



नवीन एवं
नवीकरणीय ऊर्जा मंत्रालय
MINISTRY OF
**NEW AND
RENEWABLE ENERGY**

AGRI-PHOTOVOLTAICS

POLICY HANDBOOK FOR INDIA



Ministry of New and Renewable Energy
October 2026



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Knowledge Partners

National Institute of Solar Energy (NISE)
Indian Council of Agricultural Research (ICAR)
Bureau of Indian Standards (BIS)
Indian Institute of Technology Roorkee
India Agrivoltaics Alliance (IAA)

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Disclaimer: This handbook provides technical guidance for the planning, design, implementation, operation, and evaluation of agriphotovoltaic (AgriPV) systems in India. It should be used alongside applicable laws, regulations, statutory approvals, grid requirements, and officially notified standards. In the event of any conflict, the applicable statutory or regulatory provisions shall prevail.

AgriPV performance depends on local climate, soil, crop and cultivar, farming practices, system configuration and operational conditions. Examples, case studies and reported improvements in crop yield, electricity generation, water use or financial returns are context-specific and do not guarantee comparable outcomes elsewhere. Project decisions should be supported by site-specific assessments and advice from qualified agricultural, engineering and other relevant professionals.

References to policies, schemes and standards reflect the information available at the time of publication. Users should verify their current versions and applicability. References to particular products, technologies or organizations do not imply endorsement.

While reasonable care has been taken in preparing this handbook, errors may remain. Readers are encouraged to report corrections to the issuing organization.

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GOVERNMENT OF INDIA



FOREWORD

India support about 18 per cent of the world's population on about 2.4 per cent of its land. With abundant solar resources and a large population dependent on agriculture, India has a unique opportunity to strengthen energy security, climate resilience, and farmer livelihoods through decentralised renewable energy.

This opportunity becomes especially important in a country where land and water are precious resources, and agriculture remains fundamental to food security and rural prosperity. Agrivoltaics, which combines solar generation and farming on the same land, offers a promising pathway. It can allow farmers to continue agricultural production while also participating in India's energy transition, helping them become Urjadaata along with Annadaata.

I am delighted to see the launch of *Agro-Photovoltaics Policy Handbook* for India by the Ministry of New and Renewable Energy. The handbook proposes that cultivation continue as the primary activity, that the agricultural classification of the land remain unchanged, and that crop yield be protected through monitoring. Across the four business models it describes i.e. farmer-owned, community-owned, developer-led, and State or public-utility-facilitated, it sets out the rights that must be safeguarded: ownership of the land, the right to cultivate, the farmer's agricultural income, access to information, and a means of recourse.

Based on field research of Center of Excellence on Agri-PV, the Handbook addresses the question every farmer will ask first: what can I grow under the panels, and how? The Handbook covers crop compatibility, microclimate and soil health, and sets out water-management practices suited to AgriPv. It is also candid that crop-specific and region-specific evidence is still being built. Its framework for monitoring, reporting and verification gives projects a common way to record yield, water use, soil condition and energy output, so that experience from the field can strengthen the guidance over time.

I am confident that this Handbook will give farmers, FPOs, cooperatives, Gram Panchayats and State Governments the clarity and confidence to take Agrivoltaics from pilot to scale and will help our farmers become, in the fullest sense, both Annadata and Urjadaata. As India races towards 500 GW of non-fossil capacity and Net Zero by 2070, every field that generates clean power alongside food becomes a powerhouse for the nation. The finding of this handbook to take agrivoltaics to a far greater scale while protecting the central place of agriculture and food security in our development journey towards Viksit Bharat 2047.


(Pralhad Joshi)

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SHRIPAD NAIK

Minister of State for

New and Renewable Energy & Power

Government of India



FOREWARD

India's solar journey is one of the defining achievements of our clean energy transition. From an installed solar capacity of about 3 GW in 2014, India has crossed 171 GW in 2026. India's renewable energy programme has moved from setting targets to delivering capacity at scale. The next stage depends not only on adding capacity but on integrating it well: into the grid, into the supply chain, and into the local economies that host it. Agro-photovoltaics (Agro-PV) tests this principle in a demanding setting. When solar plants are built over working farmland, the quality of design, construction and grid connection determines whether the land stays productive and whether the plant serves its owners reliably over its working life.

I am delighted to see the launch of this *Agro-photovoltaics Policy Handbook* by the Ministry of New and Renewable Energy. It brings together, in a single framework, the engineering specifications for structures, foundations and electrical systems; standard system configurations with benchmark indicators; the assessment of grid readiness at the level of the distribution feeder; guidance on crops and water; and the testing and verification needed to show that a plant performs as designed. For manufacturers, developers and DISCOMs, this means clearer specifications and a consistent basis on which systems can be designed, built and compared.

The Handbook also looks ahead to standards and quality assurance. It records that Indian Standards specific to Agro-PV systems do not yet exist in a stand-alone form and that the Bureau of Indian Standards is developing one. It recommends a certification scheme covering modules, systems and projects, supported by quality-control measures and a staged path to adoption. These recommendations build on existing provisions, including those relating to the Approved List of Models and Manufacturers (ALMM) and domestic content, and aim to give the regulatory certainty that institutional and financial partners need to participate in the sector.

Work of this kind is possible only through collaboration between government, research institutions, the standards body and industry, and the Handbook reflects that approach. I hope that manufacturers, developers, DISCOMs, certifying agencies and financial institutions will use it to build Agro-PV systems that are safe, durable and fair to the farmers on whose land they stand.


(Shripad Naik)

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Foreword

Distributed renewable energy has become central to how India expands its clean energy capacity, and the availability of land is among the practical constraints that States and implementing agencies must work through. Agrophotovoltaics offers a way of adding solar capacity without taking cultivated land out of agricultural use. It also asks more of planners, engineers and administrators than a conventional solar project does, because the land must remain productive for the full operating life of the plant.

The *Agro-Photovoltaics Policy Handbook* for India is intended as a common technical reference for that task. It consolidates the expertise of several institutions into one coherent document that follows a project through its life: identifying sites suited to both farming and solar generation, including the readiness of the local grid; designing and engineering the plant; selecting crops and managing soil and water; operating and maintaining the installation; and monitoring, reporting and verifying its performance on the farm and on the grid.

For States Nodal Agencies, DISCOMs and other implementing agencies, it offers criteria that can be applied consistently across projects. For researchers, it offers monitoring protocols that make results comparable from site to site. For developers and farmer groups, it sets out plainly what a project proposal must address, including the crop plan and the protection of the farmer's interests.

The Handbook is open about its limits, and users should read it accordingly. Estimates of Agro-PV potential based on geospatial data are preliminary and require validation on the ground. Guidance on crop suitability is subject to update as per Center of Excellence on Agri-ICAR field trials are completed. The Indian Standard specific to AgroPV is still under development by the Bureau of Indian Standards.

I acknowledge the National Institute of Solar Energy, the Indian Council of Agricultural Research, the Bureau of Indian Standards, the Indian Institute of Technology Roorkee and the India Agrivoltaics Alliance, whose contributions in their respective areas are brought together in this Handbook. I hope it will help States and agencies plan and implement AgroPV projects on a sound technical footing, and generate the evidence by which this guidance can be improved.

(Santosh Sarangi)

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List of Abbreviations

Abbreviation	Expansion
AC / DC	Alternating current / Direct current
AgriPV	Agri-photovoltaics (agrivoltaics); used interchangeably in this Handbook
ALMM	Approved List of Models and Manufacturers
AMR	Automatic meter reading
APER	Loi relative à l'accélération de la production d'énergies renouvelables (France)
APR	Agri-Photovoltaic Performance Ratio
ASCE	American Society of Civil Engineers
BIS	Bureau of Indian Standards
BtM	Behind-the-meter
CAZRI	Central Arid Zone Research Institute (ICAR)
CEA	Central Electricity Authority
CEIG	Chief Electrical Inspector to Government
CFA	Central Financial Assistance
CFD	Computational fluid dynamics
CoE	Centre of Excellence
CPI	Consumer Price Index
CUF	Capacity Utilization Factor
DCR	Domestic Content Requirement
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DISCOM	Distribution Company
DLI	Daily light integral
DPR	Detailed Project Report
DT	Distribution Transformer
EC	Electrical conductivity
EIA	Environmental Impact Assessment
EL	Electroluminescence
EPC	Engineering, Procurement and Construction
ET / ETo / ETc	Evapotranspiration/reference ET/crop ET
FD / HD	Full-density / Half-density (panel configuration)
FGL	Finished ground level

Abbreviation	Expansion
FPO	Farmer Producer Organization
FRA	Forest Rights Act
GCR	Ground Coverage Ratio
GHI	Global Horizontal Irradiance
GIS	Geographic Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GM	Ground-mounted (PV)
HDG	Hot-dip galvanizing
HFL	Highest flood level
Hc	Clear height
IAA	India Agrivoltaics Alliance
ICAR	Indian Council of Agricultural Research
IARI	Indian Agricultural Research Institute
IEC	International Electrotechnical Commission
IoT	Internet of Things
IPM	Integrated pest management
IS	Indian Standard
ISO	International Organization for Standardization
LCOE	Levelized cost of electricity
LCP / LSP	Light compensation point / Light saturation point
LER	Land Equivalent Ratio
LLR	Land loss ratio
MAFF	Ministry of Agriculture, Forestry and Fisheries (Japan)
MiTE / MASE	Ministero della Transizione Ecologica / Ministero dell'Ambiente e della Sicurezza Energetica (Italy)
MNRE	Ministry of New and Renewable Energy
MoAFW	Ministry of Agriculture and Farmers' Welfare
MRV	Monitoring, Reporting and Verification
NA	Non-Agricultural (land reclassification)
NABARD	National Bank for Agriculture and Rural Development
NBSS	National Bureau of Soil Survey (ICAR-NBSS&LUP)
NISE	National Institute of Solar Energy

Abbreviation	Expansion
NREL	National Renewable Energy Laboratory (USA)
NSEFI	National Solar Energy Federation of India
O&M	Operation and maintenance
PAR	Photosynthetically active radiation
PESA	Panchayats (Extension to Scheduled Areas) Act
POA	Plane of array
PPA	Power Purchase Agreement
PPFD	Photosynthetic photon flux density
PR	Performance Ratio
QCO	Quality Control Order
RESCO	Renewable Energy Service Company
RFP	Request for Proposal
RPG	Renewable Power Generator
SCADA	Supervisory control and data acquisition
SEB	State Electricity Board
SECI	Solar Energy Corporation of India
SNA	State Nodal Agency
SOC	Soil organic carbon
SPD	Surge protective device
STC	Standard test conditions
TERI	The Energy and Resources Institute
TPIA	Third-Party Inspection Agency
VGf	Viability Gap Funding
WDPA	World Database on Protected Areas
WEF	Water-Energy-Food (nexus)
WPI	Wholesale Price Index
WUA	Water User Association
WUE	Water use efficiency

CHAPTER 1

DEFINITION, CLASSIFICATION AND TYPOLOGY OF AGRIPHOTOVOLTAICS (AgriPV) SYSTEMS

1.1 Definition of Agriphotovoltaics

The following are three distinct conceptual frameworks (OPTIONS) for agriphotovoltaics within the context of this Handbook.

