 billion. Millets are hardy crops and have short growth periods, typically ranging from 60 to 100 days depending on the variety. Millets are also drought-tolerant and can be cultivated in a wide range of weather conditions. Research has shown that millets emit fewer greenhouse gases, making them a promising option for reducing the contribution of agri-food sector to global warming *(Wang et al., 2018)*.

Cereal cultivation is important for food security and rural employment. Also, advancements in irrigation, high-yielding seed varieties, and climate-resilient farming practices have improved productivity and sustainability of cereal crops. The country's diverse agro-climatic zones allow for the cultivation of a wide range of cereals, strengthening both domestic food supply and global trade opportunities. Major crops grown in India and their area under cultivation and production for the year of 2023-2024 is given in *Table 11*.

Table 11: Major crops and area under cultivation for 2023-2024

Crop	Area (Lakh hectare)	Production (Lakh/tonnes)
Rice	478.32	1357.55
wheat	314.01	1105.54
Nutri/Coarse Cereals	240.7	573.19

(Source: Agricultural Statistics at a Glance, by the MoAFW,2023)

5.2 Horticultural Crops

India is one of the largest producers of horticulture crops in the world. Horticulture is divided into wide variety of crops including fruits/orchards, vegetables, spices, flowers, medicinal plants, and plantation crops. In 2023, India produced of 350.87 million tons of horticultural crops, cultivated across an area of 28.5 million hectares.

5.2.1 Orchard crops

Mango

Custard Apple

Apple

Orange

Guava

Pomogranate

Figure 24: Orchard

The horticulture sector has become increasingly significant in India, especially as a means to diversify agricultural production and enhance farmer's income. The shift towards horticulture has been encouraged by the government due to its lower water requirements compared to traditional crops, higher yield per unit area, and capacity to generate higher economic returns.

The diverse climate in India has significant potential for cultivating orchard crops. *Table 12* presents major orchard crops cultivated in different agro-climatic zones.

Table 12: Major orchard crops grown across agro-climatic zones of India

Sr. No.	Agro-climatic regions/zones	States represented	Major horticulture crops
1	Western Himalayan region	Himachal Pradesh, Jammu & Kashmir, Uttarakhand	Apples, Pears, Peaches, Plums, Cherries, Walnuts
2	Eastern Himalayan region	Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, West Bengal	Kiwi, Orange, Pineapple, Guava, Banana
3	Lower Gangetic plain region	West Bengal	Mango, Litchi, Papaya, Jackfruit
4	Middle Gangetic plain region	Uttar Pradesh, Bihar	Guava, Mango, Citrus fruits, Vegetables
5	Upper Gangetic plain region	Uttar Pradesh	Mango, Guava, Citrus fruits, Pomegranate
6	Trans Gangetic plain region	Chandigarh, Delhi, Haryana, Punjab, Rajasthan	Fruits: Citrus, Kinnow, Grapes; Vegetables: Cauliflower, Onion, Tomato
7	Eastern plateau and hills region	Chhattisgarh, Jharkhand, Madhya Pradesh, Maharashtra, Odisha, West Bengal	Pineapple, Guava, Citrus fruits, Jackfruit
8	Central plateau and hills region	Madhya Pradesh, Rajasthan, Uttar Pradesh	Mango, Guava, Pomegranate, Cherries
9	Western plateau and hills region	Madhya Pradesh, Maharashtra	Grapes, Pomegranates, Oranges, Custard apple
10	Southern plateau and hills region	Andhra Pradesh, Karnataka, Tamil Nadu	Mango, Banana, Coconut, Grapes
11	East coast plains and hills region	Andhra Pradesh, Odisha, Pondicherry, Tamil Nadu	Cashew, Coconut, Banana, Mango
12	West coast plains and ghat region	Goa, Karnataka, Kerala, Maharashtra, Tamil Nadu	Coconut, Areca nut, Mango, Pineapple
13	Gujarat plains and hills region	Gujarat, Dadra & Nagar Haveli, Daman & Diu	Mango, Papaya, Banana, Vegetables
14	Western dry region	Rajasthan	Kesar mango, Pomegranate, Guava, Dates
15	Island region	Andaman & Nicobar Islands, Lakshadweep	Coconut, Spices (Cardamom, Clove)

5.2.1.1 Performance of orchrd crops under AgriPV systems

Fruit crops suitable for cultivation under AgriPV systems are berries like strawberries, blueberries, and raspberries. Grapevines (Vitis vinifera) benefit from partial shade, which reduces diverse effect of sun and improves water-use efficiency, and enhaces overall fruit quality. Several studies have explored the suitability of horticultural crops for partial shading under solar panels. According to *Amaducci et al. (2018)*, shading from solar panels positively influenced grape cultivation. Moderate shading protected them from excessive heat while improving fruit development, (*Adeh et al., 2019)*. Citrus fruits (Orange, lemon, lime) adapt well to partial shading while maintaining high fruit quality and yield. (*Marrou et al., 2017)* found that reduced soil moisture loss under PV shading improves drought resistance in citrus orchards, making them a viable option in water-scarce regions. In a vineyard Agrivoltaics field test in France, Sun'Agri reported that PV-shaded vines required 12%–34% less water due to reduced evapotranspiration. Additionally, the Agrivoltaic setup improved the aromatic property of the grapes, increasing anthocyanin content (red pigments) by 13% and acidity by 9%–14% *(Dawnbreaker, 2022).*

Apple production benefits from cultivation under solar panels compared to open-field conditions, as reported in several studies. *Lopez et al. (2024)* found that air temperature around Agrivoltaic trees was lower than that of open field trees due to a 50% reduction in daily incident radiation. Cooling effect reduced sunburn damage in Agrivoltaic apples, which were also found to be cooler than apples grown in controlled conditions, leading to uniform, market-preferred produce. *Sekiyama and Nagashima (2019)* observed improved fruit uniformity under these conditions, leading to higher market acceptance. Pomegranates (Punica granatum) are another suitable crop, as partial shading reduces water stress and improves fruit set. *Elamri et al. (2020)* demonstrated the feasibility of growing pomegranates under AgriPV, particularly in semi-arid environments. These findings underline the viability of integrating high-value fruit crops with AgriPV installations for sustainable and profitable farming.

5.2.2 Vegetable crops

The field crops like rice, wheat, and sugarcane have been the backbone of Indian agriculture for centuries. Howver, there is a growing realisation that vegetable farming holds immense potential to boost India's GDP and overall economic health *(Kumar et al., 2021).* Key vegetable crops include tomatoes, potatoes, onions, cabbage and leafy greens, etc.

As demand grows due to population increase and health awareness, sustainable practices will be crucial for ensuring global supply. Global vegetable production plays a vital role in food and nutritional security. Major producers like China, India, and the U.S. contributes to over 1.1 billion metric tons annually *(FAOSTAT, 2017).* In 2024, global vegetable production was estimated to be around 209.39 million tonnes. India ranks second in vegetables production in the world, after China. India ranks first in pea and okra and 2nd in tomato, cauliflower, potato, onion and brinjal production *(Kumar et al, 2017).*

The consumption pattern in India is changing, with an increasing emphasis on a healthier lifestyle. This shift has led to a surge in demand for fresh and nutritious vegetables. Vegetables are not only a vital source of essential nutrients but also contribute to the diversification of diets. Vegetable production in India is reaching new milestones each year, establishing itself as the most favored agricultural commodity among farmers. In 2017-18, production was 184 million tons from 10.3 million hectares, a significant rise from less than 20 million tons at the time of independence. To meet the projected demand of 1.5 billion people by 2030, growth must be sustained *(MoAFW, 2018).*

Diverse climate of India allows cultivation of all type of vegetables in one or another agroclimatic zones. The Table 13 presents the cultivation of vegetable crops across varying agroclimatic zones.

Table 13: Major vegetable crops grown in different agro-climatic zones of India
(Source: Rai et al., 2008)

SN	Agro-climatic regions/zones	States represented	Major Vegetable Crops	Climatic Characteristics
1	Western Himalayan region	Himachal Pradesh, Jammu & Kashmir, Uttarakhand	Peas, Cabbage, Cauliflower, Radish	Cold winters, cool summers; suitable for temperate crops
2	Eastern Himalayan region	Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, West Bengal	Ginger, Chilli, Cabbage, Peas	Humid, subtropical; heavy rainfall
3	Lower Gangetic plain region	West Bengal	Potato, Tomato, Brinjal, Cucumber	Hot and humid; moderate to high rainfall
4	Middle Gangetic plain region	Uttar Pradesh, Bihar	Potato, Okra, Brinjal, Tomato	Sub-humid to dry; good for diverse vegetable cultivation
5	Upper Gangetic plain region	Uttar Pradesh	Potato, Tomato, Onion, Cauliflower	Hot summers, cold winters; suitable for seasonal vegetables
6	Trans Gangetic plain region	Chandigarh, Delhi, Haryana, Punjab, Rajasthan	Cauliflower, Cabbage, Carrot, Radish	Arid to semi-arid; irrigation essential
7	Eastern plateau and hills region	Chhattisgarh, Jharkhand, Madhya Pradesh, Maharashtra, Odisha, West Bengal	Pumpkin, Bitter Gourd, Brinjal, Tomato	Warm and humid; monsoon rains critical
8	Central plateau and hills region	Madhya Pradesh, Rajasthan, Uttar Pradesh	Tomato, Brinjal, Okra, Chilli	Semi-arid; varying rainfall
9	Western plateau and hills region	Madhya Pradesh, Maharashtra	Tomato, Onion, Chilli, Garlic	Hot and semi-arid; requires irrigation
10	Southern plateau and hills region	Andhra Pradesh, Karnataka, Tamil Nadu	Tomato, Brinjal, Capsicum, Chilli	Warm and semi-arid; good for diverse vegetable crops
11	East coast plains and hills region	Andhra Pradesh, Odisha, Pondicherry, Tamil Nadu	Brinjal, Chilli, Tomato, Onion	Hot and humid; moderate rainfall
12	West coast plains and ghat region	Goa, Karnataka, Kerala, Maharashtra, Tamil Nadu	Amaranthus, Cucumber, Bitter Gourd, Snake Gourd	Hot and humid; high rainfall
13	Gujarat plains and hills region	Gujarat, Dadra & Nagar Haveli, Daman & Diu	Onion, Tomato, Potato, Okra	Hot and semi-arid; irrigation critical
14	Western dry region	Rajasthan	Onion, Garlic, Carrot, Radish	Arid; low rainfall; irrigation essential
15	Island region	Andaman & Nicobar Islands, Lakshadweep	Cucumber, Pumpkin, Watermelon, Bitter Gourd	Tropical and humid; heavy rainfall

5.2.1.2 Cultivation of vegetables under AgriPV

The increasing impacts of climate change, water shortages, and soil degradation necessitate sustainable agricultural practices. AgriPV can play a significant role in enhancing the land productivity through vegetable cultivation and solar energy production from the same land. AgriPV system not only increases land-use efficiency but also offers, economic, and environmental benefits. Vegetables crops are relatively more suitable for AgriPV system as many of these crops can be grown under partial shading.

Ideally, crops suitable for AgriPV should be short and perennial. They should not interfere in any way with solar panel. Crops such as green leafy vegetables, herbs, and root vegetables are suitable for cultivation in AgriPV system *(Santra et al., 2020)*. The shade provided by panels can protect crops from extreme heat in semi-arid and arid regions.

Figure 25: Cultivation of vegetables crops under solar panel
(Khare Energy Pvt. Ltd. AgriPV site, Sagar)

5.2.1.3 Benefits of integrating vegetable crops with solar panels

1. **Optimizing land use**: AgriPV systems enables the dual use of agricultural land. Considering solar energy potential in India, integrating vegetable cultivation with production of electricity from solar energy enhances land use efficiency, particularly in regions with land constraints. For example, crops like **tomatoes, brinjal, chilies, and leafy vegetables,** which can be grown under partial shading can successfully be cultivated under AgriPV systems.

2. **Improved microclimate in hot and arid regions for crop growth**: AgriPV systems can create a favourable microclimate for crops in hot and arid climate. Solar panels act as partial shading structures that protect crops from extreme heat and excessive

sunlight, thereby reducing evapotranspiration and water stress, particularly in hot arid and semi-arid regions. This leads to better water conservation, which is critical in water-scarce areas where crops are heavily dependent on irrigation.

3. **Improved water use efficiency**: AgriPV systems with vegetable crops help in reduce the water requirement of crops by lowering the soil temperature and limiting direct sunlight exposure. This cooling effect lowers the amount of water lost through evapotranspiration.
4. **Economic benefits for farmers**: Integrating agricultural production with solar energy generation provides an additional source of income to farmers. In addition to the income from crop, farmers can benefit from the generation of solar energy, either for individual use or by selling the surplus energy to the grid. This helps in diversify the farm income and making farming more resilient to market fluctuations and adverse weather conditions.

5.2.1.4 Selection criteria for vegetable crops for AgriPV systems

Selecting vegetable crops for AgriPV system requires careful consideration of factors such as shade tolerance, water and temperature requirements, growth habit, yield potential, and market demand. By selecting suitable crops, AgriPV systems can maximize both agricultural productivity and solar energy generation. AgriPV systems have shown to increase land productivity by 60–70% and increase the value of energy production system by 30% *(Dinesh et al., 2016).*

Not all vegetable crops are suitable, but plants with less root density and a high net photosynthetic rate are more suitable for AgriPV system. Cucumber and lettuce grown under solar panels had lower soil water potential, resulting in higher fresh weight yields *(Marrou et al., 2013)*. Summer crops benefit more from solar panel shade than winter crops like pea *(Dupraz et al., 2011)*. Some of the key considerations for selection of vegetable crops for AgriPV is given in *Table 14*.

Table 14: Considerations for selection of crops

S.No.	Crops	Shading and sheltering benefit	Light requirement	Height of crop	Marketing opportunities
1	Brinjal	High	Medium	Medium	High
2	Okra	Low	Medium	High	High
3	Tomato	High	Medium	Medium	Low
4	Chillies	Medium	Medium	Medium	Low
5	Pumpkin	High	High	Medium	High
6	Cabbage	High	Medium	Low	High
7	Cucumber	Low	High	Medium	High
8	Beans	Medium	Medium	Medium	High
9	Bottle gourd	Low	High	Medium	Medium
10	Onion	Medium	Medium	Low	High
11	Peas	Medium	Medium	Medium	Medium
12	Potato	Medium	Medium	Medium	High
13	Radish	Medium	Medium	Low	Medium

14	Bitter Gourd	Medium	Medium	Medium	Medium
15	Ridge Gourd	Medium	Medium	Medium	Medium
16	Capsicum	High	Medium	High	High
17	Carrot	High	Medium	Low	Medium
18	Lettuce	High	Medium	Low	High
19	Green leafy vegetables	High	Medium	Low	Medium

(Source: Trommsdorff et al., 2021)

5.2.3 Floriculture and medicinal crops

Floriculture is the cultivation and trade of flowers. It includes the flower production, processing, and marketing of ornamental plants. India is the second largest flower growing country after China and is at 14th position in exporting floriculture products *(Anumala & Kumar, 2021)*. About 297 thousand hectares of the area were under cultivation for flowers in 2023-24.

India and China are leading exporters of medicinal and aromatic plants. India is a global leader in ethical herbal trade by supporting sustainable agriculture and medicinal plant cultivation *(Raju & Das, 2024)*. Medicinal and aromatic plants are traded both as raw materials and as highly processed final products. There are at least 8,000 species of medicinal plants in India, accounting for about 80% of all higher flowering plant species in the country *(Sharma et al., 2020)*. Additionally, medicinal and aromatic plants represent approximately 40% of the known diversity of vascular plant species in India.

India has the wide range of agro-climatic conditions required for the year-round cultivation of numerous flower other ornamental crops. Some of the high value flower crops like Rose, Gerbera, Carnation, Anthurium, Lilium, Orchids and Chrysanthemums are also grown in protected condition.

Medicinal plants can also be the potential crops if the PV plant is located on rocky scrubs or degraded lands e.g. Cassia angustifolia (Senna), Convolvulus microphyllus Sieb.ex Spreng., (Shankhpushpi), Aloe vera (‘gwarpatha’), Withania somnifera (Linn.) Dunal (Ashwagandha), Barleria acanthoides Vahl. (‘vazradanti’), etc, *(Santra et al., 2020)*.

The floriculture under solar photovoltaic system holds good potential. Moderate light availability favours the elongation of vegetative plant parts, making it ideal for crop growth under AgriPV system. This can particularly be beneficial for medicinal plants, making them highly suitable for cultivation in partially shaded systems. Among medicinal plants, the Lamiaceae family is notably intriguing, providing valuable natural compounds and high-quality raw materials *(Disciglio et al., 2023)*.

Figure 26: Flower crops under solar panel (Manwath AgriPV plant, Maharashtra)

5.3 Plantation Crops

Plantation crops are the perennial commercial crops of tropical and subtropical climate which are cultivated on an extensive scale in contiguous areas managed by an individual or a company, requiring care throughout the year and the products of which are consumed only after processing. Plantation crops play an important role in the agricultural economy of several states in India. The main plantation crops cultivated in the country include coconut, arecanut, oil palm, cashew, tea, coffee, and rubber. Spice and cocoa crops are also plantation crops *(Anandaraj, M. 2015)*. India is the largest producer and consumer of cashewnut and arecanut. Tea and coffee processing units are oldest industries in the country, which provide ample employment opportunities to the people and hold immense potential for export.

In India, the plantation sector is largely driven by millions of small and marginal farmers, predominantly located in regions that are economically and ecologically vulnerable. Factors such as changing cropping patterns, climate change, constraints on natural resource use, and decreasing profitability highlight the need for innovative strategies and approaches to tackle these challenges and promote accelerated growth within the sector.

Plantation crops suitable for AgriPV system are given below:

- **Coffee**: Coffee is a promising crop for AgriPV systems due to biological characteristics. As a shade-loving plant, coffee requires indirect sunlight for optimal growth. Excessive sunlight can cause leaf wilting and reduce yield and quality.
- **Tea:** Tea plants grow better with moderate light intensity. Shade from solar panels can provide ideal growing conditions.
- **Rubber:** Rubber tree grows best in tropical climates with moderate shade. The AgriPV system can provide ideal environment while also reducing water loss and improving overall land productivity.
- **Spices:** Spice crops often require shade to protect them from direct sunlight. AgriPV offers a good environment to cultivate these crops.

- **Cocoa:** Cocoa trees are highly sensitive to direct sunlight and require a shaded environment to flourish. AgriPV can provide the favourable conditions to enhance cocoa growth.

Coffee

Tea

Rubber

Spices

Cocoa

Figure 27: Plantation crops

5.4 Sericulture

Sericulture, or silk farming, is the process that involves mulberry (*Morus spp*.) cultivation, rearing of silkworms for the production of silk, and the collection of silk thread for the textile industry. Sericulture is an agro-based industry with a short gestation period, low investment, continuous cash flow and high pay off. Silk was first produced in China as early as the Neolithic period. Today, China and India are the two main producers, with more than 60% of the world's annual production. India is the only country blessed with all the four types of silkworms i.e. Mulberry, Tasar, Eri and Muga. India is the second-largest producer of silk in the world with the major mulberry-silk-producing states are Karnataka, Andhra Pradesh, West Bengal, Tamil Nadu and Jammu and Kashmir, which together account for 92% of the country's total mulberry raw silk production *(Babu, 2020)*.

Mulberry cultivation, essential for sericulture, grow well in climates with temperatures from 24 to 28˚C and well-distributed rainfall. Relative humidity should be between 65 to 80 %, with sunshine duration of 5 to 12 hours per day. Ideal soils are slightly acidic, with good depth and drainage. Regular irrigation, pruning, and fertilization are key to healthy plants and high-quality leaves, which are vital for silkworm rearing and contribute significantly to the silk industry. For optimal growth, mulberries require consistent moisture, especially during dry spells, to prevent premature fruit drop. Cultivation-wise, mulberry trees are hardy and grow under a wide range of conditions, and their leaves are food source for silkworms, making them vital for sericulture.

5.4.1 Types of silk

Mulberry

Silkworms feed soleley on mulberry leaves to produce mulberry silk. Karnataka, Andhra Pradesh, West Bengal, Tamil Nadu, adn Jammu & Kashmir together produce 92% of India's mulberry raw silk. mulberry trees have been grwon for horticultural, industrial, silvicultuarl, ornamental, and pharmaceutical purposes.

Muga

Muga silk, known for its natural golden-yellow shine, is produced by silkworm raered on som (machilus bombycina) leaves. Found only in Assam *(Tuigong et al., 2015)*, it is used in making sarees, mekhalas, and chaddars, reflecting cultural and economic value.

Tasar

Tasar silk, derived from silkworms (Antheraea mylitta) raised on oak leaves and similar species, makes up 5% of India's silk production. Jharkhand, Chattisgarh, and Odisha are key producers, alongside Maharashtra, West Bengal, and Andhra Pradesh. It's a vital livelihood for many tribla communities *(Babu et al., 2013)*.

Eri

Eri silk, made by silkworms feeding on cator plant leaves, is white or brick-red *(Tuigong et al., 2015)*. Cultivated mainly in Assam and India's northeastern states, as well as Bihar, West Bengal, and Odisha *(Dhavalikar, 1962)*, its cocoons vary in softness, with uses in both mechnical and hand spinning *(Sonwalkar, 1969)*.

Figure 28: Types of silk

In sericulture, maintaining an optimal microclimate is crucial for ensuring the health, growth, and productivity of silkworms, thereby enhancing silk yield. Ideal environmental conditions include a temperature range and relative humidity which are essential for different developmental stages of silkworms (Babu, 2013). Adequate ventilation is necessary to maintain proper oxygen levels and prevent mold growth, while diffused lighting minimizes stress on the silkworms. Protection from external environmental factors such as wind, dust, and pollutants are also key to preventing stress and ensuring high-quality silk production.

5.4.2 Benefits of sericulture under AgriPV system

1. **Dual-use of land**
   - Enables silk farming and solar power generation on the same land.
   - Maximizes land use efficiency, especially in areas with land scarcity.
2. **Energy for farm operations**
   - Solar panels generate renewable energy to power sericulture activities like silkworm rearing and mulberry farming.
   - Reduces energy costs and dependency on non-renewable sources.
3. **Improved microclimate for silkworms**
   - Solar panels provide shade, helping maintain optimal temperatures for silkworms.
   - Reduces temperature fluctuations that could harm silkworm health.

4. **Economic gains**
   - Income from both silk production and solar energy sales enhances financial stability for sericulture farmers.
5. **Climate resilience**
   - Solar panels shield crops and silkworms from extreme weather, making the sericulture setup more resilient to climate change.

5.5 Impact of AgriPV on Crop Performance, Microclimate, and Agricultural Mechanization

5.5.1 Impact of shading

Shading, or reduced light exposure, can significantly impact crop growth, with effects varying with crop species, shade level, and developmental stage. While some crops benefit from shading, others require full sunlight for optimal growth and yield. Certain crops, particularly leafy greens and some vegetables, can exhibit increased growth, yield, and quality under moderate shading conditions. Under shaded conditions, leaf chlorophyll content, including chlorophyll a and b, tends to increase compared to leaves exposed to full sunlight. This results in a darker green color, an adaptation that allows plants to maximize photosynthesis in low-light environments. *Delucia et al. (1996)* found that plants typically increase photosynthetic efficiency under shading by expanding leaf area to improve light utilization. Similarly, *Abrams (1987) and Lambers & Poorter (1992)* reported that shading leads to an increase in leaf chlorophyll content while decreasing the chlorophyll a/b ratio to enhance plant photosynthetic activity.

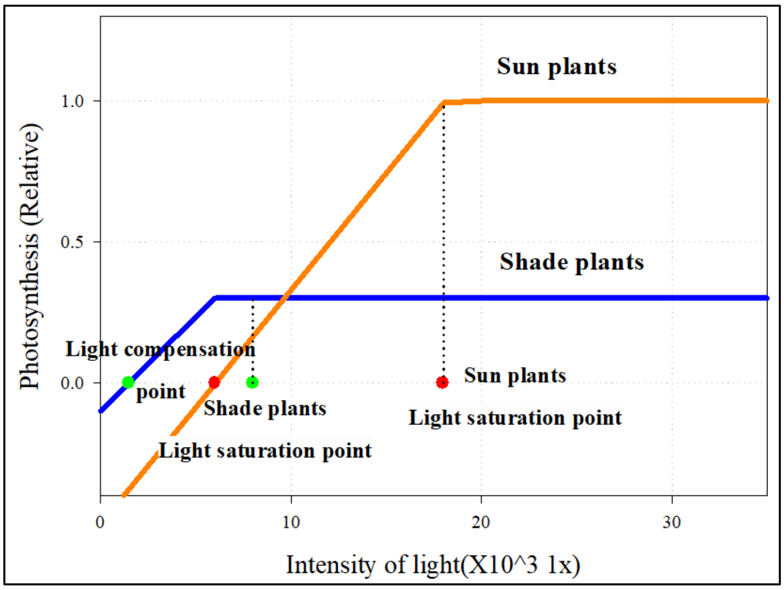


Figure 29: Light compensation point and light saturation point

(Source: Park et al., 2021)

Two important concepts in understanding the impact of shading on crops are the light compensation point and the light saturation point. The light intensity at which the rate of photosynthesis equals the rate of respiration, meaning there is no net carbon dioxide uptake is called light compensation point (LCP). The light intensity beyond which further increases in light do not lead to increased photosynthesis is called is light saturation point (LSP). Plants can be categorized into sun loving and shade tolerant based on their light requirements. The light compensation and saturation points of a plant indicate its shade tolerance. The lower these values, the stronger the shade tolerance of the plant *(Bestva, 2021)*. Understanding these parameters helps in optimizing light conditions for various crops to maximize growth and yield.

Several studies have examined the effects of shading and light intensity on tomato and other crops, highlighting various outcomes related to yield, quality, and agronomic practices. The impact of shading varies with crops and variety. The shading could lower energy and water consumption while enhancing fruit productivity and quality *(Ahmed et al., 2020).* Shading affects oil crops by altering fatty acid composition, with lower light intensity increasing polyunsaturated fatty acids. Forage crops and leafy vegetables like cabbage and lettuce can benefit from reduced solar irradiation by increasing leaf area and total biomass. In fruit trees like kiwi and mango, moderate shade improves fruit quality and sometimes yield. Crops well-adapted to shade, such as forage crops, herbaceous plants, and leafy vegetables, may maintain or increase yields. For blueberries and blackberries grown under shading nets, harvesting period can be extended to fetch better market prices *(Lobos et al., 2013; Rotundo et al., 1998).* Coffee benefits from additional shade in agroforestry systems *(Jezeer et al., 2018).* Seasonal differences in shading patterns affect crop production based on whether cultivation occurs in spring or summer *(Dupraz et al., 2011; Marrou et al., 2013). Chowdhury et al. (2025)* examined the growth and yield of shade-tolerant crops—including tomato, brinjal, green chili, lettuce, and aloe vera—under both shaded and non-shaded conditions. Their findings indicate that brinjal, lettuce, and aloe vera benefit from shading in the AgriPV system, whereas green chili experiences yield disadvantages, and tomato shows no significant difference. While some studies provide insights into shade tolerance, their applicability to AgriPV is limited due to varying climatic conditions.

These findings highlight the significant effects of shading in AgriPV systems, emphasizing the importance of selecting suitable crop species and varieties to optimize yields and quality.

5.5.2 Microclimate

In AgriPV systems, altered microclimate becomes crucial for crop cultivation. The primary change is the reduction in solar radiation under the panels, which directly influences air temperature. The cooling effect under the panels reduces the Crop evapotranspiration (ETc) due to reduced soil evaporation and transpiration. However, the effect depends on the crop species cultivated, as ETc is driven by leaf area. Under AgriPV, the crop cover increases for lettuce but decreases for cucumber.

The AgriPV systems can improve water use efficiency (WUE) and help prevent water losses under dry climates, if suitable crop species are chosen *(Marrou et al., 2013a)*. This is in accordance with findings for citrus grown under shading nets, where WUE increased with lower solar irradiation *(Medina et al., 2002)*. In simulations based on data of 40-year, cultivating maize under AgriPV in non-irrigated conditions reduced soil evaporation and increased average yield. The highest yield variation was obtained under full-sun conditions. AgriPV may lead to yield stabilization, mitigating yield losses in dry years *(Amaducci et al., 2018).*

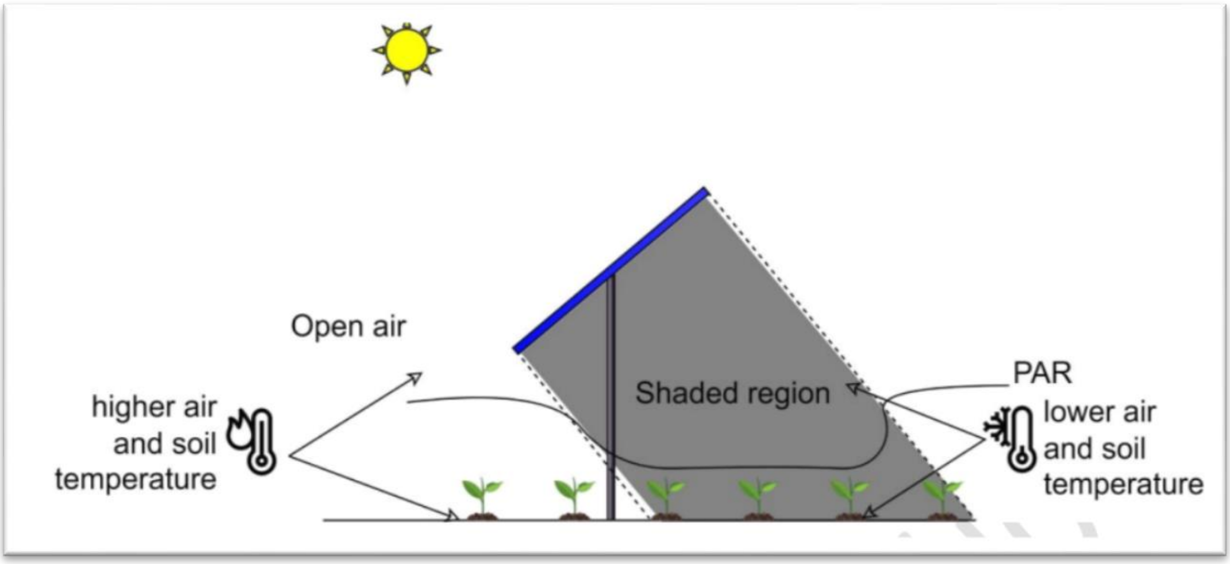


Figure 30: Simplified representation of microclimate beneath solar panels
(Source: Pandey et al., 2025)

Altered microclimate conditions in AgriPV systems can impact crop yield and quality. **Limited data exists for many crop species,** with most findings derived from shade net and agroforestry studies. The most significant change is reduced light availability, which may lead to yield losses in most crops *(Amaducci et al., 2018)*. Thus, there is need for crop specific research under AgriPV.

5.5.3 Air temperature

In AgriPV systems, air temperature significantly influences both crop growth and solar panel efficiency. The shade provided by solar panels can lower air and soil temperatures, creating a more favourable microclimate for plants by reducing heat stress and improving water use efficiency in hot semi-arid and arid climate. This moderated environment helps plants to grow while enhancing the efficiency of photovoltaic cells, as lower temperatures prevent the decline in panel performance under high temperature.

Air and soil temperatures under AgriPV showed different patterns during day and night, affecting crops like wheat, lettuce, and cucumber *(Medina et al., 2017)*. The increased temperatures and solar radiation in May negatively affected the nutritional quality of cherry tomatoes in Spain *(Rosales et al., 2018)*.

5.5.4 Yield

There is a strong correlation between grain yield and irradiance in cereals like wheat, rice, and maize *(Weselek et al., 2019)*. The extent of yield reduction depends on the shading intensity, duration, and growth stage. For example, rice yields can decrease by up to 73% under severe shading conditions with a reduction of incoming radiation up to 77% *(Islam et al., 1992)*. In wheat, yield reduction is due to fewer grains per spike and spikes per unit area. Mild shading can sometime increase yields in some wheat cultivars *(Fischer et al., 1985)*. In maize, yield reductions are more due to shading during flowering and grain filling stages, but stover yield remains relatively unaffected *(Reed et al., 1988)*. When predicting impacts on agricultural yields, it is important to account for the predictable loss of production areas between the stilts that are difficult to reach by agricultural machinery.

5.5.5 Mechanisation

One crucial factor to consider when designing the PV structure is that it should not hinder the normal agricultural operation with machine. Therefore, the structure must be carefully planned and constructed to allow the implements and machineries to move freely and work efficiently *(Mouhib, E. et al., 2024)*. The AgriPV systems require modifications to accommodate agricultural machinery. The PV panels must be raised to a height to allow harvesters and other machineries to pass, and the distance between pillars should align with planting distances and machinery widths. Experienced operators are required to operate machineries under the AgriPV without causing damage.

Chapter 6
Scope of AgriPV in different Agroclimatic Zones

India faces challenges in food security, energy security, and low farmer income, with 47% of the population reliant on agriculture. The country has committed to produce 50% of its energy from renewable energy sources by 2030 *(Yadav et al., 2024)*. However, solar PV generation is a land-intensive venture, and it needs around 2 ha of land per MW of power generation *(Shukla et al., 2022)*. Given this, AgriPV technology has emerged as a promising solution, offering benefits to both the energy and food sectors.

The potential of AgriPV systems varies across different agroclimatic zones, as each region presents unique challenges and opportunities for both agriculture and solar energy production. Agroclimatic factors such as temperature, rainfall, solar radiation, and soil type play a crucial role in determining the suitability and effectiveness of AgriPV systems. In regions with abundant sunlight and water scarcity, such as arid and semi-arid zones, AgriPV can offer significant benefits by enhancing crop resilience while generating renewable energy. Understanding the specific characteristics of each agroclimatic zone is essential for optimizing the design and implementation of AgriPV systems to balance agricultural productivity with solar power generation.

6.1 Solar Irradiation in Some States of India

India has a high potential for solar power generation with about 300 direct sunshine days per year. The regular solar incident in India varies with an annual sunlight of 4 to 7 kWh/m^2, which is about 1500 to 2000 hours above the irradiation level gross energy consumption. Around 58% of the country's land area may be solar hotspots, with annually average global insolation of more than 5 kWh/m2/day *(Ramachandra et al., 2011)*. *Table 15* shows the major irradiation level solar hot spot in India.

Table 15: Major solar irradiation hotspot in India

SN	States	Total Area (1500 Ha)	Total solar potential energy (GW)	High irradiation insolation level(kWh/m^2/day)
1	Karnataka	19050	24.7	3.5-4.0
2	Rajasthan	34270	4.8	5-7
3	Maharashtra	30758	64.32	3-4
4	Himachal Pradesh	4548	33.8	3-4
5	Jammu Kashmir	3781	111.05	3-4
6	Andhra Pradesh	27505	38.4	3-4.5
7	Gujarat	18866	35.7	4-4.7
8	Odisha	15043	25.7	4-4.7
9	Madhya Pradesh	30756	61.6	2.9-4.0
10	Uttar Pradesh	24170	22.8	2.9-3.9
11	Haryana	18096	73.2	3.5-4.5

(Source: Albert et al., 2020)

The *fig.15* illustrates that several regions of India, including the Gangetic plains (Trans, middle, and upper) region, the Plateau regions (Central, western, and southern), the Western dry region, the Gujarat plains and Hill region, as well as the West Coast Plains and ghat region, experience an annual global insolation above 5 kWh/m²/day. These areas include states of Karnataka, Gujarat, Andhra Pradesh, Maharashtra, Madhya Pradesh, Rajasthan, Tamil Nadu, Haryana, Punjab, Kerala, Bihar, Uttar Pradesh, and Chhattisgarh.

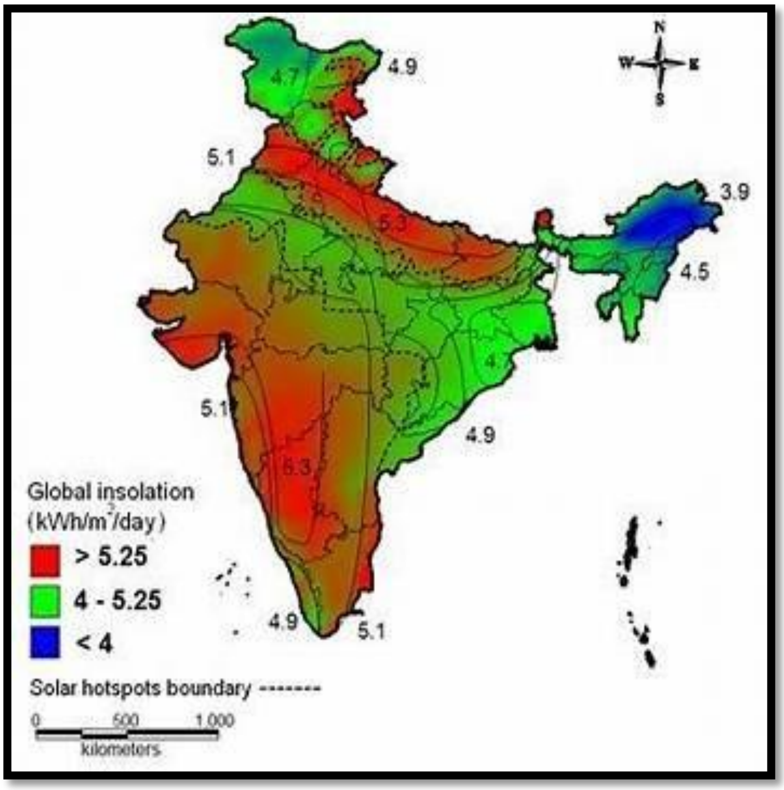


Figure 31: Annual average global insolation map of India

(Source: Directorate of Economics and Statistics, GOI, wgbis.ces.iisc.ac.in)

Eastern part of the Ladakh region (Jammu & Kashmir) along with minor parts of Himachal Pradesh, Uttarakhand, and Sikkim, located within the Himalayan belt, also receive comparable levels of global insolation annually. These regions, with significant solar potential, represent solar hotspots covering approximately 1.89 million km², or roughly 58% of India's land area. These zones present promising opportunities for AgriPV system. The Eastern Himalayan states of Arunachal Pradesh, Nagaland, and Assam experience an average annual global insolation of less than 4 kWh/m²/day *(Ramachandra et al., 2011).*

6.2 Land Characteristics

Land, being a limited resource, is subject to continuous transformation driven by factors such as rapid urbanization, infrastructure development, changing agricultural practices, and the demand for food, feed, fiber, and fuel production, as well as the need to maintain critical ecosystem services *(Land Use & Cover Mapping and Monitoring Division India, 2024)*. Simultaneously, per capita land availability is declining due to population growth. Rapid industrialization and population growth further stress land resources through soil erosion, desertification, pollution, food and water shortages, land conflicts, and climate change *(Vol. II-Environment Accounts, India, 2020).*

According to Ministry of Home Affairs, Government of India, India encompasses a total land area of 3,287,260 km^2, with a land border extending 15,200 km (9,445 miles) and a coastline measuring 7,516.5 km. The country's diverse landscapes range from the Himalayan Mountain range in the north, spanning over 2,500 km from Jammu & Kashmir to the Northeastern region. The Indo-Gangetic plains, enriched with highly fertile alluvial soil, are particularly suitable for cultivation. The western part of India is characterized by the arid Thar Desert. Estimates reveal that about 4.89 million ha of barren and unculturable land is available in Gujarat and Rajasthan. Even a small fraction of this waste land (0.1% or 4890 ha) could support nearly 1222 MW capacity.

Table 16: Area of barren or unculturable land in representative states of identified solar hotspots in India

State/Union Territory	Total area	Barren or unculturable land	
	(1000 ha)	(1000 ha)	%
Andhra Pradesh	27505	2056	7
Bihar	9360	432	5
Chhattisgarh	13790	308	2
Goa	361	0	0
Gujarat	18866	2595	14
Haryana	4371	103	2
Himachal Pradesh	4548	656	14
Jammu Kashmir	3781	288	8
Karnataka	19050	788	4
Kerala	3886	25	1
Madhya Pradesh	30756	1351	4
Maharashtra	30758	1718	6
Punjab	5033	24	0
Rajasthan	34270	2295	7
Sikkim	723	107	15
Tamil Nadu	13027	492	4
Uttarakhand	5673	224	4
Uttar Pradesh	24170	507	2
West Bengal	8684	21	0
Chandigarh	7	0	0
Delhi	147	16	11

(Source: Directorate of Economics and Statistics, Government of India [2011])

6.3 Potential of AgriPV Across Various Agroclimatic Zones in India

The crop selection, mounting height, optimal tilt angle, solar irradiation and local climate play a role in the optimal selection of PV system geometry for an AgriPV system. Also, the performance of photovoltaic (PV) systems depends on the solar irradiation received by the modules. The shading on the PV module varies according to the time of the year and height of the crops planted between the module rows *(Mavani et al., 2019)*. Similarly, crop yields depend on the radiation conversion efficiency, which refers to the process of converting photosynthetically active radiation (PAR) in the 400-700 nm range, into dry matter *(Mavani et al., 2019)*.