Definition 1 - Dual Land-Use System (Technical-Legal Framing)

1.1.1 For the purposes of this Handbook, an AgriPV project is recommended to be defined as a solar photovoltaic (PV) installation on agricultural land, wherein solar panels are configured and elevated in a manner that enables dual and concurrent land use: agricultural production and electricity generation, subject to the following essential conditions:

- Agricultural production is recommended to be the primary activity and electricity generation is recommended to be the secondary activity on the designated land parcel. The economic and operational primacy of agriculture is not merely aspirational; it is recommended to be structurally supported through the design parameters, crop plans, and monitoring mechanisms recommended in this Handbook.
- Solar panels are recommended to be installed at an elevation sufficient to permit unhindered crop cultivation, irrigation operations, and mechanized farming activities underneath or around the panel structure.
- The agricultural land-use classification of the project site is advised to remain unchanged; no conversion or reclassification of land use is recommended to be required or permitted for purposes of establishing an AgriPV project.
- Agricultural yield is recommended not to be compromised below 80% of the baseline yield of the same crop on the same land under conventional unshaded cultivation (see Section 5.2.2). Projects that result in a sustained reduction of agricultural output beyond thresholds established in the annual monitoring framework are recommended to be subject to review and remedial action.



IMPLEMENTATION NOTE

A land parcel can retain its agricultural classification in revenue records while ceasing entirely to function as productive agricultural land. Classification is an administrative category - it does not guarantee that farming actually continues. Definition 1 protects the label and the agronomic reality. The yield-protection clause is therefore the operative safeguard, not the land classification. Monitoring mechanisms recommended in this Handbook give operational content to the yield-protection recommendation.

International Alignment - Definition 1:

Table 1.1: International Alignment - Definition 1

Country / Authority	Yield / Land Condition	GCR or Coverage Limit	Source
Japan (MAFF Solar Sharing)	≥ 80% of pre-installation crop yield SHALL be maintained annually; approval revoked if yield falls below threshold ¹	Shading rate capped at 27-39% (implied GCR limit)	MAFF Directive 2013; 3rd Amendment 2021
France (APER Law 2023 + Decree 2024)	≥ 90% of normal agricultural yield SHALL be maintained; projects denied/revoked if not met ²	Max GCR 40% for projects > 10 MW; land loss cap ≤ 10%	Loi APER n° 2023-175; Décret 2024-318
Germany (DIN SPEC 91434, 2021)	≥ 66% of reference agricultural relative yield required to qualify as agriphotovoltaic ³	Land loss ≤ 10% (Category I, overhead); ≤ 15% (Category II, interspace)	DIN SPEC 91434
Italy (MASE Guidelines, 2022)	70% of surface area SHALL remain available for agricultural activity	Max 40% PV coverage ⁴	Italian Environmental Ministry Guidelines

¹Japan Ministry of Agriculture, Forestry and Fisheries (MAFF). 2013 (amended 2021). Guidelines on Solar Sharing. Tokyo: MAFF. Original notification: Noushin Article 2131 (April 2013); 3rd Directive: Notification No. 2 Noushin Article 3854 (March 2021). The requirement that annual crop yield shall be no less than 80% of the average yield before PV installation has been the operative standard since 2013 and is enforced through annual cultivation reports submitted to prefectural authorities. Penalty: withdrawal of the temporary land conversion permit. See also: Doedt, C., Tajima, M., & Iida, T. (2024). "Agrivoltaics in Japan: A Legal Framework Analysis." AgriVoltaics Conference Proceedings, 1. <https://doi.org/10.52825/agripv.v1i.533>.

²République Française. 2023. Loi n° 2023-175 du 10 mars 2023 relative à l'accélération de la production d'énergies renouvelables (Loi APER). Implementing decree: Décret n° 2024-318 du 8 avril 2024. Key provisions relevant to AgriPV definition: (a) Agricultural production is the primary activity; energy is supplementary; (b) Large-scale projects (> 10 MW) must not exceed a GCR of 40%; (c) Land loss caused by structures, access roads, posts, and shading shall not exceed 10%; (d) Large-scale projects must maintain at least 90% of normal agricultural yield; (e) Structures with a torque tube at 4 m height distinguish "agrivoltaic" from mere "solar on agricultural land." See also: AFNOR Certification. 2022. "Projet agrivoltaïque" label criteria. <https://www.afnor.org>.

³Deutsches Institut für Normung (DIN). 2021. DIN SPEC 91434: Agrivoltaic Systems - Requirements and Test Methods. Berlin: DIN. Under this standard, Category I (elevated overhead systems) must preserve at least two-thirds (≥ 66%) of the reference agricultural relative yield; Category II (lower systems) allows up to 15% ground coverage; soil protection and full reversibility/removability are mandatory. See also: Böhm, J. et al. (2024). "Key Advantages of Agrivoltaic Systems in Germany." AgriVoltaics Conference Proceedings, 2. <https://doi.org/10.52825/agripv.v2i.1005>.

⁴Ministero della Transizione Ecologica (MiTE). 2022. Linee Guida in materia di Impianti Agrivoltaici [Guidelines on agrivoltaic installations]. Rome: MiTE (now Ministero dell'Ambiente e della Sicurezza Energetica), June 2022. Available: <https://www.mase.gov.it>.

Country / Authority	Yield / Land Condition	GCR or Coverage Limit	Source
India (proposed)	Agricultural yield is recommended not to be compromised below 80% of baseline; projects with sustained yield loss subject to remediation	Pathways, inverter pads and access: agricultural land loss (LLR) 10-15%; GCR 30-40% for suggestive field crops (advisory); the range may vary depending on crop and site-specific conditions	Through this Handbook

Note: International research demonstrates that a GCR below 25% is generally required to ensure that crop relative yields remain above 80%, across a range of crop types and system configurations.⁵ Indian parameters align with this benchmark while allowing wider spacing for mechanized farming.

Definition 2 — Agricultural Producer and Energy Generator Identity (Rights-Based Framing)

1.1.2 For the purposes of this Handbook, in an AgriPV project, the Renewable Power Generator (RPG) on whose land the project is established is recommended to hold the concurrent identity of agricultural producer and energy generator such that:

- In the capacity of agricultural producer, the farmer remains the primary actor on the land, responsible for, and entitled to the full benefits of, the cultivation, irrigation, harvesting, and sale of crops grown on the project site throughout the project period.
- In the capacity of energy generator, the RPG participates in the solar power enterprise conducted on the same land - whether directly as the RPG or as a beneficiary of the revenue stream arising from power sold to the grid - and is recommended not to be reduced to the role of a passive land lessor whose connection to the energy enterprise is limited to the receipt of a fixed lease rent without any participation in, or recourse to, the project's energy economics.
- The agricultural yield of the site is recommended not to be subordinated to energy optimization goals. Where a trade-off between panel configuration and crop light access arises, the panel configuration *is advised to* yield to agronomic requirements.

⁵Dupraz, C. 2023 (print 2024). "Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity." *Agroforestry Systems*, 98(8), 2679–2696. <https://doi.org/10.1007/s10457-023-00906-3>.

 IMPLEMENTATION NOTE	<p><i>Developers may serve as the RPG. In developer-led models, the farmer is structurally a land lessor. Definition 2 does not prohibit developer-RPG arrangements; it establishes a minimum protection floor: the farmer is recommended to retain the benefits of agricultural production and is recommended not to be wholly disintermediated from the energy enterprise. The revenue-sharing and rights provisions in Section 1.4 (Business Models) operationalize this protection for each model type.</i></p>
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International Alignment - Definition 2:

This definition corresponds most closely to the farmer-centric co-benefit model advocated in the IEA PVPS Task 13 (2025) framework, which identifies farmer income enhancement and preservation of farmer agency as critical social acceptance factors for agriphotovoltaic deployment.⁶ The India Agrivoltaics Alliance (IAA) similarly emphasizes that “farmers are the cornerstone of agriphotovoltaic systems, providing the land and managing agricultural activities” and that “neither farming nor energy generation is compromised” in any model.⁷

Definition 3 — Electricity Generation as a Second Activity (Agronomic-Policy Framing)

1.1.3 For the purposes of this Handbook, the generation of electricity by the solar photovoltaic installation on an AgriPV project site is recommended to be recognized as a second activity on the designated land parcel, the first activity being the agricultural production on the same land parcel across its Kharif (monsoon), Rabi (winter) and, where practiced, Zaid (summer) seasons. Both activities draw on the same incident solar resource. Electricity is therefore treated as an additional income from the land and not as a crop; the expression “third crop” MAY be used informally to promote AgriPV but is recommended not to be used in project documents, agreements or eligibility assessments. The second activity is subject to the following essential conditions:

- The second activity is recommended to be understood as an additional and supplementary source of income from the land arising from the same parcel, the same sunlight, and the same farmer, and is recommended to neither substitute nor displace the agricultural production that constitutes the primary output of the land parcel.

⁶IEA PVPS Task 13. 2025. Dual Land Use for Agriculture and Solar Power Production: Overview and Performance of Agrivoltaic Systems. Report T13-29-2025. International Energy Agency Photovoltaic Power Systems Programme. Available: <https://iea-pvps.org>. The report reviews international definitions and concludes that “countries with a narrower definition like Japan, Germany, and France have set minimum agricultural production requirements to ensure the agricultural relevance of agrivoltaic systems.” It identifies farmer income enhancement and preservation of farmer agency as critical social acceptance factors.

⁷India Agrivoltaics Alliance (IAA). 2024. Business Models of Agrivoltaics and its Potential Socio-economic Impacts. New Delhi: IAA Secretariat/NSEFI. Version 1.0, 16 July 2024. Working Committee Chair: CSTEP. Available: <https://indiaagripv.org>. The IAA is anchored at the National Solar Energy Federation of India (NSEFI) and includes TERI, CEEW, CAZRI, IWMI, ISAE, GIZ (IGEF), CSTEP, and Shakti Sustainable Energy Foundation among its steering organizations. The publication classifies four primary business models (Individual Farmer-Owned, Community-Owned/FPO, Developer-Owned, DISCOM-Owned) and four variant models, and provides detailed CapEx/OpEx breakdowns for each.

- The second activity derives its character and its policy legitimacy solely from its co-existence with agricultural production on the same land parcel. A solar installation from which agricultural production has been displaced, abandoned, or rendered residual loses the character of a second activity and is recommended not to be treated as an AgriPV project for the purposes of this Handbook.
- The output of the second activity will, by design and intent, reflect the agronomic priority accorded to agricultural production, including the reservation of incident solar radiation for crop photosynthesis, the structural spacing required for mechanized farming, and seasonal variation in generation arising from crop management activities. DISCOMs, State Electricity Regulatory Commissions, and grid planning authorities *are advised to* take this into account in tariff determination and capacity utilization assessments applicable to AgriPV projects covered by this Handbook.

 IMPLEMENTATION NOTE	<p><i>The reference to the Kharif, Rabi and Zaid seasons describes the agricultural calendar around which generation operates; it does not imply that any particular crop (for example paddy, wheat, maize or pulses, which appear on the Negative List in Boundary Conditions, Section 1.2, on grounds of shade incompatibility) is permitted. The Positive and Negative Lists in Section 1.2 govern which crops are recommended to be cultivated; Definition 3 governs only the conceptual and policy status of electricity generation as a second activity. The Negative List prevails over any implied crop permission in Definition 3.</i></p>
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International Alignment - Definition 3:

The “second activity” framing is conceptually analogous to Japan’s “solar sharing” framework, where electricity generation is treated as an additional income layer that shares the same incident solar resource as the food crop below, with the food crop retaining priority on incident radiation.⁸ The French APER framework articulates the same principle: “*energy production is supplementary and must not compromise agricultural production.*”⁹ India’s

⁸Japan Ministry of Agriculture, Forestry and Fisheries (MAFF). 2013 (amended 2021). Guidelines on Solar Sharing. Tokyo: MAFF. Original notification: Noshin Article 2131 (April 2013); 3rd Directive: Notification No. 2 Noshin Article 3854 (March 2021). The requirement that annual crop yield shall be no less than 80% of the average yield before PV installation has been the operative standard since 2013 and is enforced through annual cultivation reports submitted to prefectural authorities. Penalty: withdrawal of the temporary land conversion permit. See also: Doedt, C., Tajima, M., & Iida, T. (2024). “Agrivoltaics in Japan: A Legal Framework Analysis.” AgriVoltaics Conference Proceedings, 1. <https://doi.org/10.52825/agripv.v1i.533>.