AgriPV's potential varies across India's diverse Agroclimatic Zones. Effective implementation requires understanding local conditions and tailoring practices accordingly. India is divided into several agroclimatic zones based on factors like temperature, rainfall, soil types, and crop suitability *(Sarkar, A. 2008)*. These zones are essential for understanding the potential of AgriPV systems. The major Agroclimatic Zones in India include arid, semi-arid, tropical, subtropical, and temperate regions, each distinct climatic conditions and agricultural practices.

- **Arid and Semi-Arid Zones** (Rajasthan, Gujarat, parts of Maharashtra): These regions receive high solar radiation with an annual global insolation above 5 kWh/m²/day, making them ideal for AgriPV systems, where solar panels can generate electricity. However, challenges such as water scarcity, high initial setup costs, and suitable crop selection must be addressed. An example of AgriPV in this region is located in CAZRI, Jodhpur, where the plant operates in an arid climate. The region experiences an average horizontal surface irradiance of 6.11 kWh/m²/day. The plant utilizes a rainwater harvesting system attached to PV-modules, collecting up to 150,000 liters annually for cleaning and irrigation.
- **Tropical and Subtropical Zones** (Kerala, Tamil Nadu, Andhra Pradesh): These areas benefit from both high solar energy and diverse cropping systems. AgriPV can enhance the productivity of crops like banana, tea, coffee, ginger and vegetables by providing partial shade, thus reducing heat stress. An example of AgriPV in this region is located in Cochin Airport plant in Kerala, covering 45 acres, including 20 acres for AgriPV. The project primarily involves interspace cultivation, contributing to its success.
- **Temperate Zones** (Jammu & Kashmir, Himachal Pradesh): These regions are not only suited for AgriPV due to moderate temperatures but also show promise for high-value crops such as apples, grapes, and vegetables that require temperate conditions for growth. A farmer own AgriPV plant at Jahu, Himachal Pradesh having a capacity of 250 KW. The crops grown include eggplant, cabbage, onion, chili, and ladyfinger. Most of these crops are cultivated using interspace AgriPV. Additionally, some crops, such as turmeric, are cultivated underneath the PV modules.

Chapter 7
AgriPV System for 1 Acre of Land Area

In an AgriPV system, integrating solar energy generation with agricultural activities enables dual land use. A crucial aspect of this integration is determining the optimal allocation ratio between land designated for solar PV installations and land reserved for agricultural activities.

Certain areas within the AgriPV system will experience consistent shading due to solar module placement, while other areas will receive partial shade only during specific months of the year. In regions with partial shading, shade-tolerant crops can be cultivated, whereas open-field areas with minimal shading can be utilized for growing sun-loving crops.

Defining the cultivable and non-cultivable areas within an AgriPV system is essential. Non-cultivable zones may include land reserved for maintenance pathways, structural foundations, and other operational requirements.

For a one-acre land, multiple scenarios have been developed, considering safety margins for maintenance access and land occupied by the solar mounting structures.

7.1 Case 1

In this case, the cultivable area is limited to the space between and beneath the solar panels, with no cultivation considered between the mounting poles of the structure. Additionally, the area from the boundary to the solar PV panel structure is designated as non-cultivable to accurately estimate the available cultivable land.

A safety margin has been allocated at the lower end of the solar module structure, with a width of 1 meter considered for all cases.

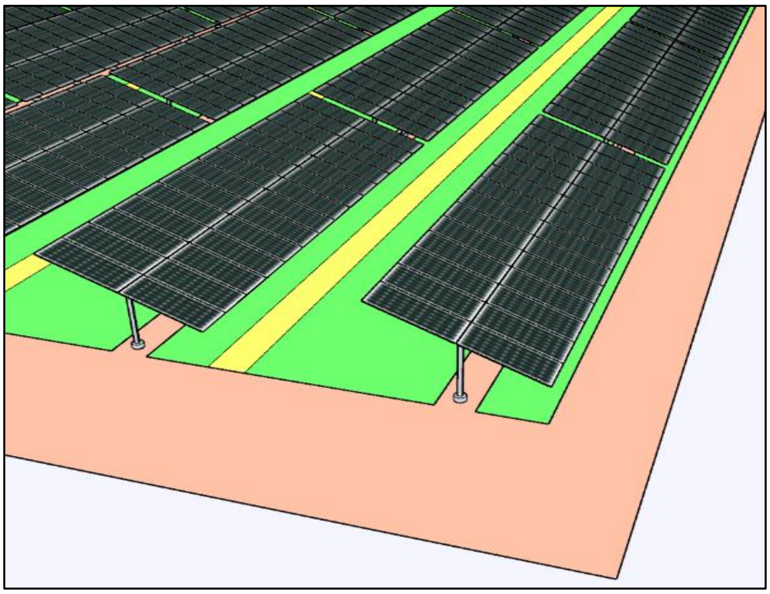


Figure 32: Case 1

7.2 Case 2

In this case the only half of the area beneath the solar PV modules is designated as cultivable land, reducing the overall cultivable area compared to Case 1.

This configuration is recommended for scenarios where a lower-height mounting structure is used, making the lower-end area of the solar panels less accessible and less practical for farming activities. The safety margin remains the same as in Case 1.

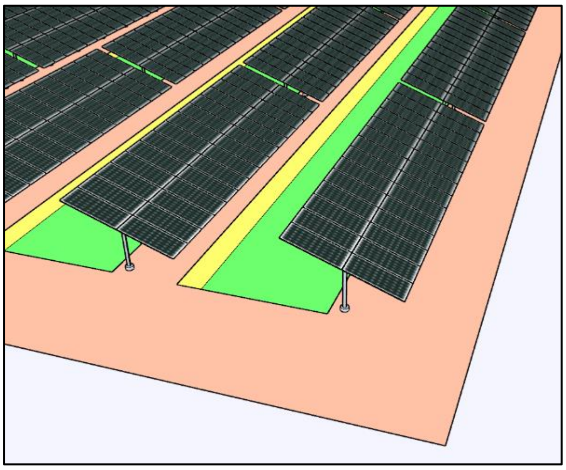


Figure 33: Case 2

7.3 Case 3

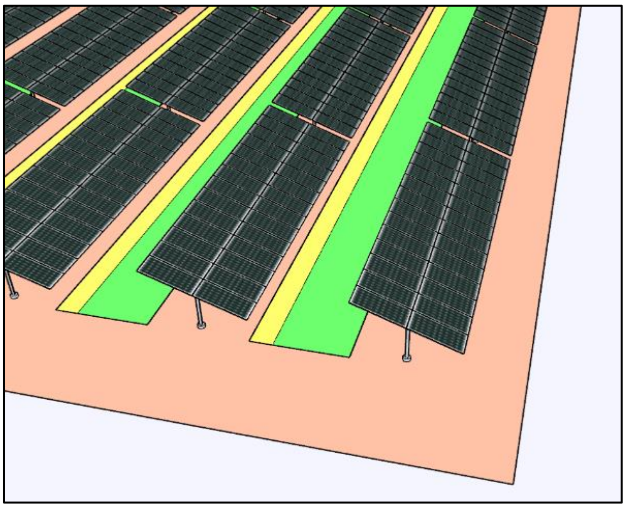


Figure 34: Case 3

In Case 3, this configuration is designed to analyse the land coverage ratio for existing solar PV systems that were not originally planned with agricultural considerations.

If an existing solar PV system is to be converted into an AgriPV site, this configuration provides insights into the available interspace area for cultivation. It helps assess the feasibility of growing suitable crops based on soil type and other agronomic factors.

7.4 Case 4

In this case the configuration is designed with the assumption that a safety margin runs parallel to the solar PV structure.

However, this scenario is less practical in real-world applications due to space constraints and operational challenges.

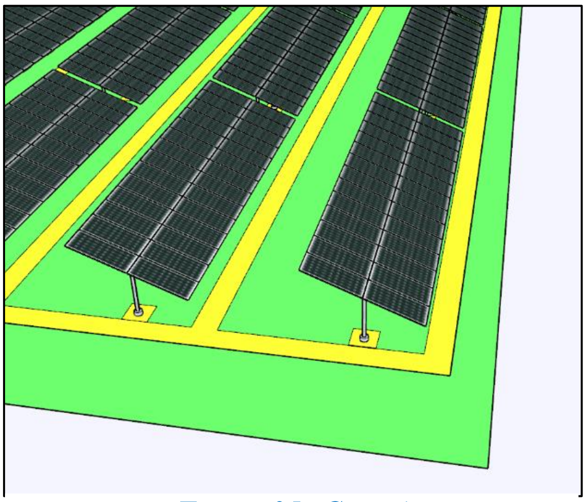


Figure 35: Case 4

7.5 Case 5

This configuration represents the most practical and commonly adopted scenario in AgriPV systems. It includes a designated safety margin and a raised structure height to minimize shading effects on crops.

Additionally, both the lower-end area and the space beneath the solar panels are efficiently utilized for cultivation. Crop rotation planning will be guided by agricultural experts to optimize yield and sustainability.

With only a 12% reduction in cultivable land, this configuration is recommended as a standard for AgriPV system to achieve optimal agricultural productivity while maintaining solar energy generation efficiency.

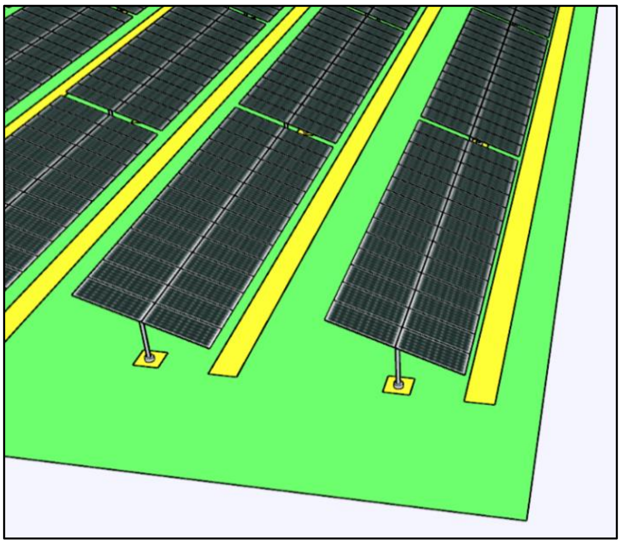


Figure 36: Case 5

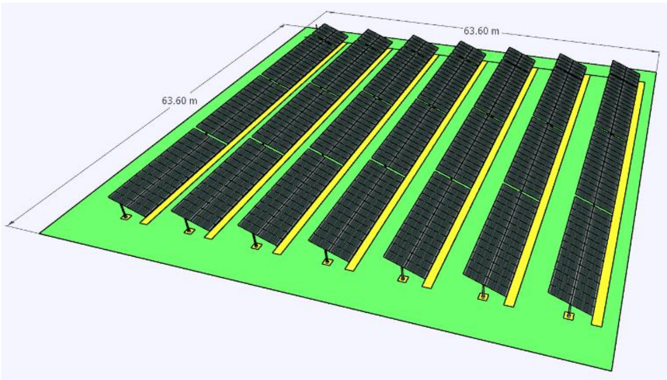
Table 18 presents five different cases outlining the distribution of land use within an AgriPV system.

Table 17: Distribution of land use under different cases

Land Description	Case 1	Case 2	Case 3	Case 4	Case 5
Total area available for cultivation (Acre)	**0.62**	**0.45**	**0.29**	**0.84**	**0.88**
Open Area available for cultivation (%)	29.7	28.9	29.00	46.00	50.00
Area under panel available for cultivation (%)	32.30	16.10	0.00	38.00	38.00
Total area not available for cultivation (Acre)	**0.38**	**0.55**	**0.71**	**0.16**	**0.12**
Safety Margin Area / Walkway area (%)	9.40	9.40	9.40	12.54	9.3
Mounting Pole Coverage Area (%)	0.24	0.24	0.24	0.24	0.24
Excluded area (%)	28.22	44.44	60.46	0.00	0.00
Safe distance from mounting pole for growing crop (%)	0.00	0.00	0.00	3.22	2.56

From the table, it can be observed that in Case 5, approximately 88% of the land is allocated for cultivation.

To ensure agriculture remains the primary focus in AgriPV systems, it is recommended that a minimum of 85% of the total area be designated as cultivable land. The remaining 15% of total project land area can be allocated for solar PV system installation, walkways, and O&M activities. This ratio ensures that solar energy generation complements rather than compromises agricultural activities. Future AgriPV developments should strictly adhere to this balance to maximize land-use efficiency and sustainability.



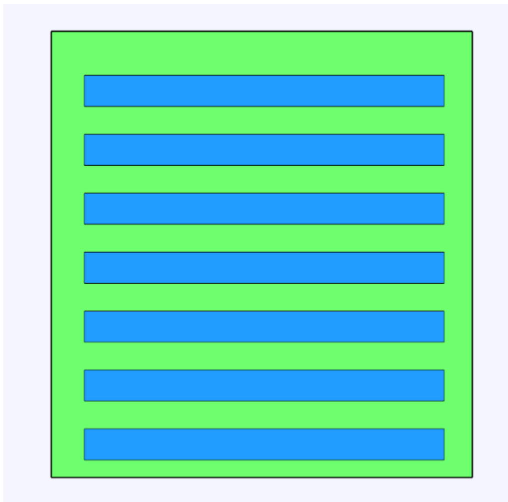
: Total area not available for cultivation
: Total area available for cultivation

Figure 37: Minimum cultivable area for AgriPV System

For Case 5, the distribution of open land and the area under the solar PV modules were analysed. This distribution is also referred to as the land coverage area.

In this case, the PV module covers 42% of the total one-acre land, while the remaining 58% is classified as open area. This ratio provides valuable insights for selecting suitable crops based on their specific growth requirements, such as height, shade tolerance, and water needs. By knowing the distribution of shaded and open areas, farmers can optimize crop selection to maximize agricultural yield while ensuring compatibility with the solar PV system.

Land Coverage			
Area beneath Solar PV System	0.42	Acre	42%
Area open to atmosphere	0.58	Acre	58%
Total Area	1.00	Acre	100%



: Solar panel land coverage area / area beneath the solar PV panels
: Area open to atmosphere / area not beneath the solar pv panels

Figure 38: Land coverage area

It is recommended that the PV module coverage in AgriPV systems in India be kept below 40% to prioritize agricultural activities while integrating renewable energy generation. This approach ensures a balanced land-use strategy, supporting both sustainable farming practices and solar power production.

Chapter 8
Crop Matrix for AgriPV System

A crop matrix for AgriPV is a structured dataset of crops in tabular form that shows the suitability of various crops grown under the partial shade. It considers key factors including crop type, crop height, light requirement (PAR) of different crops, crop growing season and climatic conditions. This matrix helps in identifying which crops can thrive under different shading conditions and how system design impacts overall productivity. Also, it serves as a valuable tool for farmers, stakeholders, and researchers in selecting appropriate crops for specific regions and optimizing land use within an AgriPV setup.

Crop matrix development is essential for choosing crops that are suitable to cultivate under AgriPV systems based on light and climatic conditions. Factors such as Photosynthetic Photon Flux Density (PPFD), Daily Light Integral (DLI), Light Saturation Point (LSP), Growing Degree Days (GDD), Light Compensation Point (LCP), and Photothermal Units (PTU) significantly influence crop productivity. The PPFD and DLI are essential for assessing the amount of light available for photosynthesis, while LSP and LCP help identify the light levels at which crops achieve maximum growth or begin to experience stress. The GDD and PTU, which consider temperature and light, are important for assessing plant development and growth cycles.

Knowing the shading effects of solar panels in AgriPV systems, it becomes imperative to develop a crop matrix with suitable crops to minimise the effect of shading on yield under modified light conditions. This paper presents a crop matrix to select crops that can be grown under AgriPV conditions, thereby enhancing overall system efficiency and productivity.

Typically, an AgriPV system consists of two distinct zones: the area beneath the panels, where sunlight intensity is reduced due to shading, and the area between the panels, where shading effects are minimal. To maximize growth and productivity, crops should be categorized based on their light requirements for each zone. However, extensive research through AgriPV pilot projects is necessary to validate the effectiveness of the proposed crop matrix.

The method used to classify land into two zones:

- **Zone 1 (Area under the panels):** This area has more shade, suitable for shade-tolerant crops that either maintain or increase the yield under reduced light.
- **Zone 2 (Area between the panels):** This area has lower shading, suitable for light-demanding crops that require higher solar intensity for optimal growth with moderate yield reduction.

8.1 Factors Affecting the Crop Selection for AgriPV System

Crop selection is based on the **Photosynthetically Active Radiation (PAR)**, **Daily Light Integral (DLI)** requirements necessary to sustain an optimal photosynthetic rate. The **Light Saturation Point (LSP)**, which is the maximum light intensity beyond which photosynthesis does not increase further, is another critical factor though not an important parameter for AgriPV system. The factors influencing crop growth are explained below.

8.1.1 Photosynthetically Active Radiation (PAR)

Photosynthetically Active Radiation (PAR) refers to the spectral range of solar radiation between 400-700 nm, which photosynthetic organisms use for photosynthesis. This range largely corresponds to the wavelengths of light in visible wavelength. In plants, leaves primarily absorb red and blue light due to chlorophyll's absorption properties. Green light penetrates deeper into the leaf structure and is more effective than red light. Green and yellow wavelengths can also transmit through chlorophyll and the entire leaf, playing a significant role in supporting growth beneath the plant canopy *(Bhattacharya, 2019)*.

8.1.2 Photosynthetic Photon Flux Density (PPFD)

Photosynthetic Photon Flux Density (PPFD) is defined as the number of photosynthetically active photons that fall on a given surface in the range of 400-700 nm, which constitute about 42-49% of the total energy of the whole solar spectra *(Faust & Logan, 2018; Moretti & Marucci, 2019)*. It is another metrics used to measure light for plant growth. While PAR describes the spectrum of light, PPFD measures the amount of light that reaches a plant. PPFD is a crucial determinant in the rate of photosynthesis in plants. Studies indicate that increasing PPFD, elevated rate of photosynthesis, thereby enhancing crop growth and yield *(Chauhan et al., 2013; Hidaka et al., 2013; Kläring & Krumbein, 2013; Ohashi-Kaneko et al., 2007; Sivakumar & Virmani, 1984)*. This would help in conducting research on crop suitable for AgriPV system.

However, positive trend in photosynthesis is typically observed only up to a specific PPFD threshold, referred to as the light saturation point, beyond which the increasing trend was flattened. The PPFD value at the light saturation point varies among different crop species *(Yano & Cossu, 2019)*. While extensive research exists on the required PPFD for horticultural crops, there is a scarcity of information for field crops. This is attributed to the difficulty of conducting controlled experiments to measure the light requirements for field crops. In contrast, experiments on horticultural crops are more feasible due to the ease of establishing controlled environments within greenhouses using artificial lighting. It has been generally observed that the PPFD at the light saturation point for horticultural crops ranges from 450 to 1630 $\mu mol\ m^{-2}\ s^{-1}$, with an average value of 992 $\mu mol\ m^{-2}\ s^{-1}$.

8.1.3 Growing Degree Days (GDD)

Growing Degree Days (GDD), or heat units, is used to estimate the growth and development of certain crops and pests during the growing season. GDD is a way of assigning a heat value to each day. The values are added together to give an estimate of seasonal growth of plants

In the absence of extreme conditions such as drought or disease, plants grow in a cumulative stepwise manner which is strongly influenced by the ambient temperature. The GDD allows grower to predict the plants' pace toward maturity. Daily growing degree day values are added together from the beginning of the season. This provides an estimate of the energy available for plant growth. Growing Degree Day totals are used for comparing the progress of a growing season to the long-term average and are useful for estimating crop development stages and maturity dates.

$$GDD = [\ (T_{max} + T_{min}) / 2] - T_{base}$$

Where,
T_{max} represents the highest canopy temperature recorded over a 24-hour period

T_{min} is the lowest canopy temperature during the same period
T_{base} is the base temperature representing the minimum temperature required for growth. It varies from season to season and region to region.