⁹République Française. 2023. Loi n° 2023-175 du 10 mars 2023 relative à l’accélération de la production d’énergies renouvelables (Loi APER). Implementing decree: Décret n° 2024-318 du 8 avril 2024. Key provisions relevant to AgriPV definition: (a) Agricultural production is the primary activity; energy is supplementary; (b) Large-scale projects (> 10 MW) must not exceed a GCR of 40%; (c) Land loss caused by structures, access roads, posts, and shading shall not exceed 10%; (d) Large-scale projects must maintain at least 90% of normal agricultural yield; (e) Structures with torque tube at 4 m height distinguish “agrivoltaic” from mere “solar on agricultural land.” See also: AFNOR Certification. 2022. “Projet agrivoltaïque” label criteria. <https://www.afnor.org>.

framing extends this to explicitly acknowledge the seasonal agricultural calendar of Kharif, Rabi and Zaid as the primary temporal structure around which solar generation operates.

1.2 Boundary Conditions

The following technical and operational conditions are recommended to guide the design, installation, and operation of AgriPV projects. All standards below are marked [ADVISORY] and represent best practice guidance; deviations are advised to be documented and justified in the project application.

Table 1.2: Boundary Conditions for AgriPV Projects

Parameter	Standard
Solar Capacity	Up to 2 MW for plains; 300-500 kW for hilly terrain. Projects in high-value horticulture/plantation clusters under BtM or cooperative models <i>MAY</i> extend to 2-5 MW subject to feeder load capacity and State Nodal Agency approval.
Proximity to Substation	≤ 5 km (general); state-specific relaxations may apply in notified zones. Distance is recommended to be measured as achievable line-routing distance, not straight-line.
Land-Use Classification	No change in land-use classification is recommended to be required or permitted.
Structure Height	<i>Minimum</i> 3 metres clear height, measured from finished ground level to the lowest point of any module or structural member (see Section 3.3.1). <i>Recommended</i> 4.0-4.5 metres clearance for standard tractor operations and mechanized row-crop farming. 5.0 metres clearance is recommended where combine harvester access is specified in the crop plan. ^{10, 11} An absolute structural height (top edge of panel) <i>is advised not to exceed</i> 6.0 metres without engineer-certified justification. France’s agriphotovoltaic auction framework uses 4m at torque tube level as the definitional threshold distinguishing AgriPV from ground-mounted PV on agricultural land. ¹²

¹⁰SurgePV. 2026. Agrivoltaics: How Solar and Farming Work Together - Technical Guide. March 2026. Clearance height specifications by agricultural use case: hand-tool crops (≥ 2.1 m); compact tractors (≥ 3.2 m); standard agricultural tractors (≥ 4.0–4.5 m); combine harvesters (≥ 5.0 m). Available: <https://www.surgepv.com>. See also: Solaracks. 2026. Agrivoltaics Mounting Structures: Design Guide. Notes: “For most commercial agrivoltaic projects combining row crops and mechanized farming, a clear height of 3.0-4.5 metres covers the majority of operations.” <https://www.solaracks.com>.

¹¹Fraunhofer Institute for Solar Energy Systems ISE. 2021. AGRIPV-RESOLA: Agrivoltaics - Research on Optimizing Land Use Solutions. Freiburg: Fraunhofer ISE. The AGRIPV-RESOLA demonstration project near Lake Constance operated at a 5 m clearance height with a 194 kWp capacity over wheat, potatoes, celery, and clover, demonstrating that full combine-harvester access is achievable at 5 m. The project is the primary scientific reference for mechanized overhead agrivoltaics. See also: Weselek, A. et al. (2021). “Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate.” *Agronomy for Sustainable Development*, 41(5), 59. <https://doi.org/10.1007/s13593-021-00714-y>.

¹²République Française. 2023. Loi n° 2023-175 du 10 mars 2023 relative à l’accélération de la production d’énergies renouvelables (Loi APER). Implementing decree: Décret n° 2024-318 du 8 avril 2024. Key provisions relevant to AgriPV definition: (a) Agricultural production is the primary activity; energy is supplementary; (b) Large-scale projects (> 10 MW)

Parameter	Standard
Row and Column Spacing	Column-to-column: <i>approximately</i> 42 ft; Row-to-row: <i>approximately</i> 21 ft. Spacing <i>is advised</i> to be calibrated to site latitude, crop row geometry, and the working width of farming machinery. Wider spacing reduces GCR and improves agronomic performance.
Land Loss and Ground Coverage (GCR)	The recommended LLR is 10-15% of the net cultivated area of the project site. International research indicates GCR below 25% is generally required to maintain crop relative yields above 80%. ¹³ GCR (ratio of module area to ground area) is recommended at 30-40% for suggestive field crops; this range may vary depending on crop and site-specific conditions.
Crop Suitability: Positive List	Vegetables (including leafy greens, capsicum, brinjal, okra), soybean, cash crops, fodder, spices (turmeric, ginger, cardamom), floriculture, and orchard systems (case-dependent). This list is informed by the ongoing crop suitability matrix being developed at the ICAR-IARI Centre of Excellence for AgriPV, ¹⁴ ICAR-CAZRI field trials in arid zones, ¹⁵ and the global shade-tolerance literature reviewed by Yadav et al. (2025). ¹⁶

must not exceed a GCR of 40%; (c) Land loss caused by structures, access roads, posts, and shading shall not exceed 10%; (d) Large-scale projects must maintain at least 90% of normal agricultural yield; (e) Structures with a torque tube at 4 m height distinguish “agrivoltaic” from mere “solar on agricultural land.” See also: AFNOR Certification. 2022. “Projet agrivoltaïque” label criteria. <https://www.afnor.org>.

¹³Dupraz, C. 2023 (print 2024). “Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity.” *Agroforestry Systems*, 98(8), 2679-2696. <https://doi.org/10.1007/s10457-023-00906-3>. The paper synthesizes published data and demonstrates that a GCR below 25% is generally required to ensure that crop relative yields remain above 80% across a range of crop and system configurations. Relative yield thresholds for specific Indian crops under specific GCR values will be refined as CoE-AgriPV (Footnote 15) data matures.

¹⁴Centre of Excellence for AgriPV (CoE-AgriPV). ICAR-Indian Agricultural Research Institute (IARI), New Delhi, and National Institute of Solar Energy (NISE), Gurugram. Approved by MNRE, supported by GIZ India. The CoE is developing a location-specific crop suitability design matrix for Indian agro-climatic zones, with ongoing research on shading effects, spectral reflectance from crop canopies, and LCOE estimation across zones. A national workshop on AgriPV status and opportunities was held on 20 March 2024 at ICAR-IARI, New Delhi. Available: <https://coeagripv.iari.res.in>. See also: ICAR. 2025. “German Delegation Explores Indo-German Collaboration during Visit to ICAR-IARI.” <https://www.icar.gov.in>.

¹⁵ICAR-Central Arid Zone Research Institute (CAZRI), Jodhpur. Pilot agrivoltaic studies under arid Rajasthan conditions: elevated polycrystalline PV modules at 4 m height over moth bean, cluster bean, and aloe vera showed 10-15% yield improvement for shade-tolerant crops with 30-40% partial shading, 3-4°C reduction in soil temperature, and 25-30% improvement in soil moisture. Study: Pulipaka, S. & Peparthy, M. 2021. *Agrivoltaics in India: Overview of Operational Projects and Relevant Policies*. New Delhi: NSEFI. See also: Yadav, D., Babu, S., Rathore, S.S., & Rana, D.S. 2025. “Agri-photovoltaics: Integrating agricultural production and energy generation for sustainable resource use.” *Indian Journal of Agronomy*, 70 (6th IAC Special Issue): S79–S87. ICAR-IARI, New Delhi.

¹⁶Yadav, D., Babu, S., Rathore, S.S., & Rana, D.S. 2025. “Agri-photovoltaics: Integrating agricultural production and energy generation for sustainable resource use.” *Indian Journal of Agronomy*, 70 (6th IAC Special Issue): S79–S87. ICAR-Indian Agricultural Research Institute, New Delhi. This peer-reviewed ICAR publication reviews agrivoltaic system designs and performance across global and Indian studies, including CAZRI arid zone trials and Maharashtra banana plantation results (140% increase in banana yield; 55% water savings under 250 kWp single-axis tracking system). Available: <https://www.researchgate.net/publication/398038682>.

Parameter	Standard
Crop Restrictions: Negative List	Wheat, sugarcane, paddy, maize, pulses (as primary crops beneath the array). Site-specific exceptions may be considered by MNRE upon submission of an agronomic justification supported by ICAR or a recognized agricultural university, demonstrating that the specific cultivar and system design achieve $\geq 80\%$ of baseline yield under shaded conditions. ¹⁷ Moderate and low shade-tolerant crops <i>MAY</i> be cultivated in the unshaded inter-row spaces between panel arrays where light exposure exceeds 50% (see Section 4.1).
Module Type	DCR-compliant bifacial modules.
Inverter / Cabling / Cleaning	String inverters preferred; above-ground cable routing recommended; mechanized or low-water panel cleaning <i>is advised to</i> be specified.
Project Implementation Timeline	12 months from the date of registration.

1.3 Implementation Arrangements

- The Renewable Energy Power Plants (REPP) covered by this Handbook is recommended to be installed by the farmer on his own agricultural land, either directly or in partnership with a group of farmers, cooperatives, panchayats, Farmer Producer Organizations (FPOs), or Water User Associations (WUAs), or through a developer as described under the Business Models in Section 1.4.
- A group of farmers, cooperatives, panchayats, FPOs, or WUAs *MAY* develop an AgriPV project through a developer. The farmer *MAY* provide land to the DISCOM, which is then recommended to be registered as the RPG. In such a case, the landowner is recommended to receive lease rent as mutually agreed between the parties. The lease rent *MAY* be structured as ₹__ per year per acre, or as ₹__ per unit of electricity generated per acre, or as a combination of the two. In a Model Land Lease Agreement, the terms therein represent minimum protections and are recommended not to be reduced by mutual consent.
- At the time of application, the RPG is recommended to submit a Crop Plan confirming that:

¹⁷Dupraz, C. 2023 (print 2024). "Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity." *Agroforestry Systems*, 98(8), 2679–2696. <https://doi.org/10.1007/s10457-023-00906-3>. The paper synthesizes published data and demonstrates that a GCR below 25% is generally required to ensure that crop relative yields remain above 80% across a range of crop and system configurations. Relative yield thresholds for specific Indian crops under specific GCR values will be refined as CoE-AgriPV (Footnote 15)14 data matures.

- The crops proposed to be cultivated on the project site fall within the Positive List; and
- The proposed GCR, row spacing, and panel clearance height are compatible with the cultivation, harvest, and irrigation needs of the proposed crops. Where the proposed crop is not in the Positive List, prior approval of the competent authority is recommended to be obtained before submission of the application to the DISCOM, supported by an agronomic justification (Negative List exception clause).