The base temperature, also known as the threshold temperature, is the minimum temperature required for crop growth. Below this temperature, growth ceases. This threshold varies among different crops. Generally, tropical crops have higher base temperature requirements and temperate crops have lower base temperature *(Parthasarathi et al., 2013)*.

Growing Degree Days is a way to measure how temperature affects plant growth and development. Each plant species has a base temperature, representing the minimum temperature required for growth. This parameter is essential for calculating Growing Degree Days (GDD). To maintain the Growing Degree Days for optimal plant growth, it is essential to carefully monitor temperature fluctuations and adjust key factors such as irrigation, planting schedules, and crop selection according to the specific GDD requirements of the plant. Maintaining temperature within the ideal range for crop growth is critical, which can effectively be managed from daily GDD accumulation and implementing necessary adjustments to maintain the targeted GDD level.

Negative values of GDD are treated as zero and excluded from calculations. The base temperature differs among crops and is determined based on the growth characteristics of each species. Base temperature represents the threshold below which plant growth ceases. For instance, growth of cereal and forage crops is minimal when the average temperature falls below 5°C *(Gude et al., 2022)*.

GDD serve as a heat index for predicting crop maturity and can positively impact yield *(McMaster and Wilhelm, 1997)*. This was demonstrated in spring tomato trials in North Carolina, where high tunnels accumulated more daytime heat and GDD compared to open-field conditions, thereby optimizing early-season production. The accumulated GDD values were calculated using the standard equation provided by *McMaster and Wilhelm (1997)*.

8.1.4 Daily Light Integral (DLI)

The Daily Light Integral (DLI) represents the cumulative daily availability of Photosynthetically Active Radiation (PAR), whereas the Photosynthetic Photon Flux Density (PPFD) measures the instantaneous availability of PAR. PPFD fluctuates significantly from morning to afternoon, DLI is a more reliable criterion for selecting crops based on light availability, as it quantifies the total daily light exposure. By considering the DLI available under AgriPV Systems, appropriate crops can be identified. However, there is limited information in the literature on the DLI requirements for various crops. Hence, future research should focus on determining the DLI requirements for field crops, enabling the selection of suitable crops for AgriPV systems *(Santra et al., 2021)*.

Although ground-mounted photovoltaic (PV) arrays reduce the availability of PAR, they positively impact the water and energy balance in the field. Limited exposure of the ground surface to direct sunlight in AgriPV reduces evapotranspiration losses and ground heat flux. Consequently, the shade provided by PV structures in AgriPV modifies the soil hydrothermal regime and enhances the efficiency of applied irrigation water. *Marou et al. (2013b)* reported a reduction in actual evapotranspiration by 10-30% in AgriPV system, where light availability was 50-70% of full sun irradiation. To increase, water use efficiency in AgriPV, suitable crops with light requirements that match the available DLI should be selected *(Santra et al., 2021)*.

The available values of PPFD and DLI are critical for optimizing crop performance in AgriPV Systems *(Santra et al., 2021)*. Future research should aim to determine the optimal PPFD and DLI requirements for various field crops and high-value horticultural crops under open field conditions. DLI maps, corresponding to four critical days in a year, will facilitate the calculation of areas and durations where the DLI exceeds the minimum value required for growing specific crops. This will not only help in selecting suitable crops for AgriPV Systems but also help to achieve maximum yield from these systems.

8.1.5 Light Saturation Point (LSP)

Plants require adequate sunshine hours, PAR, and LSP to produce a good amount of biomass or yields *(Gayathri et al., 2023)*. The light compensation point is the minimum light intensity at which the rates of photosynthesis and respiration are equal. Net photosynthesis increases linearly with rising light intensity within the light-limited region. Beyond this point, photosynthesis reaches a plateau (photo-saturation) and then declines with excessive light intensity. This is known as photo-inhibition.

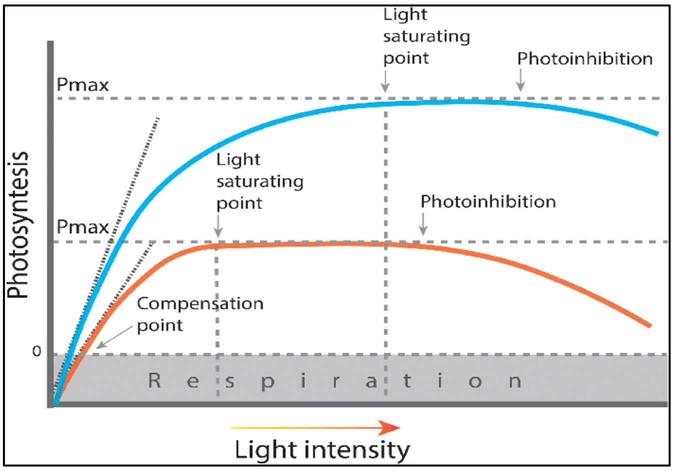


Figure 39: Light response curve for photosynthesis (Gayathri et al., 2023)

The light intensity at which photosynthesis equals the availability of photosynthetically active radiation (PAR) up to a certain threshold value is known as the light saturation point (LSP). Beyond this threshold, any excess intensity of PAR does not further increase the rate of photosynthesis. The LSP is a crucial factor in determining the shading ratio of photovoltaic (PV) modules and identifying specific crops that can be cultivated under such a system. Crops with a lower LSP can tolerate shading without any reduction in yields *(Figure 39)*. The LSP is generally higher for C4 crops compared to C3 crops. Shading is not solely a limiting factor but can also be beneficial, as it reduces crop water demand during hot summer periods.

8.1.6 Photo Thermal Unit (PTU)

A Photo-Thermal Unit (PTU) combines the average length of a day and the sum of degree-days. It is used to measure the time between a plant's emergence and flowering. It can be used to the measure the environment in terms of heat energy and the timing of plant developmental stages *(Kasirajan et al., 2021)*.

PTU is calculated by multiplying GDD with the maximum possible sunshine hours in a day *(YADAV, 2023)*. This is expressed as °C Day hour:

$$PTU = GDD \times N$$

Where, N is the maximum possible sunshine hour

8.2 Importance of Growing Degree Days in AgriPV

Temperature (T) is a key environmental factor influencing crop growth, development, and yield, particularly the rate of development. Each crop has a specific temperature requirement to complete a given phenophase or its entire life cycle. The base temperature (or minimum temperature) is the lowest temperature at which plant development ceases. At or below this threshold, leaf growth and progression toward flowering stop. As temperatures rise above the base temperature, plant development accelerates.

By using base temperature along with plant canopy temperatures (maximum and minimum), the Growing Degree Days (GDD) for different crop growth stages can be calculated. The "GDD for optimum plant growth" refers to the range of Growing Degree Days within which a plant species achieves its best growth rate. This range is determined based on the base temperature, below which no growth occurs, and is calculated by accumulating daily average temperatures exceeding the base temperature throughout the growing season. The optimal GDD varies by crop species. Therefore, the temperature beneath solar panels should be regulated to ensure that the base temperature required for crop growth is maintained. Variations in temperature can influence flowering time and harvesting periods. GDD and base temperature data for different crops have been gathered from previous studies, as shown below.

Table 18: GDD of different crops to maturity

Crop	Base temperature (°C)	GDD to maturity (°C)
Beans	10.00	648.88-704.44
Corn	10.00	1204.44-1537.78
Cotton	15.56	1037.78-1371.11
Peas	4.44	593.33-648.89
Rice	15.56	926.67-1148.89
Wheat	4.44	1148.89-1315.56
Barley	5	1537–1665
Oat	4	1482–1737
Mustard	15-25	1508–1610
Chickpea	4.5	1678–1802
Peanut	12-13	1560
Sunflower	6.7	1780–1971
Sorghum	12	1415
Pearl millet	10	905
Maize	10	1750
Rice	8	2800
Dry beans	9	1200
Pepper	10	1700
Tomato	7	1700
Sesame	10	1580

(Source: Mohamed et al., 2023; STM Weather, 2021)

8.3 Base Temperature

The base temperature for crops, also known as the minimum temperature, is the lowest temperature at which a crop begins to grow. The base temperature helps to determine the germination and growth of plants. Different crops have varying base temperatures, which means that each crop requires a specific minimum temperature to start its growth process. For instance, peas have a base temperature of around 4-5°C, and they will not begin to grow until the soil temperature reaches this level. The base temperature also plays a crucial role in calculating GDD, a measure of heat accumulation used to predict the development rates of plants. GDD helps farmers to decide optimal planting times and predict harvest dates, ensuring that crops grow under the best possible conditions.

Additionally, understanding the base temperature is essential in protecting crops from frost damage. Crops exposed to temperatures below their base temperature can suffer delays in growth or even damage. Knowledge of base temperatures enables farmers to optimize planting schedules and maximize yield and quality by ensuring crops are grown under optimal conditions. Moreover, it assists in selecting suitable crops for different climates, as crops with lower base temperatures are better suited for cooler regions, while those with higher base temperatures grow in warmer areas. By understanding and applying the concept of base temperature, farmers can make informed decisions that enhance crop productivity and sustainability.

The base temperature for different crops is presented below:

Table 19: Base temperature of various crops

Sr. no.	Crops	Base Temperature (˚C)
1	Spinach	2.2
2	Lettuce	4.4
3	Peas	5.5 (Agriculture Canada, 1977) 4.5 (Grigorieva et al., 2010) 5 (Grigorieva et al., 2010)
4	Asparagus	5.5
5	Corn Corn hybrids	10 (Agriculture Canada, 1977) 11.1 (Grigorieva et al., 2010)
6	Bean	10
7	Pumpkins	13
8	Tomatoes	13 (Agriculture Canada, 1977) 10 (Grigorieva et al., 2010) 7 (Luo, 2011)
9	Oats	4.5
10	Brussels sprouts	0
11	Parsley	0
12	Cabbage	0
13	Winter Wheat	0

14	Perennial forage crops	5
15	Wheat	5.5
16	Perennial forage crops (pasture grasses)	5.5
17	Potatoes	7
18	Soyabean	10 (Grigorieva et al., 2010) 6 (Luo, 2011)
19	Sugar beet	10
20	Sunflowers	10 6.7 (Mohamed et al., 2023)
21	Rice	8
22	Sorghum	8
23	Broccoli	0
24	Citrus	13
25	Peanut	10
26	Cotton	14
27	Maize	10 (Mohamed et al., 2023)
28	Dry beans	9
29	Pepper	10
30	Sesame	10
31	Cucumber	13
32	Eggplant	15.5
33	Muskmelon	10
34	Onion	1.7
35	Okra	15.5
36	Squash	7
37	Strawberry	3.3
38	Sweet potato	15.5
39	Watermelon	13
40	Carrot	4.4
41	Garlic	4.4
42	Turnip	4.4
43	Celery	4.4
44	Parsley	4.4

(Source: Luo, 2011; Grigorieva et al., 2010; Agriculture Canada, 1977)

8.4 Methodology for Development of Crop Matrix

The crop matrix was developed based on the information available in literature. The following steps were followed:

a) **Collection of crop data** - Identification of crops suitable for cultivation across different Indian states. Data on major crops, including cereals, pulses, vegetables, fruits, flowers, medicinal plants, spices, and cash crops, were gathered.

b) **Selection of major crops** - Identifying major crops grown across India.

c) **Collection of PAR/PPFD of major crops-** Photosynthetically Active Radiation (PAR) or Photosynthetic Photon Flux Density (PPFD) data for major crops were collected from various online sources, including research papers and websites.

d) **Analysis of Sunshine Duration -** Identification of spatial and temporal variations in average sunshine duration (photoperiod) across India.

e) **Calculation of DLI-**The DLI was calculated using PPFD and photoperiod using the formula:

$$DLI = PPFD * Photoperiod * 0.036$$

Where, DLI is in mol/m²/day; PPFD is in µmol/m²/s Photoperiod is in hours

f) **Collection of crop height data**- Collection of Crop Height Data – Crop height was considered as a key factor for cultivation under AgriPV systems. Since the standard height of solar panels in AgriPV systems is 2.1 meters, crop selection should be based panel height to prevent obstruction of growth and shading effect of vegetation on panels.

g) **Compilation of data-** Data on major crop, PAR, DLI, and crop height were compiled to classify crops based on their suitability for cultivation under AgriPV systems.

h) **Zoning of area under AgriPV systems** - Dividing the land into Zone 1 (Area under panels with significant shading) and Zone 2 (Area between panels with more direct sunlight).

i) **Classification of crops** - Crops were allocated to the respective zones based on their shade tolerance and light requirements.

j) **Development of the final crop suitability matrix** - Crops were assigned to specific zones by considering factors such as PAR, DLI and crop height and regional climatic conditions.

8.4.1 Major crops across agro-climatic zones in India

India is divided into 15 agro-climatic zones based on soil types, climate, physiography, and cropping patterns. These zones were identified by the Planning Commission of India to optimize agricultural planning and resource utilization. The 15 Agro Climatic Zones are referred to as Western Himalayan (WH), Eastern Himalayan (EH), Lower Gangetic Plain (LGP), Middle Gangetic Plain (MGP), Upper Gangetic Plain (UGP), Trans Gangetic Plain (TGP), Eastern Plateaus & Hills (EPH), Central Plateau Hills Region (CPH), Western Plateau Hills (WPH), Southern Plateau Hills Region (SPH), East Coast Plains (ECP), West Coast Plains (WCP), Gujarat Plain Hills (GPH), Western Dry (WD) regions, and Island region (Mall et al., 2021). Moreover, the following *Table 20* provides data of the major crops cultivated in different agro-climatic zones in India, compiled from state agricultural departments and literature-based studies. This information serves as a basis for understanding the crop patterns across these regions and selecting crops best suited for cultivation under the AgriPV system in a given state, considering the region's specific climate, soil, and weather conditions.

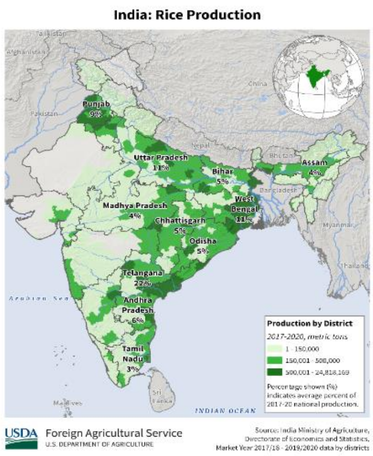
Table 20: Major crops cultivated across agro-climatic zones in India

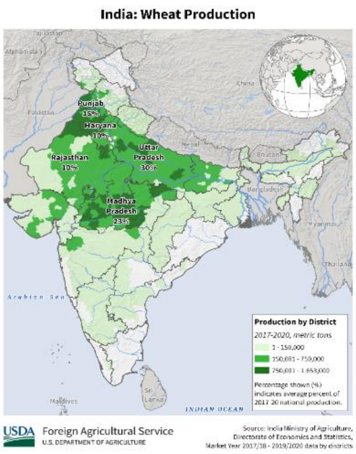
Zone	Agro-climatic zone	States represented	Major crops	Remarks
1	Western Himalayan region	Himachal Pradesh, Jammu & Kashmir, Uttarakhand	Apples, Walnuts, Pears, Plums, Peaches, Cherry, Almond, Litchis, Barley, Oats, Rice Maize, Wheat, Saffron	Major horticultural zone, high potential for medicinal plants
2	Eastern Himalayan region	Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, West Bengal	Rice, Maize, Potato, Tea, Jute, Ginger, Pineapple, Orange, Lime, Wheat, Rapeseed & Mustard	Rich biodiversity, potential for plantation crops and spices
3	Lower Gangetic plain region	West Bengal	Rice, Jute, Maize, Sugarcane, Potato, Pulses, Wheat, Banana, Mango, Citrus, Rapeseed & Mustard	High irrigation potential, pisciculture, poultry, forage production, and seed supply
4	Middle Gangetic plain region	Uttar Pradesh, Bihar	Wheat, Rice, Pulses, Sugarcane, Maize, Millets, Gram, Barley, Peas, Mustard, Potato, Rapeseed & Mustard	Prone to flood,
5	Upper Gangetic plain region	Uttar Pradesh	Wheat, Sugarcane, Rice, Millets, Maize, Gram, Barley, Oilseeds, Pulses, Cotton, Sorghum, Rapeseed & Mustard	High irrigation usage: sugarcane dominates cropping pattern
6	Trans Gangetic plain region	Chandigarh, Delhi, Haryana, Punjab, Rajasthan	Wheat, Rice, Cotton, Sugarcane, Gram, Maize, Millets (pearl millet), Pulses, Oilseeds, Rapeseed & Mustard	High mechanisation, intensive use of fertilisers
7	Eastern plateau and hills region	Chhattisgarh, Jharkhand, Madhya Pradesh, Maharashtra, Odisha, West Bengal	Rice, Millets, Maize, Oilseeds, Ragi, Gram, Potato, Tur, Groundnut, Soybean, Urad, Castor, Linseed	High forest cover, rainfed agriculture
8	Central plateau and hills region	Madhya Pradesh, Rajasthan, Uttar Pradesh	Soybean, Wheat, Gram, Jowar, Pulses, Millets, Cotton, Sunflower, Sorghum, Maize, Groundnut, Rapeseed & Mustard	Major soybean producing zone
9	Western plateau and hills region	Madhya Pradesh, Maharashtra	Cotton, Sugarcane, Groundnut, Pulses, Bajra, Wheat, Gram, Millets, Rice, Orange, Banana, Grape, Sorghum, Rapeseed & Mustard	Major cotton growing region

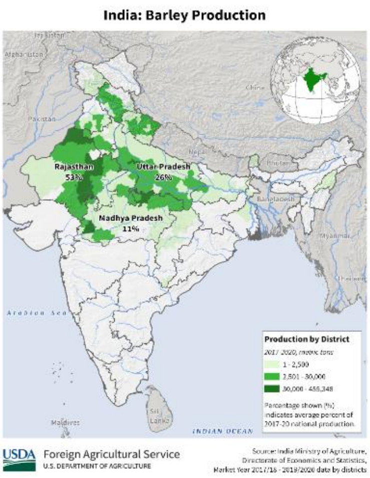
10	Southern plateau and hills region	Andhra Pradesh, Karnataka, Tamil Nadu	Groundnut, Millets, Cotton, Pulses, Rice, Oilseeds, Coffee, Tea, Cardamom, Spices, Linseed	Rainfed agriculture
11	East coast plains and hills region	Andhra Pradesh, Odisha, Puducherry, Tamil Nadu	Rice, Jute, Tobacco, Maize, Coconut, Sugarcane, Cashew, Groundnut, Rapeseed & Mustard	High fishery potential, prone to cyclones
12	West coast plains and ghat region	Goa, Karnataka, Kerala, Maharashtra, Tamil Nadu	Coconut, Arecanut, Rice, Spices, Cashew, Oilseeds, Sugarcane, Millets, Pulses, Cotton, Finger Millet, Rapeseed & Mustard	Plantation crops and spices
13	Gujarat plains and hills region	Gujarat, Dadra & Nagar Haveli, Daman & Diu	Cotton, Groundnut, Wheat, Bajra, Rice, Millets, Oilseeds, Tobacco, Rapeseed & Mustard	Salt-affected soils, high drought resilience.
14	Western dry region	Rajasthan	Bajra, Pulses, Oilseeds, Guar, Cumin, Wheat, Gram, Pearl millet, Rapeseed & Mustard	a high potential for arid-zone agriculture.
15	Island region	Andaman & Nicobar Islands, Lakshadweep	Coconut, Rice, Spices, Tropical Fruits, Maize, Arecanut, Turmeric, Cassava	High potential for fisheries and marine products, agroforestry and horticulture

(Source: Guru, 2025; Vishal, 2022, Singh et al., 2020, and agricultural departments of various states)

India is a major agricultural producer, growing crops like rice, wheat, maize, pulses, and sugarcane, cotton. Understanding these trends is crucial for planning and implementing region-specific agricultural strategies. The production of major crops are shown in *(Figure 40)*.







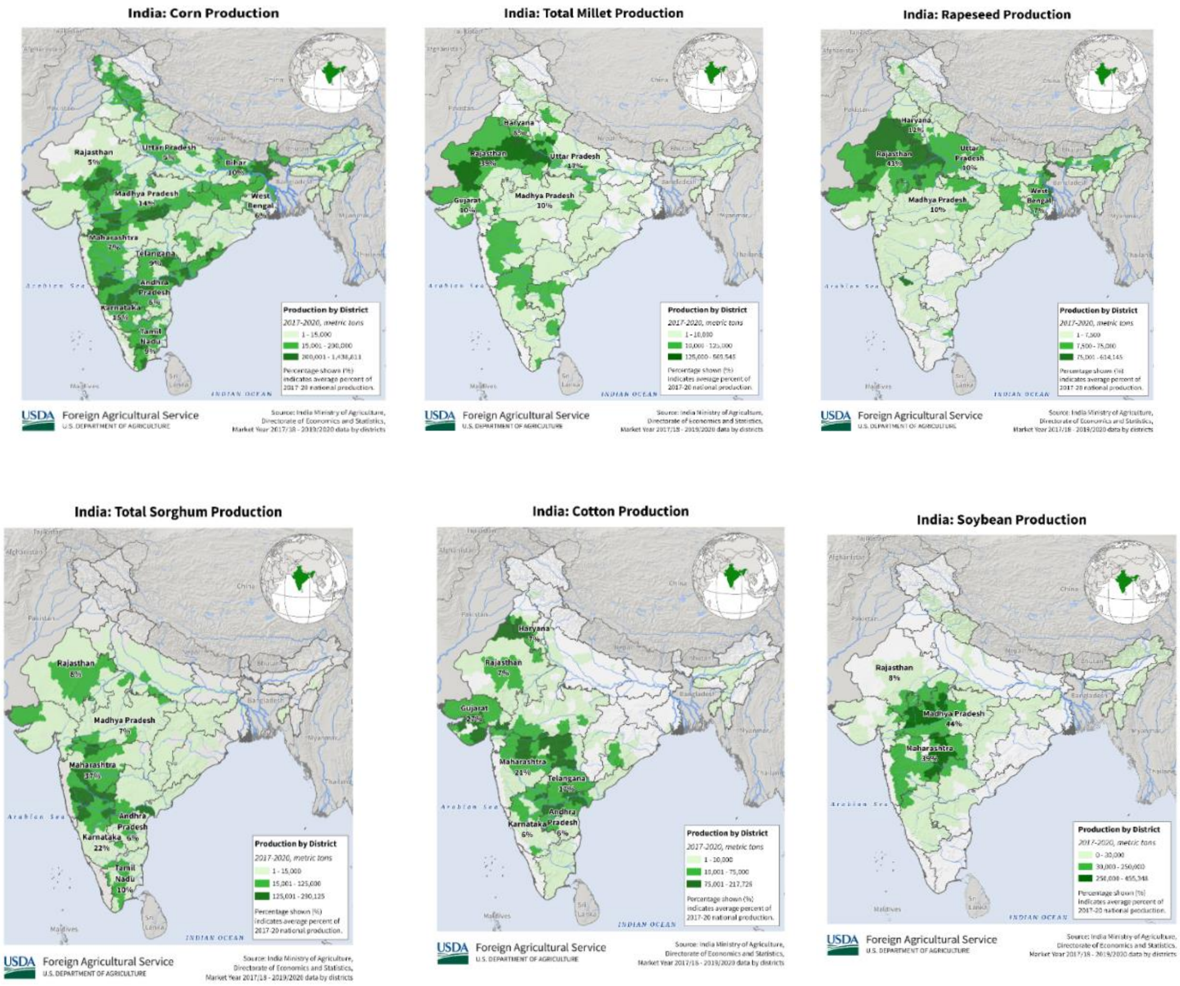


Figure 40: Average production of major crops in India
(Source: USDA_India Production)

8.5 Dynamics of Photoperiod in India

One of the key factors in calculating the Daily Light Integral (DLI) using Photosynthetic Photon Flux Density (PPFD) is the photoperiod which is the duration of the light phase within a 24-hour period. Photoperiod plays a crucial role in regulating various aspects of plant growth, including vegetative development and flowering *(Roeber et al., 2022; Osnato et al., 2022)*. It varies significantly depending on geographic location and time of year due to the Earth's axial tilt, which alters the positions of sunrise and sunset throughout the seasons. Understanding photoperiod dynamics is essential for successful crop production, as it influences plant responses, seasonal variations, and potential modifications to optimize growth. To determine the natural photoperiod for a specific location, one can use sunrise and sunset data and adjust for structural shading by deducting a portion of the total sunshine hours based on the type of structure and its shading percentage.

In India, photoperiod varies considerably across the country due to its vast latitudinal spread. Northern regions experience longer daylight hours in summer compared to southern regions, resulting in significant spatial and seasonal variations in photoperiod. Latitude is the primary factor affecting these changes, with areas closer to the equator maintaining relatively stable daylight hours throughout the year, while northern regions experience more pronounced seasonal shifts *(Journey North, 2024)*. The annual cycle includes two solstices: one in June and one in December. The June solstice marks the longest day of the year in the Northern Hemisphere and the shortest day in the Southern Hemisphere *(Bikos et al., 2025)*.

Northeastern regions of India are exposed to intense radiation much earlier in the day compared to other parts of the country. In fact, the intensity of solar radiation in the early morning hours there is equivalent to the radiation levels typically observed at noon (12:00 hours) in other regions of India *(Patil et al., 2021)*.

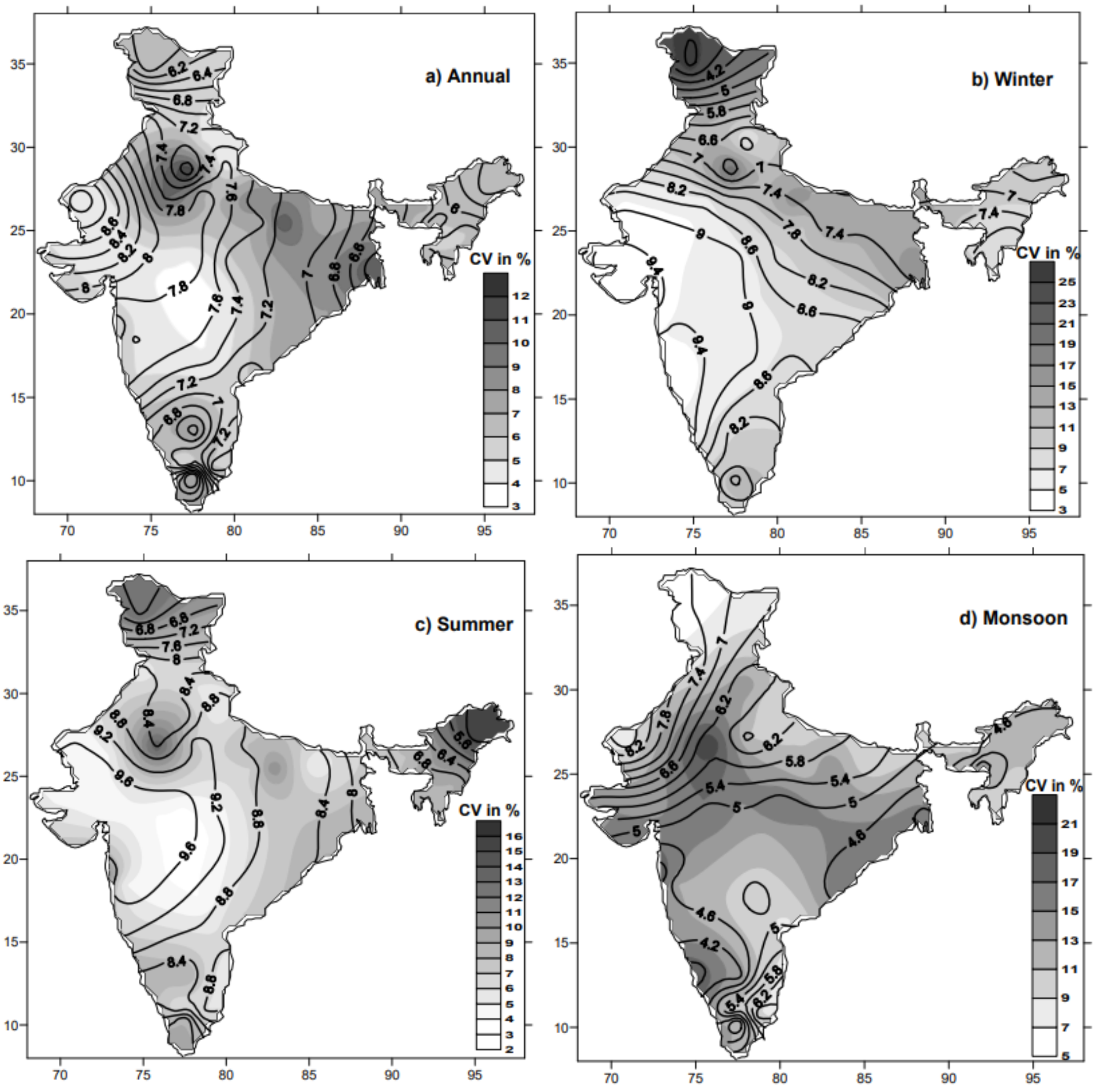


Figure 41: Geographical variation of sunshine duration in India for (a) annual, (b) winter, (c) summer, (d) monsoon (Contour lines represent sunshine duration, in hours)
(Source: Jaswal, 2009)

The *figure 41* shows the temporal and seasonal variation of average sunshine duration in India. Distribution of annual mean sunshine hours which is highest (>8.6 hours/day) over western Rajasthan and adjoining areas in north Gujarat. Regions of least amount of sunshine are over north Kashmir and northeastern states *(Jaswal, 2009)*. These dynamics of photoperiod should take into consideration while calculating DLI from PPFD. Considering the variation overall India, an average sunshine duration of 8 hrs for open field conditions was considered while preparing the crop matrix.

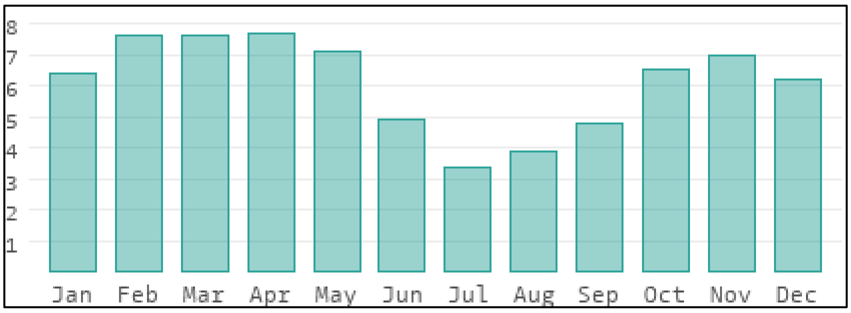


Figure 42: Hours of sunshine per day in India (Source: World Data, 2025)

8.6 Key Parameters of Major Crops in India

The key parameters for developing the crop matrix include light intensity (measured as PPFD in µmol m^{-2} s^{-1}), daily light integral (DLI), and crop height. These factors are essential in selecting crops that can grow well under AgriPV system by enhancing both solar energy and crop production. The data for various crops in India and their key parameters, obtained from a thorough literature survey, are presented in *Table 21*. Likewise, a detailed discussion of these parameters is provided in *section 8.1*.

Table 21: Factors considered for crop matrix

Crop	**Light intensity (µmol m^{-2} s^{-1}) PPFD**	**DLI (mol m^{-2} s^{-1})**	**Height of crops (m)**	**Remarks**
Cereals				
Rice	1400 - 1800	40.32- 51.84	1	400 µmol/m^2/s PPFD reduces 30–50% net photosynthesis, ultimately reducing yield by 34–55%
Wheat	400 - 800	11.52-23.04	1	
Maize	1200 - 1500	34.56-43.20	1.5-2	
Millets	1200 - 3000	34.56-86.4	1.5	
Legumes: Cowpea Pigeon pea	450 - 900	11.52-25.92	0.4	PPFD of less than 450 µmol m^{-2} s^{-1} appeared to be detrimental for growth, nutrient and water use efficiency and photosynthesis of tropical perennial legume cover crops *(Baligar et al., 2020)*
Vegetables				
Lettuce	250 - 290	6.9-15.6	0.3	Light intensity of 350–500 is recommended at low temperatures (15 °C) Light intensity of 350–600 is recommended at medium temperatures (23 °C)

				The range of 500 to 600 is a recommendable light intensity for lettuce grown at high temperatures (30 °C)
Tomato	450 – 750	22-30	0.6-1.2	Light saturation- 1610 (https://nettingland.com/how-to-choose-the-shade-rate-for-crops/)
Spinach	150 - 190	4.32-5.47	0.3	LSP- 1238 *(Erwin and Gesick, 2017)*
Broccoli	250-350	8-16	0.3	
Eggplant	300 - 600	20-30	0.8	
Capsicum	280-600	20-30	0.7	
Cabbage	70-90		0.4	Photoperiod: 14~16 $h \cdot d^{-1}$
Pumpkin	300 – 650	18-28	0.4	
Onion	400-600	11.52-17.28	0.3-0.5	LSP-504 *(Professional, 2023)*
Potato	400-800	11.52-23.04	0.6	
Garlic	200 – 400	15	0.3	
Ginger	60 – 180	12	0.91-1.22	
Okra	200 – 300	5.76 – 8.64	1.20-1.25	
Cauliflower	200 – 300	9-15	0.4	
Sweet Potato	150-300	4.32-8.64	0.4	LSP-504 *(Professional, 2023)*
Radish	150 -180	4.32-5.18	0.3	
Kidney bean	200 – 400	5.76 – 11.52	0.4	LSP-336 *(Professional, 2023)*
Soyabean	300 - 500	8.64-14.40	0.5-1	LSP-420 *(Professional, 2023)*
Elephant foot Yam	1500	43.20	1.5-2.5	
Mushroom	10-40	0.29-1.15		
Leafy vegetables	100-300	2.88-8.64	0.3-0.5	Photoperiod – 10-18 hrs
Lemon	300 – 600	21-28	2-4	
Peas	150 – 300	9-12	0.5	
Peppers *Capsicum annuum*	300 – 600	20-30	0.7	
Medicinal plants				
Basil	250 -500	12-26	0.30-1.50	
Turmeric	173	9	1	
Mint	200 – 400	10-16	0.50-0.60	
Oregano	300 – 600	20-28	0.20	
Moringa	500 - 800	14.40-23.04	1-2	
Lemon grass	500 - 800	14.40-23.04	0.61-1.22	
Fruits				
Watermelons	250-350	25-30	0.4	LSP-1344
Pineapple	350 – 700	15-30	0.6-1.25	
Orange	500 – 700	22-30	2-4	
Grapefruit	500 – 700	22-30	1.5-2	
Avocado	400 – 650	8-16	3	
Blackberry	200 – 300	10-16	1.5	

Blueberry	400 – 700	10-16	1.5	
Orange	500 – 700	22-30	2-4	
Peach	200 – 300	10-16	3	
Pineapple	350 – 700	15-30	0.6-1.2	
Pumpkins	300 – 650	18-28	0.4	
Strawberry	400 – 600	17-28	0.2	
Avocado	400 – 650	8-16	3	
Apple			4	
Flowers				
Anthurium	80 – 400	12-16	0.30-0.45	
Orchids (Low-Light)	40 – 80	8-16	0.025-4.6	
Orchids (Moderate-Light)	80 – 150	4-8	0.025-4.6	
Petunias	300 – 400	16-18	0.30-0.38	
Hibiscus	80 – 500	4-14		
Chrysanthemum	40-80	10-14		
Geranium	40-80	1.15-2.30		
Orchids	40-120	8-16		
Moderate-Light Orchids (Onc, Phrags, Epidens, Dends etc)	80-150	4-8		(https://herebutnot.com/light-recommendations-ppfd-par-for-orchids-and-houseplants/)
High-Light Orchids (Cattleya)	50-100	1.44-2.88		
Very High-Light Orchids (Vandas)	350–600	10.08-17.28		
Anthurium	80-150	4-14		(https://plantelys.dk/en/how-many-%C2%B5mol-does-my-plant-need-to-thrive/)
Rose	170-350	18-22		
Lilies	80-130	4-14		
Gerbera	80-120	2.30-3.46		
Tulip	25-90	0.72-2.59		
Begonia spp.	20-40	0.58-1.15		Shade plants (Link)
Lily	90	2.6		
Cash crops				
Cotton			1.2-1.5	LSP-420 *(Professional, 2023)*
Coffee	500	14.40	2-3	
Tea			1.5-2	
Oilseed crops				
Mustard	250 – 650	7.22-18.72		
Sessame			1	
Groundnut			0.4	
Castor				

8.7 Structured Crop Matrix for Implementation

For the preparation of final crop matrix crops were classified considering the data of factors given above. Crops were assigned into two different zones (Zone 1 and zone 2) of AgriPV set up mainly considering their light requirement for optimum growth. Crops that can be cultivated under solar panels are typically suitable for lower PPFD levels, meaning they can tolerate moderate shade, with ideal ranges generally falling between 200 - 400 µmol m^{-2} s^{-1}. The PAR value that is necessary for normal plant development varies with the considered species *(Moretti & Marucci, 2019)*.

8.7.1 Classification of Plants Based on DLI *(Moe, 1994)*:

- **Low light crops:** DLI between **5-10 mol/m² per day**
- **Medium light crops:** DLI between **10-20 mol/m² per day**
- **High light crops:** DLI between **20-30 mol/m² per day**

Crop height is also a crucial consideration, ensuring that plant shading does not interfere with solar power production.

8.7.2 Additional Considerations:

Light Intensity & Temperature *(Zhou et al., 2022)*

- Low temperatures (15°C): Recommended light intensity 350–500 µmol·m−2·s−1
- Medium temperatures (23°C): Recommended light intensity 350–600 µmol·m−2·s−1
- High temperatures (30°C): Recommended light intensity 500–600 µmol·m−2·s−1

Classification Based on Light Intensity *(Bodolan & Bratucu, 2013)*:

- Demanding plants (184-276 µmol m−2 s−1): Solanaceous, cucurbits, beans, okra
- Less demanding plants (92-161 µmol m−2 s−1): Root vegetables, bulb vegetables, cabbage, leafy peas
- Plants with small light requirements (23-69 µmol m−2 s−1): Green onions, perennial onions, beet leaves
- Plants that do not require light during edible part growth: Cauliflower, chicory, asparagus, mushrooms

8.7.3 Crop matrix for AgriPV system

The developed crop matrix for AgriPV system is presented in Table 22 and Figure 42:

Table 22: Crop matrix for AgriPV system

Zone 1 (Under panels)	**Zone 2 (Between panels)**
(PPFD: upto 400 µmol $m^{-2}s^{-1}$; Crop Height: 1–2m, DLI: 0-12 mol $m^{-2}s^{-1}$)	(PPFD: 400 and above µmol $m^{-2}s^{-1}$, Crop Height: 2 and above, m)) (Lower shading, suitable for high-light crops)
Horticultural: Blackberry, Blueberry, watermelon, strawberry, **Vegetables:** Lettuce, tomato, spinach,	**Cereals:** Rice, wheat, maize, millets, legumes (Cowpea, pigeon pea) **Horticultural:** avocado, pineapple, orange,

broccoli, eggplant, capsicum, cabbage, pumpkin, garlic, ginger, cauliflower, sweet potato, radish, kidney bean, soybean, leafy vegetables, peas, peppers, mint, **Flowers:** anthurium, petunias, hibiscus, chrysanthemum, orchids, roses, lilies, gerbera, tulip, begonia, geranium, **Medicinal:** aloe vera, basil, oregano, turmeric	grapefruit, peach, apple, **Vegetables:** tomato, eggplant, capsicum, onion, pumpkin, potato, okra, elephant foot yam, lemon, **Medicinal:** moringa, lemongrass, **Oilseeds:** mustard, castor, sesame, **Cash crops:** cotton, coffee, tea

Figure 43: Crop matrix for AgriPV system

Crop matrix was developed from literature-based studies and insights gained from the visit to AgriPV pilot projects. This will be helpful to farmers, stakeholders, and developers in selecting suitable crops for AgriPV systems across different agro-climatic zones in India. However, there is a need for conducting intensive research and to develop crop matrix through findings from AgriPV pilots in different agro-climatic zones in India.

Future development of the crop matrix will be based on data obtained from field studies conducted over a few years for AgriPV systems across various pilot plants in different agroclimatic zones in India. This extended research will provide comprehensive insights into crop performance under AgriPV conditions, enabling more precise recommendations for crop selection in diverse environmental contexts.