1.4 Business Models for AgriPV Projects

AgriPV projects covered by this Handbook *MAY* be implemented through any of the following four business models. These models are drawn from and consistent with the India Agrivoltaics Alliance (IAA) framework for business model classification, published in July 2024.¹⁸

Farmer Rights — Recommended Across All Models

Irrespective of the business model adopted, the following rights of the farmer/landowner are recommended to be protected in every AgriPV project covered by this Handbook:

- **Right to land ownership:** The agricultural land is advised to remain the property of the landowner throughout the project period.
- **Right to agricultural operations:** The farmer is recommended to retain the right to cultivate, irrigate, harvest, and manage crops on the project site. No instruction to cease or curtail agricultural operations may be issued by any developer, DISCOM, or third party without a remediation mechanism specified in the agreement.
- **Right to agricultural income:** All income from the sale of agricultural produce is recommended to accrue exclusively to the farmer, unless a voluntary and explicitly documented revenue-share arrangement on agricultural produce is agreed in writing with full disclosure of prevailing market prices.
- **Right to information:** The farmer is recommended to have the right to receive annual reports on electricity generation, tariff receipts, and any lease or revenue-share calculations.
- **Right of recourse:** The farmer is recommended to have access to the dispute resolution mechanism without requiring legal representation for claims below ₹5 lakh.

Note: Schematics follow the layout, nodes, arrows, and labels of the IAA diagrams (Red = Investment, Green = Revenue) in a different colour treatment.

¹⁸India Agrivoltaics Alliance (IAA). 2024. Business Models of Agrivoltaics and its Potential Socio-economic Impacts. New Delhi: IAA Secretariat/NSEFI. Version 1.0, 16 July 2024. Working Committee Chair: CSTEP. Available: <https://indiaagripv.org>. The IAA is anchored at the National Solar Energy Federation of India (NSEFI) and includes TERI, CEEW, CAZRI, IWMI, ISAE, GIZ (IGEF), CSTEP, and Shakti Sustainable Energy Foundation among its steering organizations. The publication classifies four primary business models (Individual Farmer-Owned, Community-Owned/FPO, Developer-Owned, DISCOM-Owned) and four variant models, and provides detailed CapEx/OpEx breakdowns for each.

Model 1: Farmer-Owned Model (Individual Farmer Owned)

Source: IAA - Business Models for Agriphotovoltaic in India analysis of Various Business Models and Their Socio-Economic Impact

The AgriPV project is recommended to be developed, owned, and operated by an individual farmer on his/her own agricultural land. The farmer is recommended to undertake agricultural activities and is entitled to the full benefits arising from the sale of both electricity and agricultural produce.

Farmer Rights: Under this model, the farmer is simultaneously the landowner, the RPG, the energy generator, and the agricultural producer. The farmer retains all ownership, income, and decision-making rights. No third-party arrangement can alter this without the farmer's explicit written consent.

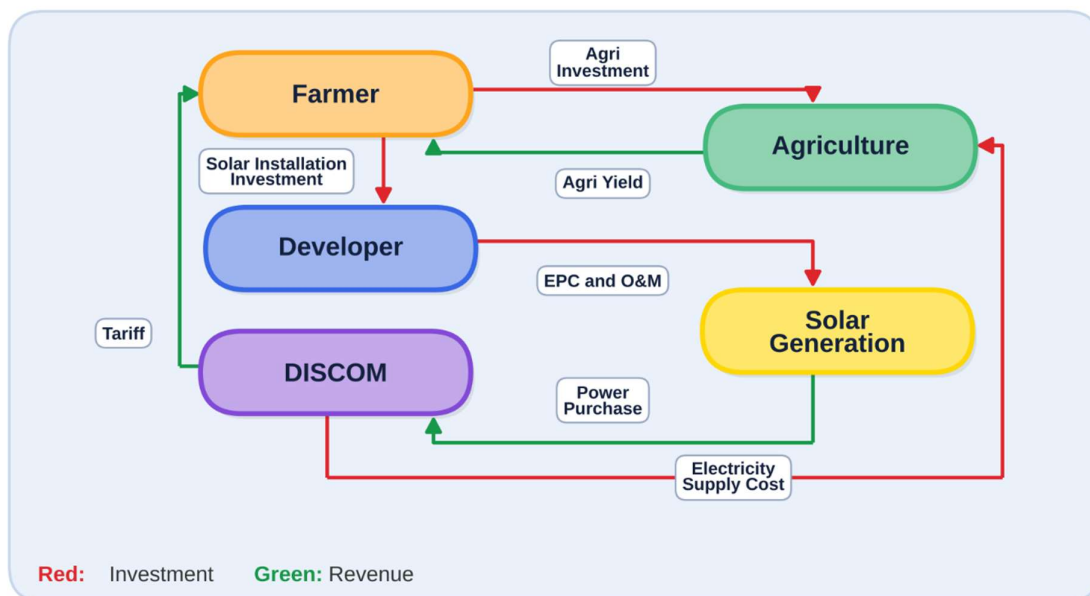
Investment Structure - CapEx Model:

The farmer is recommended to fund 100% of the solar infrastructure capital cost, which *MAY* be structured as: - Equity from the farmer's own resources; - Bank/NBFC loan against project assets or land collateral; - State-level subsidy channelled through the SNA.

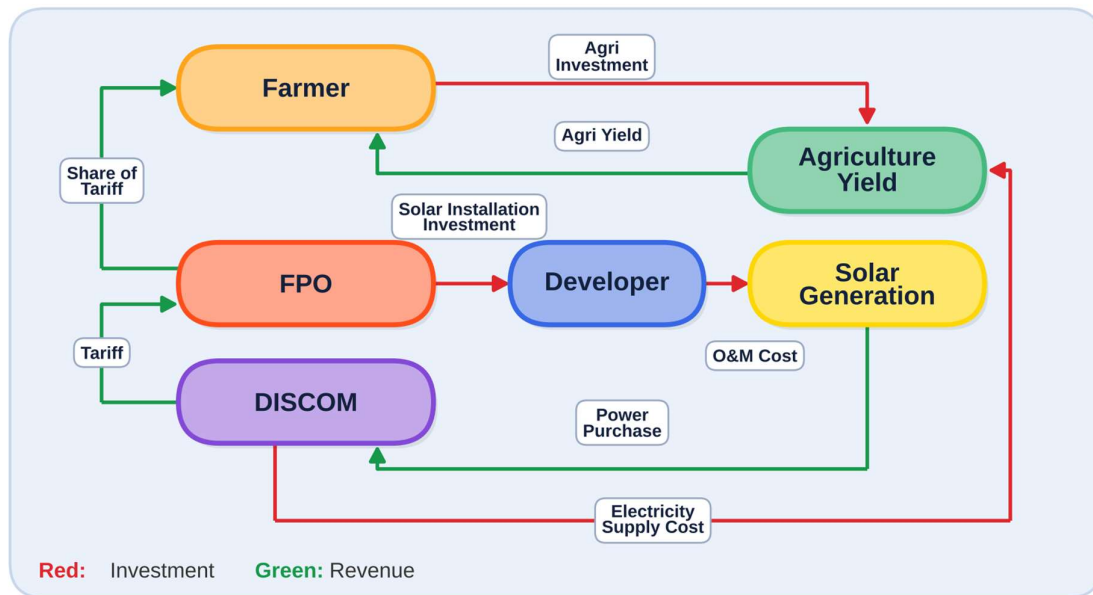
Operational expenditure (O&M) MAY be outsourced to an EPC provider under a maintenance agreement. The farmer retains ownership of all assets.

Revenue Streams: Electricity tariff from DISCOM PPA + income from agricultural produce.

Recommended for: Land-owning farmers with ≥ 2 acres available, access to institutional credit, and proximity to an 11 kV feeder within 5 km.



Model 2: Community-Owned Model (Community-Owned by Farmer Producer Organizations)



Source: IAA - Business Models for Agriphotovoltaic in India analysis of Various Business Models and Their Socio-Economic Impact

The AgriPV project is recommended to be developed and owned by a group of farmers, Cooperatives, Panchayats, Farmer Producer Organizations (FPOs), or Water User Associations (WUAs), either directly or through an authorized entity. Participating farmers are recommended to continue agricultural activities on their respective land parcels.

Farmer Rights: Individual participating farmers retain ownership of their land parcels and full rights to agricultural income therefrom. Revenue from electricity sales is recommended to accrue to the community institution in accordance with its governing framework, provided that:

- No participating farmer is denied access to their land for agricultural operations;
- Revenue distribution among members is recommended to be governed by a transparent profit-sharing formula disclosed to all participants before registration;
- No farmer is recommended to be required to contribute land without a formal land contribution agreement specifying the terms of use and exit arrangements.

Investment Structure - CapEx Model:

The FPO/Cooperative/**Panchayat is recommended to** arrange project financing through:

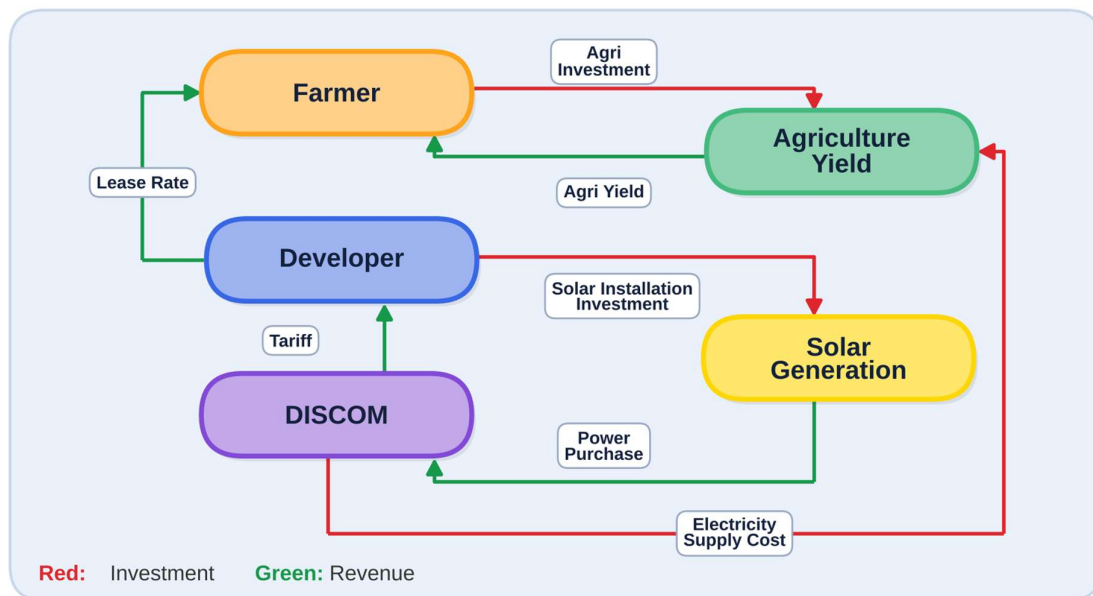
- Pooled equity from member farmers;
- Institutional loans (NABARD, cooperative banks, NBFC);
- CFA channelled through the community institution as RPG.

The community institution is advised to engage an EPC contractor for installation and MAY engage an O&M provider for system maintenance. Financial management is advised to be subject to annual external audit.

Revenue Streams: Electricity tariff (to community institution, distributed per agreed formula) + individual agricultural income.

Recommended for: Clusters of smallholder farmers where aggregated community land enables viable capacity; regions with established FPO infrastructure.

Model 3: Developer-Led Model - Sub-variant A (Developer-Led)

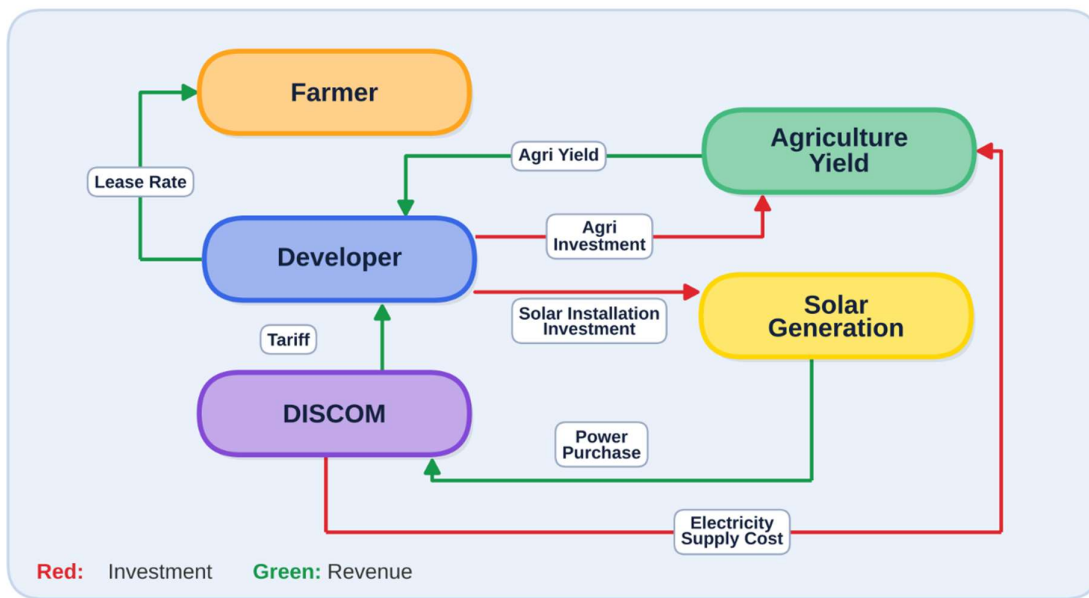


Source: IAA - Business Models for Agriphotovoltaic in India: Analysis of Various Business Models and Their Socio-Economic Impact

Model 3: Developer-Led Model - Sub-variant B (Developer-Managed)

The AgriPV project may be developed, owned, and operated by a Project Developer on agricultural land taken on lease from an individual farmer or eligible community institution. The developer may undertake either:

- **Sub-variant A (Developer-Led):** Developer owns and operates the solar installation; the farmer continues all agricultural operations independently and retains all agricultural income.
- **Sub-variant B (Developer-Managed):** Developer owns and operates both the solar installation and the agricultural operations, directly or through an agricultural contractor. The farmer/landowner receives lease rent; agricultural income may be shared per agreement.



Source: IAA - Business Models for Agriphotovoltaic in India: Analysis of Various Business Models And Their Socio-Economic Impact

Farmer Rights: The following rights are recommended to be protected in both sub-variants regardless of the specific arrangement:

- Continued land ownership throughout the lease period.
- Right to agricultural operations: In Sub-variant A, the farmer is recommended to independently manage all farming. In Sub-variant B, where the developer manages agriculture, the farmer is recommended to retain the right to inspect agricultural operations, receive the agreed share of agricultural income, and terminate the agricultural management arrangement with [notice period per Lease Agreement] if farming standards are not maintained. Selection of crops is recommended to be done in consultation with the farmers.
- Lease arrangements, including lease rental payments, are to be discussed and determined by the respective State, considering that agriculture is a State List subject. The following points are indicative and are not intended to prescribe a uniform lease arrangement:
 - i. Not less than the fair market rental value of the land for comparable agricultural use in the district;
 - ii. Indexed annually to the Wholesale Price Index (WPI) or All-India CPI (Rural), whichever is higher;

- iii. Paid punctually on the dates specified in the Lease Agreement, with a grace period of not more than 30 days;
 - iv. Secured by a performance bank guarantee held by the SNA.
- The farmer is recommended not to bear any cost of solar infrastructure installation, operation, or maintenance.
 - The farmer is recommended to receive the project's annual electricity generation report.

Investment Structure — CapEx Mode:

The developer is recommended to fund 100% of the solar infrastructure capital cost. Revenue flows: electricity tariff receipts to developer; lease rental + agricultural income to farmer (Sub-variant A) or lease rental + agricultural income share to farmer (Sub-variant B).

Investment Structure — RESCO / OpEx Mode:

Under the RESCO model, the developer installs and operates the AgriPV plant under a long-term services agreement with the DISCOM or community institution, without requiring the farmer to contribute equity. Revenue flow is structured as: - DISCOM pays a services fee/tariff to the RESCO developer for electricity supplied; A portion of the RESCO revenue is recommended to be shared with the farmer as a revenue-share component, the minimum rate of which *is advised to be specified* in the model RESCO agreement.

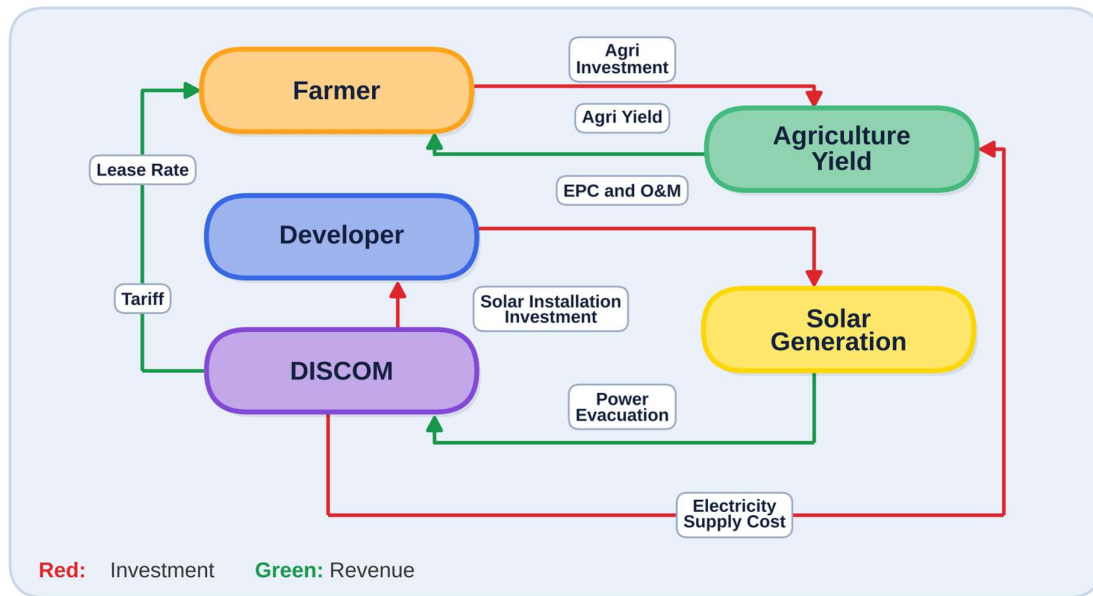
RESCO mode is recommended for areas where farmer equity is constrained, land holdings are fragmented, and developer financing is available at competitive terms.

Revenue Streams: Electricity tariff to developer (CapEx) or RESCO fee (RESCO mode) + lease rent and/or agricultural income to farmer.

Recommended for: Large-format projects where developer capital and technical capacity accelerate deployment; regions where farmers prefer stable lease income over project risk.

Model 4: State/Public Utility-Facilitated Model (IAA: DISCOM-Owned)

The AgriPv project *MAY* be developed, owned, and operated by a Distribution Licensee (DISCOM), State Electricity Board, or State-designated public entity on agricultural land taken on lease from eligible landowners. The public entity is recommended to be entitled to the benefits arising from the utilization or sale of electricity.



Source: IAA - Business Models For Agriphotovoltaic In India Analysis Of Various Business Models And Their Socio-Economic Impact

Farmer Rights: The following rights are recommended to be protected:

- Land ownership remains with the farmer throughout.
- Agricultural operations continue under farmer control. The farmer is recommended to retain full rights to cultivate, harvest, and sell agricultural produce.
- All income from agricultural produce is recommended to accrue to the farmer.
- **Lease rental payments are recommended to be:**
 - i. Based on a published rate notified by the SNA, pegged to local agricultural land rental benchmarks;
 - ii. Indexed annually to WPI or CPI (Rural);
 - iii. Paid by the public entity directly into the farmer's bank account;
 - iv. Secured by the public entity's balance sheet commitment under the arrangement.
- The lease agreement is recommended to be formally registered, and the farmer is recommended to receive a certified copy before commencement of construction.
- The farmer is *advised to* have priority access to any captive or subsidized power supply facilitated by the installation for on-farm use, where technically and commercially feasible.
- The public entity is recommended to provide the farmer with an annual electricity generation statement.

Investment Structure - RESCO / OpEx Mode:

The public entity *MAY* engage a private developer on a competitive tender basis to install, own, and operate the plant under a 25-year services agreement, with the public entity as the electricity off-taker. In all RESCO arrangements, the public entity is recommended to ensure that farmer rights enumerated above are fully incorporated into the tripartite agreement among the farmer, the developer, and the public entity.

Revenue Streams: Electricity (utilized by or sold by the public entity) + lease rental and agricultural income to the farmer.

Recommended for: Remote or hilly areas where private developer interest is limited; regions where farmer financial capacity is insufficient for independent investment.

Provided that, under all four business models, the ownership of the agricultural land is recommended to remain with the respective landowner(s), and the implementation arrangement is advised to be governed by the agreements executed between the participating entities and the provisions of this Handbook. No business model arrangement is recommended to have the effect of permanently alienating the farmer from their land or from the primary benefits of agricultural production on that land.

CHAPTER 2

SITE ASSESSMENT

This chapter sets out the site-assessment process for AgriPV projects. It moves from a GIS-based estimate of AgriPV potential (Section 2.1), through feeder-level grid readiness (Section 2.2) and site-level biophysical, infrastructure, and land-tenure, to regulatory compliance (Section 2.4). The purpose is to identify sites where agricultural production can continue as the primary land use alongside solar generation, before resources are committed to detailed project design. The methodology and criteria draw substantially on TERI (2025).¹⁹

The stages of the assessment and the points at which a site exits the process are summarized in Figure 2.1.

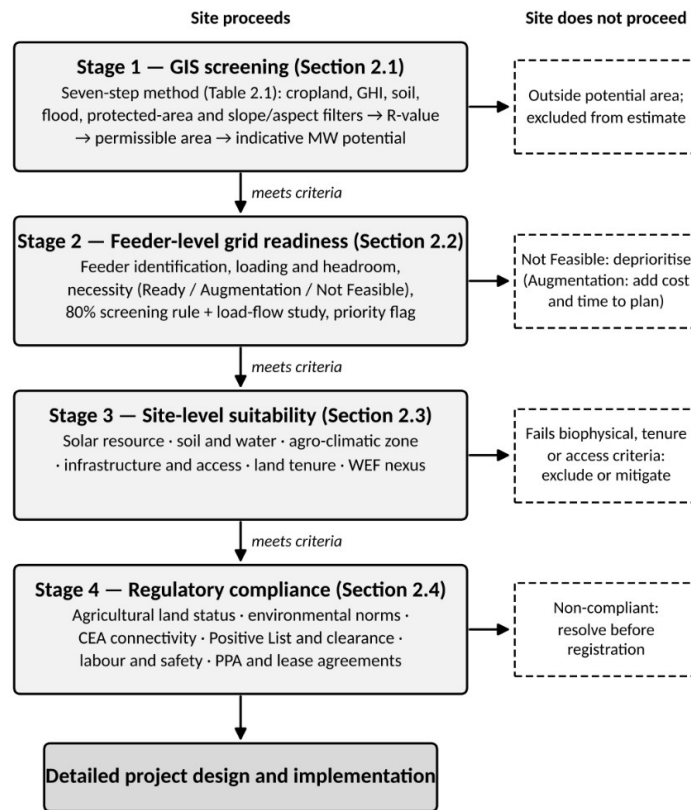


Figure 2.1: Site-assessment workflow for AgriPV projects (summary of Sections 2.1–2.4)

¹⁹TERI. 2025. *Agri-Photovoltaics Potential in India: Pathways for Sustainable Energy–Food Solutions*. The Energy and Resources Institute, New Delhi. This is the primary source document for the 7-Step GIS Methodology (Figure 5, p. 15), the R-value weighted suitability framework, the GHI threshold of ≥ 4.5 kWh/m²/day, the power density range (0.42–0.75 MW/ha), and the agro-climatic zone alignment tables. The GIS methodology, biophysical suitability criteria (Section 2.3), and infrastructure accessibility criteria (Section 2.3.4) in Chapter 2 of this Handbook are adapted from TERI (2025) with permission. All tables in Chapter 2 reproduced or adapted from this source carry the attribution: “Source: Adapted from TERI (2025), [Table/Figure reference].” Sources: Sections 2.1 and 2.3 are largely adapted from TERI (2025), with technical elaboration on grid-readiness (Sections 2.2 and 2.3.4) and land tenure (Section 2.3.5). Where data or criteria are drawn from TERI research, this is noted at the section head.