8.8 Instruments for Monitoring Plant Health and Environmental Conditions in AgriPV Systems

Monitoring plant health and microclimate conditions is essential for optimizing cultivation under AgriPV. Although may of these instruments are costly, especially given that AgriPV is still in its early stages in India, their use in ongoing research can help generate valuable data. This data can be further utilized for modelling and simulation studies, ultimately improving system efficiency. Below are some of the key instruments commonly used in AgriPV research and applications:

8.8.1 InfraRed Gas Analyzer (IRGA) photosynthesis system

In an AgriPV system, measuring the photosynthetic rate helps to assess how efficiently plants use light for photosynthesis, especially under the shade of solar panels. This is achieved by measuring the light reaching the plants (PPFD) and monitoring the intake of CO_2 and the release of oxygen from the leaves.

The InfraRed Gas Analyzer (IRGA) Photosynthesis System is an advanced electronic scientific instrument designed for the non-destructive measurement of photosynthetic rates directly in the field. Rather than being a single instrument, the system is an integrated assembly of various instruments used to measure essential parameters such as carbon dioxide (CO_2), water vapour (H_2O), air and leaf temperature, flow rate, photosynthetically active radiation (PAR), and pressure. These measurements are crucial for calculating photosynthesis rate, transpiration rate, and stomatal conductance. The heart of this instrument is CO2 and H2O measuring instrument called infrared gas analyser or IRGA. Therefore, the photosynthesis system is simply called IRGA. The main components of a photosynthesis system include a leaf chamber, the IRGA unit, power supply (batteries), and a console equipped with a keyboard, display, and memory for data handling. Some advanced systems also feature modules for controlling light and temperature, enabling to assess the impact of these environmental factors on photosynthesis. During operation of the system, the leaf intended for analysis is placed in the leaf chamber, and the IRGA measures the CO_2 concentration to assess photosynthetic activity.

Principle:

The main function of an IRGA is to detect and measure the concentration of carbon dioxide (CO_2). It is highly sensitive and capable of detecting changes as small as 1 part per million (ppm) in CO_2 levels. To assess CO_2 fluxes, a leaf or plant is placed inside a sealed chamber, and the changes in CO_2 concentration within the chamber air are monitored. IRGAs are also used to measure a variety of heteroatomic gas molecules, including CO_2, H_2O, NH_3, and N_2O. These gases have unique absorption spectra in the infrared (IR) region. The amount of IR radiation absorbed by a specific gas is directly related to its concentration in the air, in accordance with Beer-Lambert's law. CO_2 has a primary absorption band at 4.25 µm, along with secondary absorption peaks at 2.66 µm, 2.77 µm, and 14.99 µm. among the gases typically present in the atmosphere, only water vapor has an IR absorption spectrum that overlaps significantly with that of CO_2. As a result, it is important to minimize water vapor interference during CO_2 measurements.

Measurement of photosynthesis

Two commonly used types of IRGA systems for measuring photosynthetic rate are the closed system and the open system. In a closed system, a leaf is enclosed within a chamber where the air is recirculated around it. The rate of photosynthesis is calculated based on the reduction in CO_2 concentration over time. In an open system involves continuously passing ambient air through the chamber containing the leaf. The photosynthetic rate is determined by comparing the CO_2 concentration of the air before it enters the chamber and after it exits. Unit of rate of photosynthesis is micro mole/m2/sec. Examples of such systems include CI-340 Hand-Held Photosynthesis System and LI-6400XT Portable Photosynthesis System.

Figure 44: LI-6400XT Portable Photosynthesis System (Source: LI-6400/XT | the System Components, n.d.)

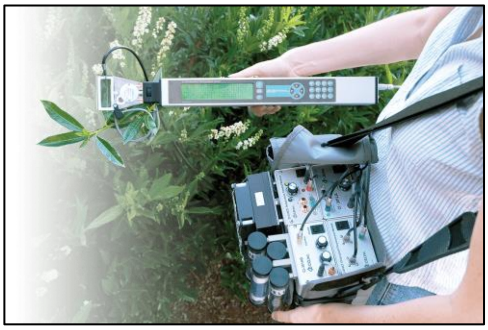


Figure 45: CI-340 Hand-Held Photosynthesis System
(Source: CID Bio-Science Portable Instruments for Precision Plant Measurement Inc., n.d.)

8.8.2 Non-Contact Infrared (IR) thermometer

A non-contact infrared (IR) thermometer is an instrument to measure the surface temperature of opaque objects without physical contact. This device operates by detecting infrared radiation emitted by the surface of an object. It consists of a lens that focuses the infrared radiation onto a detector, which converts the radiation into an electrical signal. This setup allows for accurate temperature readings from a distance, making it especially useful in situations where traditional contact-based sensors like thermocouples or probes cannot be used.

Temperature Calculation

The device calculates the temperature of the object using the measured infrared radiation and the known emissivity of the surface. This process is based on the Stefan-Boltzmann law, which relates the amount of emitted infrared radiation to the temperature of the object. Examples of IR thermometer are 1. Fluke Non-Contact Infrared (IR) thermometer and Apogee Infrared (IR) Thermometer Sensor.

Figure 46: Fluke Non-Contact Infrared (IR) thermometer (Source: Fluke, n.d.)

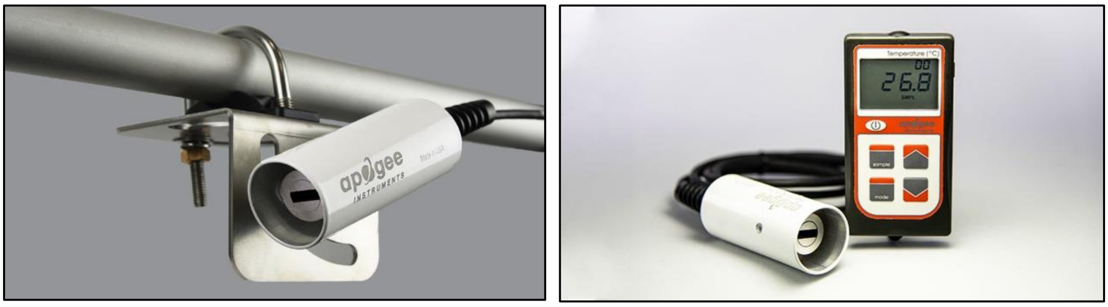


Figure 47: Apogee Infrared (IR) Thermometer Sensor
(Source: SI-1H1-SS: Research-Grade Horizontal Field of View Infrared Radiometer Sensor, n.d.; MI-2H0: Research-Grade Horizontal Field of View Infrared Radiometer with Handheld Meter, n.d.)

8.8.3 Infrared thermal imaging cameras

Infrared thermal imagers detect and measure the infrared radiation emitted by an object and convert it into a visual representation of surface temperature. The device uses an optical system to focus infrared light onto a specialized detector chip, known as a sensor array, which contains thousands of pixels arranged in a grid. Each pixel responds to the incoming infrared radiation by generating an electrical signal. The camera's processor in the camera collects these signals and performs calculations to create a colour coded temperature map, where each colour represents a specific temperature value. This thermal map is stored in memory and displayed as a thermal image, visually illustrating the temperature distribution across the surface of the object.

Thermal imaging cameras are widely used in agriculture for a variety of applications, including monitoring plant health, scheduling irrigation, detecting diseases, estimating fruit yield, assessing water distribution in drip irrigation systems, and tracking canopy temperature. By continuously capturing thermal images, these cameras give useful information on how irrigation practices and environmental factors affect crop water stress and overall plant condition. FLUKE Infrared thermal imaging camera is an example.

Figure 48: Fluke TiX1060 Thermal Camera *(Source: Fluke, n.d.-b)*

8.8.4 Vane anemometer

A Vane anemometer is a handheld instrument used to measure wind speed, volumetric airflow and temperature. It consists of a small turbine or fan that rotates in response to air flow, along with a digital display that shows the measured values. The working principle of a vane anemometer is based on the relationship between wind speed and the rotation of the turbine. As air flows through the device, the turbine spins at a rate that is directly proportional to the wind velocity. After calibration, the anemometer converts the rotational speed of the turbine into a wind speed reading, which is then shown on the digital screen.

Examples of commonly used vane anemometers include the Fluke 925 Vane Anemometer and the HTC Digital Vane Anemometer.

Figure 49: (a) Fluke 925 Vane Anemometer (Source: Fluke, n.d.-c)
(b)HTC Digital Vane Anemometer (Source: HTC Instrument, 2024)

8.8.5 Plant canopy analyser

A Plant canopy analyser is a non-destructive tool used to measure the Leaf Area Index (LAI), which is a critical parameter for assessing the structure and growth status of plant canopies. The LAI is defined as the total leaf area per unit ground area, considering only one side of each leaf. This index provides valuable information about plant health, productivity, and biomass accumulation.

Some canopy analyser systems work by measuring Photosynthetically Active Radiation (PAR) within crop canopies. These systems capture both incident and transmitted PAR to estimate LAI and biomass production, offering direct readings of LAI on the device. Another widely used approach is the gap fraction method, which evaluates how much of the sky is visible from beneath the canopy. A higher gap fraction indicates more visible sky (less foliage), while a lower gap fraction suggests denser foliage. By assuming that leaves are randomly distributed, the amount of canopy foliage can be calculated based on the observed gap fraction.

An example of such a system is the SS1 SunScan Canopy Analysis System. This instrument determines LAI by measuring the ratio of transmitted to incident radiation through the canopy. It consists of a 1-meter probe embedded with 64 PAR sensors and connects to a handheld personal digital assistant (PDA) using an RS-232 cable. When a reading is taken, all sensors are scanned simultaneously, and the data is transmitted to the PDA for display and analysis.

Figure 50: SS1 SunScan Canopy Analysis System (Source: Delta-T, 2025)

8.8.6 Line quantum sensor

A Line Quantum Sensor is a portable, handheld device designed to measure Photosynthetically Active Radiation (PAR) within the wavelength range of 400 to 700 nm. This range corresponds to the portion of the light spectrum that plants use for photosynthesis. The sensor integrates PAR measurements over its entire 1m length, making it effective for capturing light conditions in areas where the light distribution is uneven, such as beneath plant canopies.

These sensors are commonly used to assess PPFD in a variety of settings, including outdoor agricultural fields, greenhouses, and controlled growth chambers. They are useful for measuring reflected light or light transmitted through plant canopies, providing data for evaluating plant light environments and optimizing growing conditions.

An example of such a device is the MQ-301X Apogee Line Quantum Sensor. This sensor provides a spatial average of PAR using a 1m sensor bar equipped with 10 individual sensors. The sensor bar is connected to a handheld meter through a cable, allowing users to easily view and record measurements in real time.

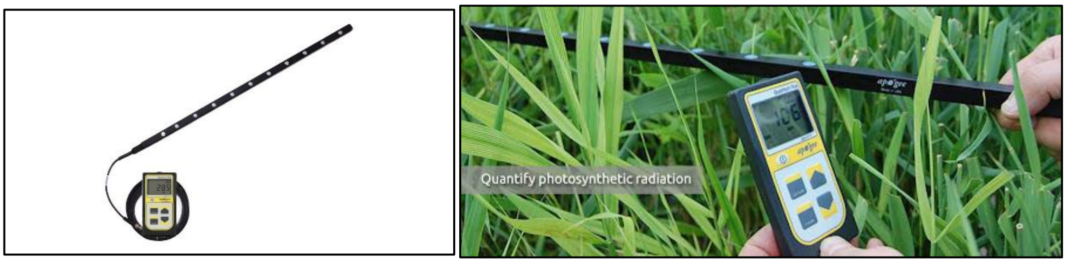


Figure 51: Apogee line quantum sensors (Source: MQ-301X: Line Quantum With 10 Sensors and Handheld Meter, n.d.; User, n.d.)

8.8.7 Albedometer

An albedometer is an instrument primarily used to measure the reflectance of the Earth's surface, known as albedo. This device plays an important role in evaluating thermal effects in buildings and assessing the energy generation potential of solar panels. The albedometer operates using two horizontally mounted pyranometers. One pyranometer faces upward to measure the incoming solar irradiance, while the other faces downward to measure the irradiance reflected from the surface. The readings are given in watts per square meter (W/m^2). These values are obtained by dividing the output voltage from each pyranometer by its specific sensitivity, allowing for accurate calculation of irradiance in both directions.

The upward-facing pyranometer measures global solar radiation (direct and diffuse sunlight), while the downward-facing one captures the amount of solar radiation reflected off surfaces. Together, they provide a reliable measurement of surface reflectivity or albedo. Some common examples of albedometers include the Apogee model SP-700 and instruments produced by Kipp & Zonen.

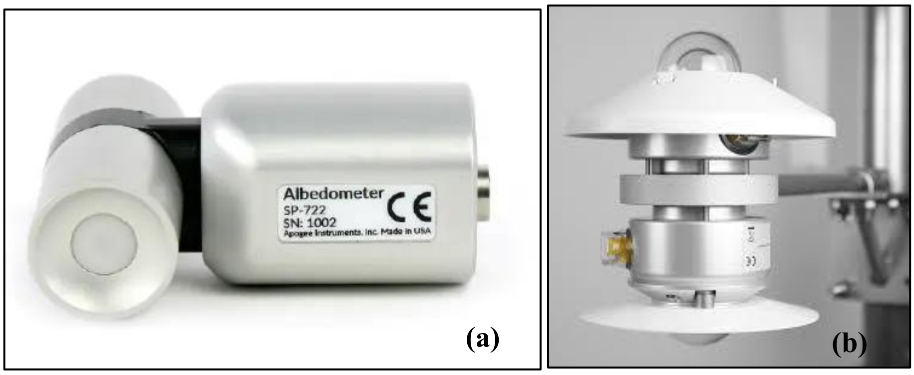


Figure 52: (a) Apogee model SP-700 Albedometer (*Source: Apogee Instruments, Inc., 2025*)
(b) Kipp & Zonen albedometers (*Source: Earth Sciences, 2021*)

8.8.8 Chlorophyll meter

A chlorophyll meter is a device used to instantly measure the chlorophyll content, or "greenness," of plant leaves. This measurement helps farmers and agronomists monitor plant health, enabling them to detect nutrient deficiencies early and avoid the risks of under- or over- fertilization. By assessing chlorophyll levels, the meter provides information on the physiological status of crops, often revealing changes in plant health well before visible symptoms appear.

The amount of chlorophyll in plant leaves is closely Linked to the overall condition of the plant, making it a reliable indicator of when additional fertilization may be required. The working principle of a chlorophyll meter is based on light absorption. It measures how much light is absorbed by the leaf at two specific wavelengths including red and near-infrared. Chlorophyll strongly absorbs red light but does not absorb near-infrared light. By calculating the ratio of light transmittance at these two wavelengths, the device estimates the relative chlorophyll concentration in the leaf. This value is then displayed on the device, typically in units of micromoles of chlorophyll per square meter ($\mu mol/m^2$).

Common examples of chlorophyll meters include the SPAD-502 Plus and the Apogee chlorophyll concentration meter.

Figure 53: SPAD-502 Plus Chlorophyll meter (Source: Konica Minolta, n.d.)

Figure 54: Apogee chlorophyll concentration meter (Source: Portable Chlorophyll Meters Optimize Nitrogen Use - Cultivar Magazine, 2025)

8.8.9 Automatic weather monitoring station

An Automatic weather monitoring station is a comprehensive, integrated system designed to measure, record, and often transmit a wide range of weather-related parameters. These include temperature, humidity, wind speed and direction, solar radiation, and rainfall. The AdvanceTech model is an advanced, all-in-one station equipped with essential tools for real-time environmental monitoring and data analysis.

This station includes a built-in data logger, a cloud-based dashboard for remote access and analysis, and flexible storage options such as SD cards and USB drives for local data backup. It incorporates various components that work together to capture and transmit atmospheric data. These components include multiple sensors for detecting temperature, humidity, wind characteristics, rainfall, and solar radiation, as well as a protective sensor shelter, a display for on-site weather visualization, and a weather camera for capturing visual conditions. Also, the system is powered by a solar panel and battery setup, ensuring uninterrupted operation in remote or off-grid locations. It is widely used in agricultural, environmental, and research applications for accurate and efficient weather monitoring.

Figure 55: AdvanceTech Digital Automatic Weather Station (Source: Automatic Weather Station Manufacturer Exporter Supplier from Zirakpur India, n.d.-b)

Chapter 9
AgriPV : Initiatives & Policies

Several intiatives have been taken in recent years to promote AgriPV system. Research institutions have initiated studies on both the agricultural and solar aspects of AgriPV. Both government and non-governmental organizations are engaged in research activities and providing funding to support advancements in this field. Various workshops, webinars, stakeholders consulation and training programs are being organized for different stakeholders to enhance knowledge and adoption of AgriPV. Some key developments are:

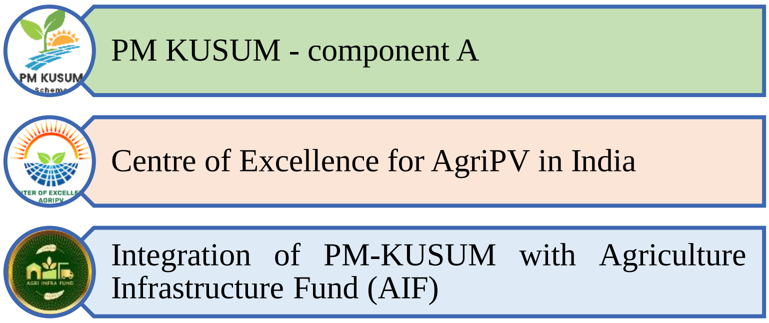


Figure 56: Recent developments to promote AgriPV in India

9.1 PM-KUSUM scheme

The Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan (PM-KUSUM) scheme is playing a crucial role in promoting renewable energy adoption in the agricultural sector, ensuring energy security for farmers and reducing carbon emissions. PM-KUSUM Scheme, launched in 2019, aims to enhance energy security for farmers in India and promote the use of clean energy in the agriculture sector. The scheme seeks to achieve commitment of India to increase the share of non-fossil fuel sources in the installed capacity of electric power in the country.

9.1.1 Components of PM-KUSUM scheme

i. **Component A: installation of small solar power plants (SEPP)**

- Individual farmers, groups of farmers, cooperatives, panchayats, Farmer Producer Organizations (FPOs), and Water User Associations (WUAs) can set up solar power plants with capacities ranging from 500 kW to 2 MW.
- If these entities are unable to arrange the required equity, they can opt for developing the plants through developers or local distribution companies (DISCOMs).
- DISCOMs will purchase the solar power generated at a feed-in-tariff determined by the State Electricity Regulatory Commission.
- DISCOMs will receive a performance-based incentive (PBI) of Rs. 0.40 per unit purchased or Rs. 6.6 lakh per MW of installed capacity, whichever is less, for five years from the Commercial Operation Date (COD).

ii. **Component B: standalone solar powered agriculture pumps**

- Individual farmers will be supported in installing standalone solar-powered agriculture pumps of up to 7.5 HP in off-grid areas without access to grid supply.

- The scheme provides a capital subsidy of 30% of the benchmark cost or the tender cost, with the state government offering a minimum subsidy of 30%.
- Farmers can avail bank finance, paying only 10% of the cost initially and the remaining 30% as a loan.
- In select regions, such as North Eastern States, Sikkim, Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Lakshadweep, and Andaman & Nicobar Islands, the capital subsidy is 50%.

iii. **Component C: solarisation of grid-connected agriculture pumps**

- Farmers with grid-connected agriculture pumps can receive support to solarize their pumps.
- Solar PV capacity up to twice the pump capacity in kilowatts is allowed.
- A capital subsidy of 30% of the benchmark cost or the tender cost is provided, with the state government offering a minimum subsidy of 30%.
- Farmers can avail bank finance, paying only 10% of the cost initially and the remaining 30% as a loan.
- In select regions, the capital subsidy is 50%.

In a bid to enhance the implementation of solar projects on agricultural lands, the Central Government is considering Linking the PM-KUSUM scheme with the Agriculture Infrastructure Fund (AIF). This move aims to provide farmers with access to cheaper loans for setting up solar projects and procuring equipment.

9.2 Centre of Excellence (COE) for AgriPV in India

The Ministry of New and Renewable Energy (MNRE) has recognized a Center of Excellence (COE) for AgriPV, jointly led by the ICAR - Indian Agricultural Research Institute (IARI), New Delhi and the National Institute of Solar Energy (NISE), Gurugram.

Primary objectives of the COE for AgriPV are:

- Development of innovative photovoltaic solutions for agricultural applications.
- Providing technical assistance and support for establishing AgriPV pilot projects in India.
- Advancing research, innovation, and knowledge exchange in the integration of solar energy and agriculture.
- Facilitating cooperation between Indian and German research institutes/companies on AgriPV solutions.