2.1 GIS Methodology for AgriPV Potential Assessment

TERI Methodology Note - Slope Threshold and Aspect Filter

Terrain and external shadowing are screened using slope and aspect exclusion criteria applied in the underlying GIS suitability methodology: sites with slope $\geq 8^\circ$ are recommended to be excluded from consideration, and only sites with S/SE/SW-facing aspect are retained as suitable. This threshold is more permissive than the $\sim 5^\circ$ threshold commonly cited in European AgriPV literature, reflecting India's more varied topography and the ability of elevated overhead structures to accommodate moderately sloped terrain through appropriate foundation design. Both the slope and aspect filters are applied as eliminatory criteria at the GIS-screening stage (Step 2 of Table 2.1); a site failing either filter is excluded regardless of performance on other biophysical measures. External shadowing from features below satellite resolution (adjacent tree lines, structures) remains a separate field-verification item, applied independently of the slope/aspect screen.

Table 2.1: 7-Step GIS Methodology for AgriPV Potential Assessment

Step	Description	Data Sources and Technical Parameters
1. Resources Identification	Establish the universe of agricultural land available for AgriPV assessment. Total agricultural area under cultivation (State-wise) = X	Ministry of Agriculture and Farmers' Welfare (MoAFW): State-wise agricultural land area statistics (2024-25).
2. GIS Restriction Criteria	Apply sequential geospatial exclusion filters to identify the suitable sub-area $Y \subseteq X$ satisfying all biophysical and environmental constraints.	Land Use (ESA/ESRI): cropland extent extracted. Solar GHI (Global Solar Atlas): $GHI \geq 4.5 \text{ kWh/m}^2/\text{day}$ extracted. Soil Productivity (ICAR-NBSS): only productive soil types retained. Flood Hazards (NASA/SRTM): extreme event-prone regions excluded. Protected Areas (WDPA): 1 km buffer excluded. Slope/Aspect (NASA/SRTM): Slope $< 8^\circ$; S/SE/SW aspects retained.
3. Weighted R-Value	Derive a spatially weighted suitability factor.	$R\text{-Value} = Y / X$, where Y = GIS-filtered suitable area; X = total agricultural area (state-wise).
4. Crop-Specific Area	Disaggregate national agricultural land by individual crop species.	National Agricultural Statistics (MoAFW 2024-25). Area under cultivation of crop (i) = A_i .

Step	Description	Data Sources and Technical Parameters
5. State-wise Cropping Intensity	Accounts for multiple cropping seasons (kharif + rabi + zaid).	Cropping Intensity: $C_i = \text{Gross crop}(i) \text{ area} / \text{Net crop}(i) \text{ area}$. MoAFW National Agricultural Statistics.
6. Permissible AgriPV Area	Compute permissible area for AgriPV per crop per state.	Permissible Area: $P_i = R\text{-Value } i \times (A_i / C_i)$.
7. AgriPV Power Potential	Apply crop-category-specific power density ranges to permissible areas.	Power Density: Max 0.75 MW/ha; Min 0.42 MW/ha. Six crop categories assessed: Fruits, Citrus, Vegetables, Plantation, Spices, Flowers.

Source: 7-Step GIS Methodology for AgriPV Potential Assessment. Reproduced and adapted from TERI (2025), Figure 5, p. 15.¹⁹ Preliminary GIS-based estimates to be updated after site assessments and ground validation.

The selection of crop categories has been made judiciously, excluding key staple crops such as wheat, rice, and pulses, considering their importance to India's food security and the current limitations of technology. Accordingly, the methodology focuses on the short-term actionable AgriPV potential, as reflected in the TERI report. In the longer term, the same methodology can be applied to assess a broader range of crop categories, including staple crops, once suitable AgriPV technologies and configurations are developed and demonstrated with minimal impact on crop yields.

Screening and Ground Validation: The GIS-based assessment provides a preliminary estimate of AgriPV potential and is not intended to substitute for project-level feasibility assessment. Identified areas are subsequently advised to undergo ground validation covering land tenure, actual land use, crop suitability, water availability, site accessibility, grid connectivity, and other applicable regulatory requirements before project development.

2.2 Feeder-Level Grid Readiness and Necessity Assessment

Following the identification of potentially suitable areas through GIS screening, grid readiness is assessed to determine whether the identified sites can be practically connected to the distribution network. This step helps narrow the theoretical/technical potential to areas with feasible grid connectivity and available network capacity.

(Primarily used by supply-side players: DISCOMs, SNAs, and project developers.)

This section bridges the gap between high-level GIS screening and detailed engineering. The assessment determines whether a specific feeder can physically and technically support a specific AgriPV project, identifying showstoppers early before agronomic or social assessment resources are committed.

Step 1: Feeder Identification

- Record Feeder ID, voltage class (typically 11 kV), type (dedicated agricultural vs. mixed), and route length.

Step 2: Loading and Headroom (Capacity Check)

- Confirm peak loading (%) and specific Distribution Transformer (DT) ratings per IS 1180 (Part 1) (standard ratings, e.g., 100/160/250/500 kVA).
- **Target Loading Band:** 60-75%. Exceeding this threshold is a caution flag for equipment life and efficiency.

Step 3: Necessity Determination

Table 2.2: Feeder Necessity Classification

Category	Condition	Implication
Ready	Spare headroom at Feeder and DT level	Proceed immediately
Augmentation	Near capacity; upgrade feasible (e.g., DT step-up)	Viable, but include upgrade costs and timeline in plan
Not Feasible	At capacity; no planned upgrades	Deprioritize site

Step 4: Compatibility Check (80% Rule)

- Peak injection is advised not to exceed about 80% of the feeder's minimum daytime load unless storage or network reinforcement is provided. [ADVISORY: SCREENING RULE]
- The 80% rule is a screening rule *to prevent voltage instability*; the injection capacity is recommended to be confirmed by a load-flow and voltage-rise study of the host feeder in accordance with the CEA (Technical Standards for Connectivity of the Distributed Generation Resources) Regulations, 2013, as amended (see Section 3.6.1).

Step 5: Agricultural Priority Flag

- Connecting to a dedicated agricultural or already-solarized feeder is a positive priority indicator. It compounds the state's daytime power objectives and *is advised to* earn a weighted bonus in the infrastructure criteria used for site prioritization (Section 2.3.4).

Step 6: Tender Release

- Based on the Ready / Augmentation / Not Feasible classification from Step 3, the DISCOM compiles a shortlist of technically viable feeders and sites.
- These shortlisted sites are floated as tenders/RFPs for AgriPV development, inviting demand-side players (developers, financiers) to bid.

2.3 Biophysical Site Suitability Criteria

Unlike conventional solar projects, AgriPV site selection is recommended to simultaneously consider solar-energy potential and the ability of the land to support continued agricultural production. Therefore, soil, water availability, agro-climatic conditions, crop suitability, and site characteristics are advised to be assessed alongside solar resource and infrastructure considerations.

Adapted from TERI (2025).¹⁹ Biophysical suitability for AgriPV involves combined evaluation of solar resource and agricultural capacity - unlike conventional solar siting, which optimizes on solar resource alone.

2.3.1 Solar Resource Assessment

Table 2.3: Solar Resource Assessment Criteria

Parameter	Minimum Threshold	Assessment Method and Justification
Global Horizontal Irradiance (GHI)	4.5 kWh/m ² /day (annual mean)	PVGIS, NASA POWER, NISE Solar Maps. Higher than global baseline (4.0) due to grid tariff economics in India. ¹⁹ <i>Advised to use seasonal breakdowns (Kharif/Rabi/Zaid) to align solar resources with crop cycles.</i> This threshold applies to the GIS potential estimate (Table 2.1); sites with 4.0-4.5 kWh/m ² /day are not ineligible for project development, while sites below 4.0 kWh/m ² /day are advised to be excluded (see Section 9.1).
Cloud Cover (Monsoon Seasonality)	30–40% diffuse during May–September	Regional climate data. Diffuse light is beneficial for shade-tolerant crops; bifacial systems capture ground-reflected light.
Terrain and External Shadowing	< 2% annual energy loss	Solar pathfinder or 3D LiDAR. Distinguish panel-induced shade (intentional) from external obstruction (loss). Prioritize south-facing slopes. Supplement satellite data with on-site checks.

2.3.2 Soil and Hydrological Criteria

Source: TERI (2025), Tables 3-4.¹⁹ Soil productivity data from ICAR-NBSS national soil database.

Table 2.4: Soil and Hydrological Criteria

Parameter	Ideal Range	Impact on AgriPV Viability
Soil Type and Depth	Sandy loam; ≥ 60 cm rooting depth	High permeability for drainage and irrigation. Shallow soils limit crop productivity and structural stability.
Soil Fertility (NPK)	Medium-High (ICAR-NBSS standards)	Degraded soils require 1-2 years of pre-amendment. Cost: ₹5,000-15,000/ha.
Water Availability	> 600 mm rainfall OR shallow groundwater (< 5 m); in zones below 600 mm (Table 2.5), assured groundwater or irrigation supply is required	Critical for crop growth under shade stress. Solar-pump irrigation: solar pump powers irrigation.

2.3.3 Agro-Climatic Zone Alignment

Source: Adapted from TERI (2025), Table 5.¹⁹ Agro-climatic zones follow the Planning Commission's 15 agro-climatic regions and the 127 agro-climatic zones delineated under ICAR's National Agricultural Research Project (NARP).

Table 2.5: Agro-Climatic Zone Alignment of AgriPV Typologies

Agro-Climatic Zone	Rainfall (mm)	Recommended AgriPV Typology	Key Crops
Indo-Gangetic Plains (IGP)	600-1000	Overhead Fixed	Vegetables, soybean, fodder
Peninsular Plateau (Rainfed)	500-800	Interspace Fixed	Soybean, vegetables, pulses
Semi-Arid (Rajasthan, Gujarat)	300-600	Vertical E-W	Fodder, cash crops, vegetables
Western Ghats and Coastal	> 2000	Structure-Integrated (Greenhouse); humidity management	Spices, floriculture, orchard

2.3.4 Infrastructure and Accessibility Criteria

Source: Adapted from TERI (2025), Section 4.2.¹⁹

Distance to Substation: A site is recommended to be within ≤ 5 km of the nearest substation, consistent with the boundary condition in Section 1.2; state-specific relaxations *may* apply in

notified zones. Proximity is recommended to be assessed as actual achievable line routing distance, not straight-line.

Grid Readiness: Distance alone does not establish that a substation or feeder can accept the proposed capacity. Grid readiness assessment at the site-selection stage *is advised to* establish (see Section 2.2):

- Preliminary capacity headroom at the substation and feeder;
- Distribution transformer proximity and capacity;
- A preliminary connectivity indication from the DISCOM, obtained before committing agronomic and social assessment resources.

All-Weather Road Access: An AgriPV site requires sustained all-weather access for the full 25-year operational life - not merely during construction - because farm machinery (tractors, harvesters, sprayers) is recommended to continue to operate under or between the array structures. Site assessment *is advised to* evaluate:

- Construction-phase access (heavy vehicles, cranes, panel delivery); and
- Operational-phase access (standard agricultural machinery year-round, including monsoon months).

2.3.5 Land Tenure, Rights, and Socio-Economic Criteria

Source: Adapted from TERI (2025), Table 6.¹⁹

Four tenure categories govern site eligibility (three eligible and one excluded), each carrying a different verification pathway:

Table 2.6: Land Tenure Categories and Eligibility

Land Classification	Eligibility Status	Documentation Required
Patta Land (Owned)	HIGHEST ELIGIBILITY; No reclassification needed	Title deed; FRA/PESA exemption (if applicable)
Community Property Resource / Community Land	ELIGIBLE - Cooperatives, Panchayats, FPOs, WUAs	Formal panchayat resolution; Memorandum and Articles of Association
Leasehold / Revenue Land (State)	ELIGIBLE if lease > 25 years; acceptable for project finance	Lease agreement; rent escalation clause analysis
Forest Land	NOT ELIGIBLE; Forest clearance liability	Explicit exclusion; regulatory barrier

Beyond the four named categories, site assessment is also advised to record tenancy and encumbrance status (any existing mortgage, dispute, or third-party claim) and the survey

number/Khasra identification, since these are the documentary anchors that every subsequent registration and financing step will reference.

2.4 Regulatory Compliance

- **Land-Use Integrity:** Confirmation that the project maintains “Agricultural” land status and does not trigger Non-Agricultural (NA) reclassification.
- **Environmental Clearances:** Verification of exemptions from EIA and adherence to local ecological norms. **[ADVISORY: verify state-specific requirements]**
- **Technical and Grid Standards:** Recommended compliance with CEA technical standards for connectivity and state-specific DISCOM metering regulations. **[ADVISORY]**
- **Agronomic Adherence:** Alignment with the Positive List and minimum structural height requirements in Section 1.2 and the clearance provisions in Section 3.3. **[ADVISORY]**
- **Labour and Safety Standards:** Enforcement of national labour laws for construction and O&M, ensuring workplace safety for both technical and agricultural staff.
- **Contractual Validity:** Presence of legally vetted PPA and Lease Agreements protecting land ownership and defining revenue-sharing rights between all parties. **[ADVISORY]**
- **Indian Standard (under development):** The Indian Standard on AgriPV Farming Production System being developed by BIS includes provisions on site assessment; site assessment *is advised to* conform to it once published.

Outcome of Site Assessment: The site-assessment process is advised to progressively refine AgriPV potential from GIS-based screening to site-specific technical, agricultural, water, grid, and regulatory feasibility. The assessment is advised to identify key site constraints, risks, and mitigation requirements, while confirming land suitability, agricultural compatibility, water availability, infrastructure, and grid connectivity. Only sites that meet the applicable eligibility and feasibility criteria are advised to proceed to detailed project design and implementation.

CHAPTER 3

STRUCTURAL, CIVIL AND ELECTRICAL ENGINEERING STANDARDS AND SPECIFICATIONS FOR AGRIPHOTOVOLTAIC (AgriPV) SYSTEMS

3.1 Introduction and Scope

This chapter specifies how AgriPV systems are recommended to be engineered so that the land beneath and between the modules remains productive farmland. It sets out verifiable structural, civil and electrical specifications that secure the primacy of agriculture, safe work within the array, soil protection, reversibility and grid compliance, based on Indian standards and regulations and on the official AgriPV frameworks of other countries. It applies to grid-connected plants of up to about 2 MW (smaller in hilly terrain) connected at 11 kV or 33 kV to a nearby substation, and to the three principal typologies of Figure 3.1: overhead (elevated), inter-row (interspace) and vertical bifacial systems.

Dupraz et al. (2011) showed that combined food and energy production can raise total land productivity,²⁰ ICAR-CAZRI, Jodhpur, has demonstrated the concept under Indian arid conditions,²¹ and recent systematic reviews confirm that agricultural and energy outcomes depend strongly on the configuration chosen.^{22, 23} Overhead systems place people and machines beneath tall, heavily loaded structures; inter-row systems keep structures low but confine farming to strips between rows; and vertical systems present a full panel face to the wind. All share soil that is tilled and irrigated for 25 years and an environment more corrosive than a conventional solar plant.

Where objectives conflict, precedence is recommended to be life safety of persons and livestock; agricultural functionality (clearance, light, water, soil); structural and electrical reliability; energy yield; and cost. The design working life is recommended to be at least 25 years.

3.2 Normative Framework

Compliance is recommended to be demonstrated, in descending order of precedence, against the Electricity Act, 2003 and CEA regulations; MNRE orders, including the Compulsory Registration Orders;²⁴ Indian Standards; IEC and ISO standards; and international AgriPV

²⁰Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., & Ferard, Y. 2011. "Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes." *Renewable Energy*, 36(10), 2725–2732. <https://doi.org/10.1016/j.renene.2011.03.005>. Introduced the land equivalent ratio (LER) for agrivoltaic systems.

²¹Santra, P., Pande, P. C., Kumar, S., Mishra, D., & Singh, R. K. 2017. "Agri-voltaics or solar farming: The concept of integrating solar PV-based electricity generation and crop production in a single land use system." *International Journal of Renewable Energy Research*, 7(2), 694-699. Describes the ICAR-CAZRI, Jodhpur, agri-voltaic system.

²²Widmer, J., Christ, B., Grenz, J., & Norgrove, L. 2024. "Agrivoltaics, a promising new tool for electricity and food production: A systematic review." *Renewable and Sustainable Energy Reviews*, 192, 114277.

²³Gomez-Casanovas, N. et al. 2023. "Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production." *Cell Reports Physical Science*, 4(8), 101518.

²⁴Ministry of New and Renewable Energy (MNRE). 2019. Approved Models and Manufacturers of Solar Photovoltaic Modules (Requirements for Compulsory Registration) Order, 2019, as amended (List-I: modules; List-II: cells). New Delhi: MNRE. See

guidance (Section 3.2.2), used only where the others are silent. The edition in force on the bid date is recommended to apply and be recorded in the Detailed Project Report (DPR).

3.2.1 Indian Codes, Standards and Regulations

Table 3.1: Principal standards and regulations for AgriPV engineering

Discipline	Key standards and regulations
Loads, structures, trackers	IS 875 (Parts 1-5), including free-standing walls and hoardings in Part 3; IS 1893 (Parts 1, 4); IS 800; IS 801; IS 8147; IS 14462 (greenhouses); IS/IEC 62817:2
Materials and corrosion	IS 2062-1; IS 1161; IS 4923; IS 2629 (Part 1); IS 2629; IS 2633; ISO 1461; IS 14191; ISO 14713-1
Geotechnical and civil	IS 1892; IS 2131; IS 2720 (series); IS 2911 (Part 1/Sec 2), (Part 3), (Part 4); IS 456; IS 15797
PV modules and array	IS 14286 / IEC 61215-1, -2; IS/IEC 61730-1, -2; IS/IEC 61701; IS 16664/IEC 62716; IS 17210 (Part 1)/IEC TS 62804-1; IS 12762 (Part 13)/IEC TS 60904-13; IS/IEC 62548-1
Conversion, cables, protection	IS 16221 (Parts 1, 2); IEC 62109-2; IS 16169; IS/IEC 61683; IS 17293; EN 50618 / IEC 62930; IS 7098 (Parts 1, 2); IS694; IS 9968 (Part 1); IS 16781/IEC 62852; IS/IEC 60269 (Part 6); IS 16463 (Part 31)/IEC 61643 (Part 31); IS 16463 (Part 10)/IEC 61643 (Part 32); IEC 63027; IS/IEC 60529
Earthing, lightning, safety	IS 3043; IEEE Std 80; IS/IEC 62305 (Parts 1–4); IS 732:2019; IS 2551; IS 2190
Grid, transformers, metering	CEA DG Connectivity Regulations, 2013 (am. 2019); CEA Safety and Electric Supply Regulations, 2023; CEA Metering Regulations, 2006; IS 1180 (Part 1); IS 16659/IEC 62770; IEEE Std 519
Monitoring, commissioning, end of life	IS/IEC 61724 (Part 1); IS/IEC TS 61724 (Part 2); ISO 9060; IS 16960 (Part 1)/IEC 62446-1; IS 16960 (Part 3)/IEC 62446-3; E-Waste (Management) Rules, 2022
Cyber Security	CEA Cyber Security Regulations and Guidelines; IEC 62443; IEC 62351; IEEE 1547.3; ISO/IEC 27001

Note: IS/IEC denotes an identical adoption by BIS. Editions are recommended to be verified against current BIS and IEC catalogues. It is recommended to include the applicable CEA (Measures Relating to Safety and Electric Supply) Regulations, 2023, as amended, along with

also: MNRE. 2017. Solar Photovoltaics, Systems, Devices and Components Goods (Requirements for Compulsory Registration) Order, 2017, as amended. Available: <https://mnre.gov.in>.

the relevant BIS/IEC safety standards, including IS 732, IS 3043, IS/IEC 62548-1, IS/IEC 62109, IEC 62446-1.

3.2.2 International AgriPV Frameworks

Table 3.2 summarizes the official AgriPV frameworks of other countries that are most relevant to India and shows where each is reflected in this chapter. DIN SPEC 91434 is the only one that distinguishes the typologies explicitly, as Category I (overhead) and Category II (interspace, including vertical systems).

Table 3.2: International AgriPV frameworks and their use in this chapter

Country and instrument	Key provisions
Germany: DIN SPEC 91434:2021; ²⁵ Fraunhofer ISE guideline ²⁶	Clear height ≥ 2.1 m (Category I, overhead); land loss $\leq 10\%$ (Category I) and $\leq 15\%$ (Category II, interspace and vertical); crop yield $\geq 66\%$ of reference; light, water and soil-protection criteria; reversible construction. The Heggelbach overhead pilot uses about 5 m clearance for combine harvesting.
France: Law 2023-175 (APER); Decree 2024-318 ²⁷	Agriculture remains the main activity; crop yield loss $\leq 10\%$ against a control zone; coverage $\leq 40\%$ for plants of 10 MWp or more; reversibility.
Italy: MiTE Guidelines, 2022 ²⁸	$\geq 70\%$ of area in agricultural use; land area occupation ratio (LAOR) $\leq 40\%$; module height ≥ 2.1 m (crops) or ≥ 1.3 m (livestock) for advanced systems; monitoring of water use, crop yield, soil and micro-climate.
Japan: MAFF solar-sharing permits ²⁹	Farmland conversion only for the post footprint; crop yield $\geq 80\%$ of the local average; periodic permit renewal; easily removable supports, typically light overhead structures.

²⁵Deutsches Institut für Normung (DIN). 2021. DIN SPEC 91434:2021-05 — Agri-photovoltaic systems: Requirements for primary agricultural use. Berlin: DIN. Category I (overhead) systems require a clear height of at least 2.1 m; agricultural land loss is limited to 10% for Category I and 15% for Category II (interspace) systems, and at least 66% of the reference yield must be maintained. Available: <https://www.din.de>.

²⁶Fraunhofer Institute for Solar Energy Systems ISE. 2022. Agrivoltaics: Opportunities for Agriculture and the Energy Transition — A Guideline for Germany (updated edition, April 2022). Freiburg: Fraunhofer ISE. Available: <https://www.ise.fraunhofer.de>. See also: Trommsdorff, M. et al. (2021b). “Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany.” Renewable and Sustainable Energy Reviews, 140, 110694. <https://doi.org/10.1016/j.rser.2020.110694>.