9.3 Agriculture Infrastructure Fund (AIF)

To bridge existing gaps in post-harvest management infrastructure, the Agriculture Infrastructure Fund (AIF) was launched in 2020-21 as a flagship initiative aimed at strengthening agricultural infrastructure. The scheme facilitates the development of farm gate storage and logistics infrastructure, enabling farmers to store and preserve their produce effectively. By reducing post-harvest losses and minimizing intermediaries, AIF helps farmers secure better market prices for their crops. The AIF scheme is designed to benefit all stakeholders in the agricultural ecosystem, contributing to the holistic developmentof the sector. It provides a financing facility of ₹1 lakh crore through lending institutions, with an interest rate cap of 9%. Loans under the scheme are eligible for an interest subvention of 3% per annum on amounts up to ₹2 crores, for a maximum period of seven years. The scheme is operational from 2020-21 to 2032-33 *(MoAFW, 2025)*.

Marking a significant milestone in mission of India to transform its agricultural sector, the Union Cabinet, chaired by Prime Minister Narendra Modi, approved a major expansion of the AIF scheme on August 28, 2024. This expansion introduces a range of measures to enhance the attractiveness of the scheme, impact, and inclusivity, reaffirming the commitment of the government to improving agricultural productivity and infrastructure. The expanded AIF aims to further strengthen nationwide agricultural infrastructure by broadening the scope of eligible projects, introducing additional support mechanisms, and fostering a more comprehensive agrarian ecosystem *(MoAFW, 2024)*.

9.3.1 Integration of PM-KUSUM with AIF:

To accelerate the implementation of solar projects on agricultural lands, the Ministry of New and Renewable Energy is Linking the PM-KUSUM scheme with the Agriculture Infrastructure Fund (AIF). The AIF provides medium to long-term debt financing facilities for investment in projects related to post-harvest management infrastructure and community farming assets. By tapping into the AIF, farmers can access cheaper loans for setting up solar projects and procuring equipment. The central government will bear 30% of the project cost, with the remaining balance shared between the state government and the beneficiary farmer.

9.4 Future Prospects and Reccommendations

While India has made progress in piloting and researching AgriPV, several aspects still lack clarity. This section highlights key recommendations and actions taken by different countries to support the future development of AgriPV in India.

9.4.1 Regulatory clarity

The legal framework for AgriPV in India remains undefined, with no specific regulations governing land use for solar PV under the existing legal system *(NSEFI, 2022)*. *Pascaris (2021)* examined U.S. policies to propose a comprehensive legal framework for agrivoltaics, suggesting that an effective system should integrate federal and state energy financing mechanisms alongside favorable state and local land use policies. Key recommendations include state-level feed-in tariffs and local government provisions for mixed-use land between solar energy and agriculture.

In India, *Arora and Kotoky (2022)* reported that BTG Legal was commissioned by the Indo-German Energy Forum Support Office (IGEF-SO), under Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, to conduct a legal assessment of AgriPV in Maharashtra and Karnataka. This study, commissioned on behalf of the Ministry of New and Renewable Energy (MNRE), Government of India, and the Federal Ministry for Economic Affairs and Climate Action (BMWK), Government of Germany, was published as a consolidated report. It evaluated the legal landscape for 1–10 MW AgriPV projects, focusing on land regulations, potential changes in land-use classifications, tax implications for farmers and developers, financial viability, and permit requirements.

Globally, various legal and policy frameworks support AgriPV development. Table 18 outlines key policies in leading countries.

Table 23: Legal and policy framework in leading countries

S. No.	Country	Legal and policy framework promoting AgriPV
1	China	• PV poverty alleviation policies to promote AgriPV in rural areas by relaxing strict land policies National level PV power generation front runner base scheme (mainly for developer and manufacturers for deploying efficient and reliable technology). • Land use regulation by Ministry of Agriculture and Rural Affairs, to ensure agriculture land used for farming activity.
2	USA	• State program: Solar Massachusetts Renewable Target (SMART) Program to provide additional feed in tariff for AgriPV Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE) initiative by National Renewable Energy Laboratory (NREL) to understand the best practices and provide foundational data to stakeholders. • Protecting Future Farmland Act to provide tax relief for land used for agricultural purpose.
3	Germany	• Common Agricultural Policy by EU to provide 85% subsidy based on the size of the farm. • Renewable Energy Sources Act (EEG) to ensure financial, legal and grid access. Construction Regulation to avoid construction AgriPV on unplanned open areas.
4	Japan	• Land Use Policy highlighting AgriPV should be treated as agriculture land • Issue of Directives to institutionalise on AgriPV by Ministry of Agriculture, Forestry and Fisheries that allowed installation of AgriPV on all categories of farmland.

(Basu et al., 2025)

9.4.2 Yield penalty of crops under AgriPV

India currently lacks a standardized framework for determining acceptable yield penalties for different crops under AgriPV. Establishing such benchmarks is essential to ensure that any reduction in crop yields does not compromise national food security or economic stability. While AgriPV can provide benefits such as crop protection, reduced sunlight exposure may negatively impact yields *(Nasukawa et al., 2016).*

Many countries regulate AV installations on croplands by imposing minimum crop yield requirements. For example, France permits AgriPV only if crop productivity is maintained, whereas Japan and Germany allow slight reductions, with minimum relative yields of 80% and 66%, respectively *(Duparz, 2023). Gonocruz et al. (2021)* reported that Japan mandates crop yields remain above 80% for agrivoltaic installations on farms. Many countries set minimum yield retention requirements between 70% and 90% relative to a reference level within their AgriPV legislative frameworks *(Czyzak & Mindekova, 2024)*. For staple crops such as cereals, achieving these thresholds is feasible only if shading is limited to 25% or less *(Duparz, 2023)*.

A study on agrivoltaic policies in Thailand *(SGtech & Naresuan University, 2024)* highlights the importance of regulations from both the agriculture and energy sectors in AgriPV implementation. In Thailand, initial project permits are granted for three years, after which renewal is required. One key approval criterion is that crop yield reductions must not exceed 20% compared to the surrounding agricultural area's average production levels.

9.4.3 Safety concerns

Safety is crucial in all PV installations. AgriPV sites present unique challenges due to the combination of agriculture and solar power. Unlike typical ground-mount systems that are gated for security, however in AgriPV sites, farmers work in close proximity to the PV modules using large machinery and irrigation, making gating impossible and increasing the potential risk of electrical shock. Animals grazing near the panels can cause cable damage, leading to potential fire hazards. Proper precautions and SOP's must be taken to mitigate these risks *(Bellehsen, 2023)*.

The AgriPV system consists of electric panels, insulated wiring mounted on a structures and other electrical gadgets. Farmers are accustomed to work in open fields, where they have unrestricted movement. Presence of PV panels significantly limit their mobility, complicating the performance of regular farming operations. Therefore, the trained manpower and safety equipments at site should be available to handle emergency. Working beneath the panels requires farmers to wear protective gadgets, such as helmets, vests, and boots.

Table 24: Safety measures for AgriPV sytem

PPE Name	PPE Picture	Use
Helmate		• White helmate for staff/contractor staff • Yellow helmate for all other (Labour, Supervisor • It compulsory on agripv site
Reflective jacket		• Green for staff/contractor staff • Orange for all other (Labour, supervisor) • It is compulsory inside the premises
Safety shoes		• Compulsory for all inside the premises

Full body harness		To do any work 2 meter above ground
Dotted hand gloves		For manual handling
Electrical hand gloves (33 KV)		33 KV handling work
Cut resistance hand gloves		Solar module replacement, broken solar module handling. Etc.
Gum boots		Waterlogging area, during rainy season, etc.
Ear plug		Inverter room and near to inverter
Safety spectacles		Compulsory for all inside the premises

(Source: Khare Energy Pvt. Ltd., 2025)

9.5 Feed-in Tariff (FiT)

Feed-in Tariff (FiT) is an energy policy designed to promote the development and adoption of renewable energy. Under a FiT scheme, energy producers utilising renewable sources such as solar, wind, or hydro receive compensation based on their generation costs *(UN ESCAP, 2012)*. This tariff guarantees a payment for each unit of energy produced over a fixed period, typically 15-20 years *(Greer, 2012)*. Studies have shown that FiTs are among the most effective mechanisms for encouraging sustained and diverse renewable energy deployment *(NREL, 2010)*. Countries like Germany and Spain have successfully used FiTs to accelerate solar photovoltaic deployment. Success of solar energy deployment in Germany is largely attributed to two key policies: guaranteed grid access for renewable energy producers and FiTs, leading to significant rooftop solar installations *(Gulati et al., 2016)*.

9.5.1 Solar feed-in tariff (FiT)

When solar panels generate more electricity than is consumed, the excess energy is sent back to the grid. A FiT provides a payment for this surplus energy, which appears as a credit on the electricity bill. This payment is made by the electricity retailer at a predetermined rate per kilowatt-hour (kWh). The FiT rate for solar power varies depending on the country or region, with different programs in place that determine the compensation rate per kWh.

9.5.2 FiT for farmers in India

FiTs play a crucial role in the expansion of renewable energy in India. When solar panels are installed on agricultural land, it offers farmers an alternative source of income while promoting sustainable power generation. When solar power plants generate surplus electricity, the excess can be supplied to the grid, reversing the usual flow of power. Special electricity meters monitor both directions of energy transfer. FiTs operate similarly to net metering, where plant owners receive a predetermined price per unit of electricity supplied to the grid. The tariff is fixed but may be adjusted annually to account for inflation and operational costs. The terms and conditions governing electricity supply are outlined in a Power Purchase Agreement (PPA). Typically, a PPA for 25 years is signed under these agreements. While State Governments set FiT rates, the Ministry of New and Renewable Energy (MNRE) provides guidelines and recommendations. However, the final decision rests with individual state commissions.

The tariff rate is generally higher than standard retail electricity prices, ensuring compensation for initial capital investments and encouraging clean energy adoption. In India, FiT rates for solar and other renewable energy sources are regulated by State Electricity Regulatory Commissions (SERCs). These rates are determined based on factors such as:

- Cost of electricity generation from renewable sources
- Prevailing electricity tariffs
- Government renewable energy targets and policies
- Financial viability and investment incentives for renewable projects
- Impact on consumer electricity bills

9.5.3 FiT rates for solar PV projects in India

The table below outlines the FiT rates offered by different Indian states for farmers:

Table 25: Feed-in-tariff

State	Scheme	FiT (INR/unit)
Karnataka	Surya Raitha Scheme	7.2 (₹6 to pay back loans; ₹1 to farmer; ₹0.2 to cooperative)
Andhra Pradesh	Grid-connected connected BLDC pumps	1.5

Gujarat	Suryashakti Kisan Yojana	3.5
Maharashtra	Rooftop solar projects	3.3
Odisha	Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan (PM KUSUM)	3.08
Chhattisgarh	PM KUSUM- Component A	3.51
Madhya Pradesh	PM KUSUM- Component A	3.07

Given the higher capital and operational costs associated with AgriPV installations, the FiT rates in such cases may need to be higher than existing rates under schemes like KUSUM.

9.6 Other key recommendations

- Crops typically require 6–8 hours of sunlight exposure for optimal yield. A study may be conducted under Indian agroclimatic conditions to assess potential yield penalties and explore mitigation strategies through crop intensification and improved agricultural practices.
- With modified shading pattern the insect, pest and disease dynamics may change; there is need to conduct simultaneous study on these aspects as well.
- Quantify compensation amounts for farmers experiencing revenue loss due to crop yield reduction.
- Quantifying the Photosynthetically Active Radiation (PAR) under varying solar panel orientations is necessary for evaluating crop suitability and identifying species with higher photosynthetic efficiency under AgriPV systems.
- Adjustment of Minimum Support Prices (MSPs) based on regional requirements.
- Conduct comprehensive analyses of deviations from baseline data for each crop, considering factors such as crop growth, agricultural yield, microclimate, soil conditions, farmer income/compensation, economic and trade dynamics (local, national, and international), and PV plant performance.
- Ensure adherence to safety guidelines and regulatory compliance.
- Encourage the adoption of new and innovative technologies.
- Provide government subsidies to scale up AgriPV initiatives.
- Develop suitable insurance policies for AgriPV system.
- Conduct periodic assessments to ensure compliance with land-use regulations and prevent illegal land acquisition.
- Establish a robust database management system to consolidate and share research findings and experimental results from various AgriPV pilot projects in India, benefiting farmers and stakeholders.
- Set up regional centers to provide dedicated technical support and guidance for AgriPV implementation.
- Enhance grid capacity of India to accommodate increased electricity generation and evacuation.

- Ensure government support for farmers, including timely maintenance of solar panels and the availability of replacement parts.

9.7 Efficient resource management

- **Light management**
  Balancing electricity generation and agricultural yield is a key challenge. Ensuring adequate and uniform light distribution can be achieved by adjusting system orientation (East or west instead of south) or incorporating tracking mechanisms that regulate shading based on plant needs.
- **Water management**
  Partial coverage by PV modules affects precipitation distribution. System design must account for this to prevent adverse effects from water runoff at the module edges. Solutions include using specialized narrow or tubular PV modules or integrating rainwater harvesting systems. Some of the water management strategies are:
  - Water balance assessment - Evaluating precipitation levels in relation to crop water needs.
  - Rainwater harvesting potential - Calculating the feasibility of collection and storage systems.
  - Integrated irrigation design - Developing preliminary layouts for irrigation systems within the AgriPV framework.
- **Fertilizer and pest management**
  The selection of fertilizers and pest control methods should consider their impact on PV modules to prevent corrosion and efficiency loss.
- **Soil management**
  Maintaining soil health is essential for sustainable agricultural production. This include regularly evaluating soil health to identify nutrient deficiencies and degradation, preventing soil compaction to promote root growth and water absorption and enhancing soil fertility.

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1. **Light saturation and shading percentage of major crops** (Link)

Crop	Light saturation (lux)	Suitable shade rate (%)
Tomato	70,000	10-30
Cucumber	55,000-60,000	30-50
Chilli	30,000	50-70
Long bean	20,000-50,000	50-80
Cabbage	40,000	40-60
Lettuce	5000-10,000	80-90
Spinach	5000-10,000	80-90
Celery	40,000-45,000	50-60
Eggplant	40,000	40-60
Mushroom	-	95%

2. **The PPFD and DLI values of crops** (Link)

Plant	**PPFD** (µmol/m²/s)	**DLI** (mol/m²/d)
Aloe	80 – 160	4 – 14
Anthurium	80 – 400	4 – 14
Avocado	400 – 650	18 – 24
Basil	220 – 500	12 – 26
Blackberry	200 – 300	8 – 14
Broccoli	300 – 700	15 – 35
Chrysanthemums	200 – 300	10 – 14
Citrus (Various)	80 – 160	4 – 16
Cucumbers	300 – 600	20 – 30
Cucumbers (Seedling)	100 – 300	5 – 15
Culinary Herbs (Small)	150 – 250	10 – 12
Dwarf Banana	100 – 350	4 – 14
Eggplants	300 – 600	20 – 30
Garden Lettuce	250 – 350	14 – 16
Hibiscus	80 – 500	4 – 14
Jasmine	– 0	5 – 16
Lemon	300 – 600	21 – 28
Mint	200 – 400	10 – 20
Monstera	80 – 500	4 – 12
Orange	500 – 700	22 – 30
Peas	150 – 300	9 – 12
Peppers	300 – 600	20 – 30
Petunias	300 – 400	16 – 18
Pineapple	350 – 700	15 – 30
Pumpkins	300 – 650	18 – 28
Roses	350 – 450	18 – 22
Strawberry	400 – 600	17 – 28
Tomatoes	350 – 800	22 – 30

Lettuce	120–270	6.9–15.6
Bitter Gourd	25	-
Turmeric	173	9
Coriander	300	20-28
Citrus (Various)	300 – 600	20 – 28
Grapefruit	500 – 700	22 – 30
Amaryllis	150 – 300	12 – 16
Anthurium	80 – 400	12 – 16
Avocado	400 – 650	8 – 16
Blackberry	200 – 300	10 – 16
Blueberry	400 – 700	10 – 16
Broccoli	300 – 700	8 – 16
Bromeliad	80 – 600	10 – 16
Cyclamen	70 – 150	8 – 16
Dill	300 – 600	10 – 16
Eggplants	300 – 600	20 – 30
Fuchsia	150 – 250	10 – 12
Garden Lettuce	250 – 350	14 – 16
Hibiscus	80 – 500	4 – 14
Kalanchoe	60 – 120	12 – 16
Lemon	300 – 600	21 – 28
Lime	300 – 600	21 – 28
Mint	200 – 400	10 – 20
Olive	400 – 1000	18 – 40
Orange	500 – 700	22 – 30
Orchids (Low-Light)	40 – 80	8 – 16
Orchids (Moderate-Light)	80 – 150	4 – 8
Oregano	300 – 600	20 – 28
Oxalis	150 – 250	2 – 10
Parsley	200 – 400	10 – 20
Peace Lily	20 – 40	4 – 14
Peach	200 – 300	10 – 16
Peas	150 – 300	9 – 12
Petunias	300 – 400	16 – 18
Pineapple	350 – 700	15 – 30
Pumpkins	300 – 650	18 – 28
Rosemary	300 – 600	20 – 28
Strawberry	400 – 600	17 – 28
Tangerine	500 – 700	22 – 30
Thyme	300 – 600	20 – 28
Zucchini	400 – 650	22 – 28

3. GDD of different crops during different development stages

Crop	Crop growing stages	GDD (°C)
Wheat	Emergence	125–160
	Leaf development	168–207
	Tillering	368–420
	Stem elongation	591–658
	Anthesis	806–900
	Seed filling	1067-1773
	Dough stage	1433–1555
	Maturity complete	1537–1665
Barley	Emergence	228-293
	Leaf development	293-363
	Tillering	586-680
	Stem elongation	912-1031
	Anthesis	1360-1716
	Seed fill	1700-2093
	Dough stage	2179-2620
	Maturity complete	2316-2771
Oat	Anthesis	760-947
	Seed fill	1019-1229
	Dough stage	1380-1625
	Maturity complete	1483-1738
Mustard	Emergence	108-136
	Leaf Stages	214-251
	Flowering	320-365
	Seed fill	506-567
	Maturity	679-747
	Swathing	886-962
	Maturity complete	1232-1322
Chickpea	Leaf Stages	179-243
		262-337
		346-431
		429-525
	Flowering	645-724
		823-910
	Seed fill	1037-1133
	Maturity	1394-1505
	Maturity complete	1679-1803
Lentil	Leaf Stages	161-192
		248-285
		335-378
		423-471
	Flowering	762-853
		931-1030

	Seed fill	1133-1241
	Maturity	1470-1594
	Swathing	1673-1806
	Maturity complete	1740-1876
PEA	Leaf Stages	198-230
		301-340
		404-449
		507-558
	Flowering	724-835
		862-982
	Seed fill	1028-1158
	Maturity	1305-1451
	Maturity complete	1527-1686
Sunflower	Emergence	138-191
	Leaf Stages	249-313
		359-435
		470-558
	Flowering	935-1077
		1081-1232
	Seed fill	1255-1417
	Maturity	1547-1725
	Maturity complete	1780-1972
Corn	Emergence – Coleoptiles	0
	2 leaves fully emerged	213
	4 leaves fully emerged	345
	6 leaves fully emerged	476
	8 leaves fully emerged	608
	10 leaves fully emerged	739
	12 leaves fully emerged	871
	14 leaves fully emerged	1003
	16 leaves fully emerged	1134
	Silking/Anthesis/Boot leaf	1397
	Kernal in blister stage/half bloom	1661
	Kernal in dough stage	1924
	Kernal begins to dent	2187
	Kernal fully dented	2450
	Physiological maturity	2713
Pearl millet	Emergence – Coleoptiles	0
	2 leaves fully emerged	251
	4 leaves fully emerged	457
	6 leaves fully emerged	659
	8 leaves fully emerged	853
	10 leaves fully emerged	-

	12 leaves fully emerged	-
	14 leaves fully emerged	-
	16 leaves fully emerged	1013
	Silking/Anthesis/Boot leaf	1043
	Kernal in blister stage/half bloom	-
	Kernal in dough stage	-
	Kernal begins to dent	1262
	Kernal fully dented	
	Physiological maturity	1661
Potato	GDD to emergence	178-240
	GDD to full flower	749-841
	GDD to harvest	1493-2840

(Source: Miller et al., 2001; Parthasarathi et al., 2013; ARABLE, 2024)

Annexture II

1. **State wise crops grown in India**

Sr. No.	States	Agroclimatic zone	Major crops
1	**Haryana**	Trans-Gangetic Plains Region	**Cereals:** Rice, Moong, Mash, Arhar, Bajra **Vegetables:** Guar, Okra, Sesame, Bottle Gourd, Barnyard millet, Kodo millet, little millet, foxtail millet, Sorghum, Niger, Bitter gourd,
2	**Delhi**	Trans Gangetic Plains region	Paddy, wheat, barley, bajra, maize, jowar, mustard, vegetables and fruits (Tomato, Brinjal, Cauliflower, Ber, Rose, Gladiolus), flowers
3	**Uttar Pradesh**	Middle Gangetic Plains Region Upper Gangetic Plains Region Eastern Plateau and Hills Region: Central Plateau and Hills Region,	**Kharif:** Paddy. Maize, Jowar, Bajra, Urad, Moong, Arhar, Sesame, Sunflower, Groundnut, Soybean, Kodo, Pigeon pea, Sugarcane, finger millet, **Rabi:** Wheat, Barley, Gram, pea, lentil, Rai/Mustard, Toria, linseed, rabi maize **Zaid:** Maize, Bajra, chena, Sawan, Urid, Moong, Sunflower, Cotton **Fruits**: litchi, jackfruit, muskmelon, watermelon, Aonla **Spices**: turmeric, dry chillies, coriander, ginger, fenugreek, fennel
4	**Rajasthan**	Trans-Gangetic Plains Region Western Dry Region	Rice, Jowar, Bajra, Maize, Cotton, Tur, Sesame, Castor, Sugarcane, Groundnut, Wheat, Barley, Gram, Rape Seed, Mustard, Linseed, Urad, Moong, Moth, Chaula, Soybean, Tobacco, Small Millets, Tobacco, Sun Hemp, Spices and Fodder, Dry Chillies, Ginger, Turmeric, Coriander, Cumin Seed, Ajwain, Garlic, Fennel Seed, Methi, Potato, Onion, Sweet Potato, Fruits & Vegetables

5	**Telangana**	Southern Plateau and Hills Region East Coast Plains and Hills Region	Paddy, Wheat, Jowar, Maize, Red Gram, Green Gram, Horse Gram, Bengal Gram, Cow Gram, Sesamum, Sunflower, Safflower, Black Gram, Groundnut, Tobacco
6	**Maharashtra**	Eastern Plateau and Hills Region Western Plateau and Hills Region West Coast Plains and Ghat Region	Rice, Wheat, Jowar, Bajra, Ragi, Maize, other cereals, Tur, Moong, Urid, Gram, other pulses, Groundnut, Sesamum, Niger Seed, Sunflower, Soybean, Safflower, Sugarcane, Cotton, Tobacco
7	**Chhattisgarh**	Trans Gangetic plain region Eastern plateau and hills region	Urad, Kulthi, Groundnut, Sesamum, Sunflower, Soybean, Niger, Wheat, Barley, Gram, Pea, Masoor, Mustard, Linseed, Safflower
8	**Uttarakhand**	Western Himalayan region	Urad, Moong, Moth, Rajma, Wheat, Gram, Green Peas, Masur, Groundnut, Soybean, Sunflower, Sarso, Sugarcane, Potato, Onion, Ginger, Garlic, Turmeric, Tobacco,
9	**Karnataka**	West Coast Plains and Ghat Region	Sorghum, Red Gram, Bengal Gram, Sunflower, Groundnut, Cotton, Sugarcane
10	**Kerala**	West Coast Plains and Ghat Region	Tapioca, Vegetables, Sweet Potato, Tubers, Groundnut, Ginger, Turmeric, Cotton, Tobacco, Onion, Tur, Sugarcane, Banana, Pineapple, Betel Leaves, Coconut, Arecanut, Cashew, Mango, Jackfruit, Tamarind, Pepper, Rubber, Tea, Coffee, Cardamom, Cloves, Nutmeg, Cinnamon, Cocoa, Papaya
11	**Tamil Nadu**	West Coast Plains and Ghat Region East Coast Plains and Hills Region	Cereals: Paddy, Jowar, Bajra, Ragi, Maize, Small Millets Pulses: Bengal Gram, Red Gram, Green Gram, Black Gram, Horse Gram, other pulses Oilseeds: Groundnut, Gingelly, Coconut,

			Castor, Sunflower, other oilseeds Other crops: Cotton, Sugarcane, Tobacco, Spices & Condiments
12	**Andhra Pradesh**	East Coast Plains and Hills Region Southern plateau and hills region	**Cereals:** Paddy, Wheat **Major And Minor Millets:** Jowar, Bajra, Maize, Ragi, Samai, Korra, Black Tapioca**,** Rocket, Foxtail Millet, Quinoa **Pulses:** Bengal Gram, Red Gram, Green Gram, Black Gram, Black Gram, Horse Gram, Cow Gram, Rajma Beans, Hyacinth Bean **Spices:** Arecanut, Chilies, Coriander, Turmeric, Pepper, Tamarind, Garlic, Ginger, Ajwain, Curry Leaf, Kothi Meera, Cumin Seeds **Fruits:** Mango, Batavia, Acid Lime, Orange & Citrus Fruits, Amla, Jujubies, Plantain, Grapes, Guava, Papaya, Sapota, Pomegranate, Anjura, Velaga, Custard Apple, Jackfruit, Muskmelon, Watermelon, Blackberry, Kino Fruit, Pineapple, Cashew Nuts, Dry Fruits **Vegetables:** Potato, Carrot, Radish, Beetroot, Tapioca, Yam, Sweet Potato, Onions, Cucumber, Bitter Gourd, Okra, Snake Gourd, Beans, Green Plantain, Brinjal, Green Leafy Vegetables, Cabbage, Cauliflower, Peas, Tomato, Bottle Gourd, Drumstick, Ridge Gourd, Green Chillies, Green Beans, Pumpkin, Ash Gourd, Capsicum **Oilseeds:** Groundnut, Sesamum, Safflower, Sunflower, Rape and Mustard, Soybean, Palm Oil, Castor, Linseed, Niger seed, Jatropha **Fodder Crops:** Fodder Jowar, Fodder Maize, Sababul, Stylohmata, Casuarina, Napier, Paragrass, Jute **Aromatic Plants:** Lemon Grass, Colius, Billa Ganaru, Kalabanda, Ashwagandha, Palma

			Rosa, Tulsi, Gayle, Cucumber for Medicine **Flowers:** Rose, Jasmine, Sampangi, Marigold, Chrysanthemum, Crossandra, Lilly, Kagada, Chandini, Astel, Maruvam
13	**Odisha**	East Coast Plains and Hills Region	Paddy, Wheat, Maize, Ragi, Mung, Biri, Other Pulses, Groundnut, Til, Mustard, Other Oil Seeds, Jute, Cotton, Dhaincha
14	**Gujarat**	Gujarat Plains and Hills Region	**Fruits:** Mango, Sapota, Banana, Guava, Pomegranate, Papaya, Aonla, Cashewnut, Coconut **Vegetables:** Potato, Onion, Brinjal, Cabbage, Okra, Tomato, Cauliflower **Spices:** Cumin, Chilli, Garlic, Coriander, Ginger, Turmeric
15	**Madhya Pradesh**	Central plateau and hills region Western plateau and hills region Eastern plateau and hills region	Paddy, Jowar, Maize, Bajra, Kodo Kutki, Wheat, Barley, Tur, Urid, Mung, Kulthi, Gram, Pea, Lentil, Groundnut, Soybean, Sesamum, Niger, Rape Seed & Mustard, Linseed, Sunflower, Cotton, Sugarcane
16	**West Bengal**	Eastern plateau and hills region Lower Gangetic Plains Region Eastern Himalayan region	Paddy, Wheat, Maize, Potato, Large Cardamom, Chilli, Ginger, Turmeric, Coriander Seeds, Fennel Seeds, Fenugreek Seeds
17	**Bihar**	Middle Gangetic plain region	**Cereals:** Rice, Wheat, Sweet Potato, Maize, Lentil, Linseed, Jute, Mustard, Moong, Toria, Gram **Fruits:** Mango, Guava, Litchi, Banana, Makhana, Pineapple, Betel Vine

			Vegetables: All Solanaceous, Cucurbits, Beans, Cole Crops, Okra, Onion **Spices:** Chilli, Turmeric, Coriander, Ginger, Garlic, Methi **Flowers:** Marigold, Rose, Tuberose, Gladiolus, Jasmine **Aromatic Plants:** Japanese Mint, Lemongrass, Pamaroja
18	**Himachal Pradesh**	Western Himalayan region	**Fruits:** Lemon, Mango, Guava, Walnuts, Almonds, Chilgoza **Vegetables:** Potato, Cauliflower/Cabbage **Spices & Condiments:** Chillies, Ginger, Jeera, Turmeric, Garlic, Coriander **Other Crops:** Cotton, Groundnut, Sesamum, Rape, Mustard, Soybean, Linseed, Taramira, Tobacco, Tea, Berseem & Lucerne
19	**Sikkim**	Eastern Himalayan region	**Cereals:** Rice, Wheat, Maize, Finger Millet, Barley, Pulses, Buckwheat **Tuber Crops:** Potato, Sweet Potato **Spices:** Large Cardamom, Ginger, Chilli, Turmeric, Coriander **Fruits:** Mandarin, Passion Fruit, Banana, Guava, Papaya, Jackfruit, Litchi **Vegetables:** Broccoli, Onion, Brinjal, Carrot, Chayote Squash, Pumpkin, Radish, Tomato, Tree Tomato, Cabbage/Cauliflower **Ornamental Crops:** Anthurium, Cymbidium, Rose
20	**Assam**	Eastern Himalayan region	Rice, Wheat, Jute, Cotton **Fruits:** Banana, Pineapple, Orange, Papaya,

			Assam Lemon, Guava, Litchi, Jackfruit, Mango **Spices:** Chilli, Turmeric, Onion, Ginger, Coriander, Garlic, Black Pepper **Nut Crops:** Coconut, Arecanut **Tuber Crops:** Potato, Sweet Potato **Pulses:** Arhar, Black Gram, Lentil, Pea, Black Gram, Green Gram, Chickpea, Rajma, Rapeseed and Mustard **Vegetables:** Okra, Cucumber, Snake Gourd, Squash, Long Beans, Indian Mustard, Spinach, Coriander, Cabbage, Cauliflower, Onion, Capsicum, Mushroom, Cherry Tomato, Carrot, Jute, Sugarcane
21	**Arunachal Pradesh**	Eastern Himalayan region	Paddy, Maize, Finger Millet, Wheat, Potato, Orange, Banana, Litchi, Pineapple, Brinjal, Oilseeds, Pulses, Black Pepper, Ginger, Large Cardamom, Soybean, Rajma, Millets, Mustard, Turmeric, Chilli, Tapioca, Betel Leaf, Bottle Gourd, Beans, Okra
22	**Nagaland**	Eastern Himalayan region	Jobs Tear, Millet, Sorghum, Broad Bean, French Bean, Pigeon Pea, Yard Long Bean, Sesame, Arecanut, Cherry Tomato, Cucumber Perrila, Rice bean, Tree Tomato, Sugarcane, Winged Bean, Ginger
23	**Manipur**	Eastern Himalayan region	Banana, Pineapple, Citrus, Guava, Papaya, Peach, Pear, Plum, Pumpkin, Bottle Gourd, Ridge Gourd, Cucumber, Dolichos, Vigna, Phosphorus, Phaseolous, French Bean, Brinjal, Tomato, Chillies, Capsicum, Cabbage/Cauliflower, Brussels Sprout, Broccoli, Mushroom, Ginger, Turmeric, Large Cardamom
24	**Mizoram**	Eastern Himalayan region	Mandarin Orange, Banana, Mango, Strawberry, Grape, Pineapple, Dragon Fruit, Cabbage, Tomato, Capsicum, Broccoli,

			Anthurium, Rose, Ginger, Turmeric, Birds Eye Chilli, Arecanut, Rice, Maize, Tapioca, Onion, Rice Bean, Arhar, Field Pea, Cow Pea, French Bean, Rajma, Soybean, Sesame, Rape & Mustard, Oil Palm, Cotton, Tobacco, Sugarcane, Potato, Banana, Chilly, Cotton, Ginger, Maize, Paddy, Potato, Rape 7 Mustard, Sesame, Soybean, Sugarcane, Tapioca, Tobacco, Tur, Turmeric
25	**Tripura**	Eastern Himalayan region	Rice, Maize, Sorghum, Foxtail/Kaon, Arhar, Moong, Black Gram, Cow Pea, Rajma, Sesame, Groundnut, Soybean, Jute, Mesta, Cotton, Sugarcane, Wheat, Lentil, Pea, Gram, Khesari, Rape & Mustard, Potato
26	**Meghalaya**	Eastern Himalayan region	Rice, Wheat, Maize, Small Millets, Gram, Tur, Jute, Mesta, Cotton, Potato, Tapioca, Tobacco, Arecanut, Cashewnut, Tea Leaf, Strawberry, Pineapple, Banana, Papaya, Citrus, Black Pepper, Ginger, Turmeric, Chillies, Soybean, Linseed, Rapeseed & Mustard, Sesame, Castor, Sweet Potato, Rubber, Coffee, Beetroot, Cabbage, Cauliflower, Radish, Tomato, Carrot, Cucumber, Capsicum, Coriander, Beans, Brinjal, Okra, Turnip, Bottle Gourd, Khol Khol, Lettuce, Pumpkin, Mustard (Leaves), Onion, Bitter Gourd, Teasle Gourd, Ridge Gourd, Broccoli, Jackfruit, Sugarcane, Litchi, Guava, Betel Leaf, Coconut, Cinnamon, Cashewnut, Grape, Plum, Peach, Pear, Apricot, Chestnut, Lemon, Orange
27	**Punjab**	Trans Gangetic plain region	Wheat, Basmati, Paddy, Potato, Peas, Cotton, Sugarcane, Maize, Kharif and Rabi Fodder, Spring Maize, Rabi Oilseed, Sunflower, Pulses, Summer Vegetables
28	**Andaman & Nicobar**	Island region	Paddy, coconut, arecanut, pulses, oilseeds, vegetables, mango, sapota, orange, banana, papaya, pineapple, root crops, pepper, clove, nutmeg, cinnamon, rubber, red oil palm, cashew,

29	**Lakshadweep**	Island region	Paddy, coconut, arecanut, pulses
30	**Goa**	West coast plains and ghat region	**Fruits:** Mango, Cashew, Coconut, Banana, Pineapple, Jackfruit, Arecanut etc. **Field crops:** Paddy, Ragi, Sugarcane, Groundnut, Cowpea etc. **Vegetables:** Brinjal, Okra, Chillies, Cucumber, Pumkin, Gourds, Musk Melons, Red Amaranthus, Radish, Knol-Khol, Cabbage, Bottle gourd, Long beans, Cluster beans etc. **Flowers:** Jasmine, Crossandra, Dahlia, Hibiscus, Marigold, Orchids, Gerbera, Anthuriums, Gladiolus, etc. **Spices:** Black Pepper, Nutmeg, Kokum, Turmeric, Cinnamon, etc. **Tubers:** Colocasia, Yam, Elephant foot, Dioscorea, Sweet Potato, etc

(Source: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19)

Annexture III

1. Average of Area, production and yield of major crops in India (Average of 2017-18 to 2021-22)

Group of Crops	Crops	Season	Area (Mha)	Production (MT)	Yield (kg/ha)
Foodgrains	Rice	Kharif	39.94	103.53	2592
		Rabi	4.78	16.86	3525
		Total	44.73	120.39	2692
	Wheat	Rabi	30.38	105.73	3480
		Total	30.38	105.73	3480
	Maize	Kharif	7.57	20.64	2727
		Rabi	2.00	9.48	4751
		Total	9.57	30.12	3149
	Jowar	Kharif	1.74	1.86	1071
		Rabi	2.69	2.55	947
		Total	4.42	4.40	995
	Bajra	Kharif	7.32	9.77	1335
		Total	7.32	9.77	1335
	Nutri/Coarse Cereals	Kharif	18.19	34.38	1890
		Rabi	5.25	13.66	2599
		Total	23.45	48.04	2049
	Tur	Kharif	4.63	4.01	866
		Total	4.63	4.01	866
	Gram	Rabi	10.11	11.57	1145
		Total	10.11	11.57	1145
	Total Pulses	Kharif	13.97	8.44	604
		Rabi	15.32	16.22	1059
		Total	29.29	24.66	842
	Total Food Grains	Kharif	72.11	146.35	2030
		Rabi	55.75	152.47	2735
		Total	127.85	298.82	2337
Oilseeds	Groundnut	Total	5.23	9.26	1770
	Soybean	Total	11.74	12.21	1039
	Sunflower	Total	0.25	0.23	890
	Rapeseed & Mustard	Total	6.73	9.80	1456
	Total Oil Seeds	Total	26.84	34.02	1267
Other Cash Crops	Sugarcane	Total	4.89	400.13	81893
	Cotton	Total	12.87	32.66	431
	Jute & Mesta	Total	0.69	9.85	14311

(Source: Horticulture Statistics Division, Department of Agriculture & Farmers Welfare, MoAFW, GoI, 2023)

2. Area and production of horticulture crops in India 2022-2023

Category of crops	Crops	Area (1000 Hectares)	Production (1000 MT)
Vegetables	Beans	288	2727
	Bitter guard	113	1419
	Bottle gourd	200	3274
	Brinjal	677	12779
	Cabbage	430	9959
	Capsicum	39	602
	Carrot	122	2374
	Cauliflower	490	9521
	Cucumber	121	1643
	Chillies (Green)	433	4583
	Elephant Foot Yam	39	1021
	Mushroom	0	308
	Okra/ Ladyfinger	547	7149
	Onion	1741	30205
	Parmal (pointed gourd)	64	772
	Peas	591	6497
	Potato	2352	60540
	Radish	201	3098
	Sitahal/Pumpkin/Kaddu	112	2400
	Sweet Potato	111	1273
	Tapioca	168	6073
	Tomato	849	20402
	Others	1672	24287
	Total Vegetables	**11358**	**212908**
Fruits	Almond	10	11
	Aonla/Gooseberry	105	1285
	Apple	315	2646
	Banana	938	35365
	Ber	51	526
	Citrus		
	(i) Lime/Lemon	307	3702
	(ii) Mandarin (Orange)	460	6134
	(iii) Sweet Orange (Mosambi)	226	3720
	(iv) Others	104	694
	Citrus Total (i to iv)	1096	14250
	Custard apple	50	447
	Grapes	169	3714
	Guava	347	5274
	Jackfruit	193	3336
	Kiwi	5	20

Category of crops	Crops	Area (1000 Hectares)	Production (1000 MT)
	Litchi	100	743
	Mango	2332	20928
	Muskmelon	66	1496
	Papaya	142	5122
	Passion Fruit	11	56
	Peach	19	122
	Pear	45	319
	Picanut	1	0
	Pineapple	109	1856
	Plum	24	91
	Pomegranate	263	3215
	Sapota	75	898
	Strawberry	2	19
	Walnut	104	289
	Watermelon	122	3521
	Others	313	2791
	Total Fruits	**7009**	**108342**
Aromatic & Medicinal		739	644
Flowers		**272**	**2854**
Plantation Crops	Arecanut	934	1469
	Cashewnut	1192	782
	Cocoa	109	30
	Coconut	2206	13764
	Total Plantation	**4441**	**16045**
Spices	Ajwain	43	38
	Cardamom	86	35
	Chillies (Dried)	850	2060
	Cinnamon/Tejpata	3	6
	Celery, Dill & Poppy	32	44
	Clove	2	1
	Coriander	711	948
	Cumin	714	462
	Fenugreek	145	228
	Fennel	89	152
	Garlic	389	3256
	Ginger	188	2304
	Nutmeg	24	16
	Pepper	305	90
	Vanilla	0	0
	Saffron	4	0
	Tamarind	44	164
	Turmeric	324	1130
	Curry Leaf	1	16

Category of crops	Crops	Area (1000 Hectares)	Production (1000 MT)
	Mint (Mentha)	347	35
	Total Spices	**4300**	**10986**

(Source: Horticulture Statistics Division, Department of Agriculture & Farmers Welfare, MoAFW, Government of India, 2023)