²⁷République française. 2024. Décret n° 2024-318 du 8 avril 2024 relatif au développement de l’agrivoltaïsme et aux conditions d’implantation des installations photovoltaïques sur des terrains agricoles, naturels ou forestiers. Journal officiel de la République française. Implements Law No. 2023-175 of 10 March 2023 on accelerating renewable energy production (Loi APER). Available: <https://www.legifrance.gouv.fr>.

²⁸Ministero della Transizione Ecologica (MiTE). 2022. Linee Guida in materia di Impianti Agrivoltaici [Guidelines on agrivoltaic installations]. Rome: MiTE (now Ministero dell’Ambiente e della Sicurezza Energetica), June 2022. Available: <https://www.mase.gov.it>.

²⁹Ministry of Agriculture, Forestry and Fisheries (MAFF), Japan. 2013, as revised. Handling, under the farmland-conversion permit system, of solar power facilities erected on supports with continued farming (solar sharing). Tokyo: MAFF. Available: <https://www.maff.go.jp>.

Country and instrument	Key provisions
United States: NREL InSPIRE; ³⁰ ASCE/SEI 7-22	Site-specific design across elevated and row-based configurations; compatibility with equipment and vegetation management; wind provisions for ground-mounted PV arrays.
Europe: SolarPower Europe; EU JRC ³¹	Good practice for design, construction, soil management and O&M of AgriPV systems.

3.3 Geometry, Clearances and Layout

3.3.1 Definitions

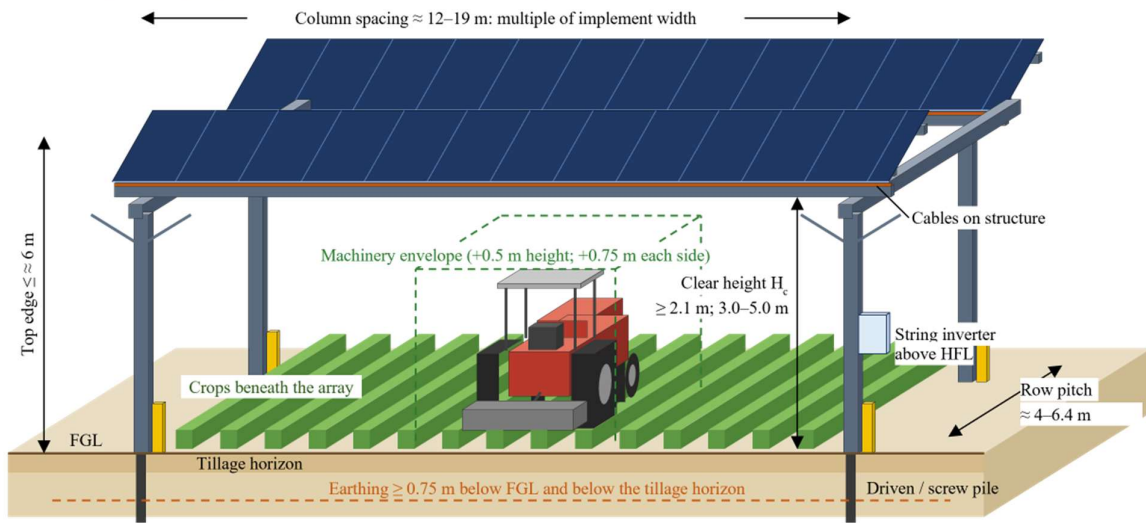
The three typologies illustrated in Figure 3.1 and the associated terms are defined below.

- **Overhead (elevated) system:** Modules raised on columns above the crop, which is cultivated beneath and between the supports (DIN SPEC 91434 Category I). The governing dimension is the clear height (H_c): the vertical distance from finished ground level (FGL) to the lowest point of any module, member, brace, gutter or cable tray above a travel lane or cultivated strip, at the most unfavourable operating position.
- **Inter-row (interspace) system:** Tilted fixed or tracked module rows close to the ground, with cultivation in strips between rows (Category II). The governing dimension is the clear cultivated strip, measured as the width of the cultivation strip between the adjacent rows of PV panels. It is measured as the distance between the projection on the ground of the upper edge of a row of PV panels and the projection on the ground of the lower edge of the next row of PV panels.
- **Vertical bifacial system:** E-W-facing bifacial modules mounted vertically on posts in N-S rows, with cultivation between rows (Category II). The governing dimensions are the clear lane between module faces and posts, and the lower-edge height.
- **Machinery operating envelope:** The space swept by the largest machine-implement combination in the crop and machinery plan agreed with the farmer, including raised implements and folded booms, plus the margins of Section 3.3.2.
- **Tillage horizon:** The maximum depth of soil disturbance by any planned operation, including deep ploughing and sub-soiling.

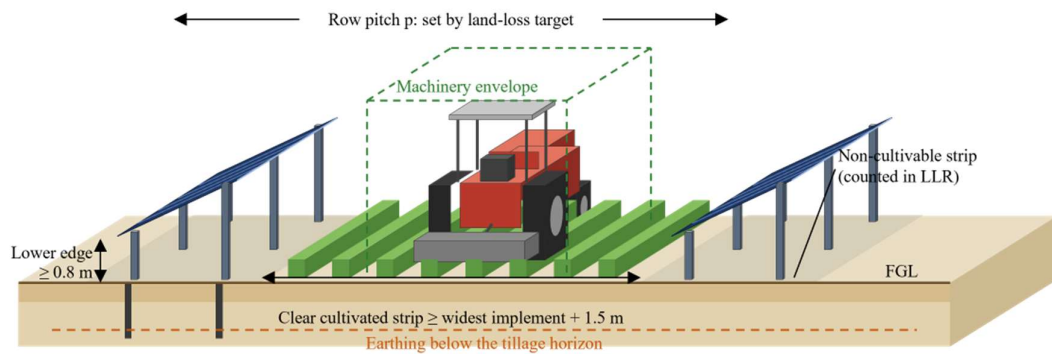
³⁰Macknick, J. et al. 2022. The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons from the InSPIRE Research Study. Technical Report NREL/TP-6A20-83566. Golden, CO: National Renewable Energy Laboratory. Available: <https://www.nrel.gov>.

³¹SolarPower Europe. 2023. Agrisolar Best Practices Guidelines, Version 2.0. Brussels: SolarPower Europe. See also: Chatzipanagi, A., Taylor, N., & Jaeger-Waldau, A. (2023). Overview of the Potential and Challenges for Agri-Photovoltaics in the European Union. Luxembourg: Publications Office of the European Union (JRC Science for Policy Report).

(a) Overhead (elevated) AgriPV: cultivation beneath the array



(b) Inter-row (interspace) AgriPV: cultivation between tilted rows



(c) Vertical bifacial AgriPV: cultivation between E-W facing rows

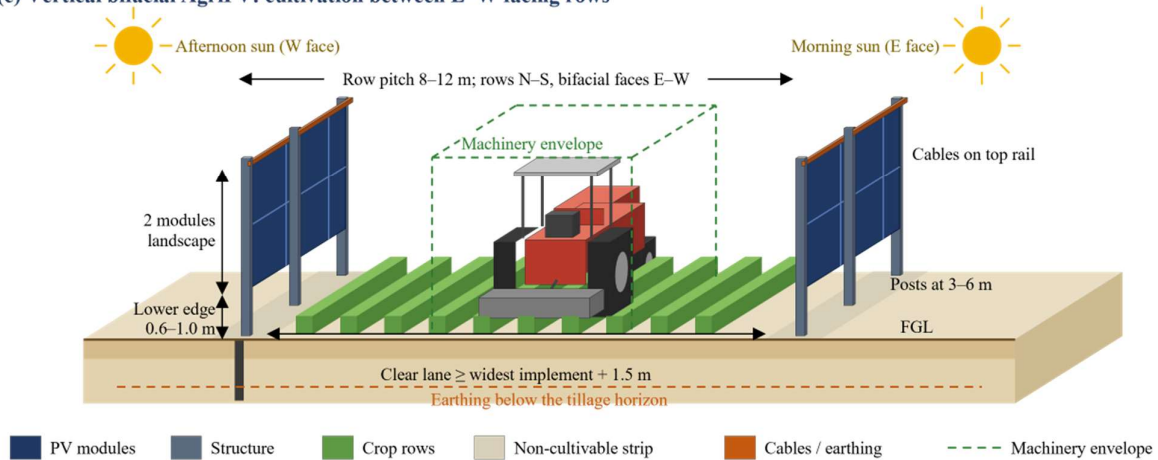


Figure 3.1: Principal AgriPV typologies with the geometric provisions: (a) overhead, (b) inter-row and (c) vertical bifacial systems (schematic, not to scale)

Table 3.3: Governing parameters of the three AgriPV typologies

Parameter	(a) Overhead	(b) Inter-row	(c) Vertical bifacial
Arrangement	Modules raised on columns above the crop; cultivation beneath	Tilted fixed or tracked rows near the ground; cultivation between rows	Vertical E-W-facing bifacial rows on posts, running N-S; cultivation between rows
DIN SPEC 91434	Category I	Category II	Category II
Governing clearance	Hc $\geq$ 3.0 m; 3.0-5.0 m for tractors; $\geq$ 5.0 m for combine harvester	Clear strip $\geq$ implement + 1.5 m; lower edge $\geq$ 0.8 m	Clear lane $\geq$ implement + 1.5 m; lower edge 0.6-1.0 m
Typical layout	Columns $\approx$ 12-19 m $\times$ 4-6.4 m (column spacing $\times$ row pitch); GCR $\approx$ 0.13-0.30; top edge $\leq \approx$ 6 m	1P or 2P tables at 15-30°, or 1P trackers; pitch set by the land-loss target	Two modules in landscape ($\approx$ 2.3 m); pitch 8-12 m; posts at 3-6 m
Governing structural action	Uplift and large base moments on tall columns	Uplift and moderate moments on many short posts	Lateral wind on the full face; end-of-row effects
Typical land loss	$\approx$ 4-8%	15-40%, depending on pitch	$\approx$ 7-15%
Typical Indian use	Mechanized cereal and vegetable systems; orchards and vineyards	Row crops and horticulture on the peninsular plateau	Mechanized cropping and grazing in semi-arid and arid zones

Note: Indicative values compiled by the authors; the typologies correspond to the spatial patterns described by Toledo and Scognamiglio (2021)³² and Bellone et al. (2026)³³ Project values are recommended to be derived from the crop and machinery plan and verified by the calculations of Sections 3.4.2 and 3.5.4.

³²Toledo, C., & Scognamiglio, A. 2021. "Agrivoltaic systems design and assessment: A critical review, and a descriptive model towards a sustainable landscape vision (three-dimensional agrivoltaic patterns)." Sustainability, 13(12), 6871. Classifies AgriPv systems by the three-dimensional arrangement of modules and crops.

³³Bellone, Y., Santangelo, E., Assirelli, A., Zainali, S., Impollonia, G., Croci, M., Campana, P. E., & Amaducci, S. 2026. "Agricultural mechanization in agrivoltaic systems: Challenges, adaptation, and possible advancements." Renewable and Sustainable Energy Reviews, 229, 116661. <https://doi.org/10.1016/j.rser.2025.116661>. Built overhead systems reported in its Table 1 have support spacing of 12 m (Po Valley, Italy), 13 m (Lovenjoel, Belgium) and 19 m (Heggelbach, Germany), module-row spacing of 4-6.4 m (Montpellier, France) and 4.7 m (Lovenjoel), and GCR of 0.13-0.30; a minimum column spacing of 3.3 m was adopted for small machinery in South Korea.

△ IMPLEMENTATION NOTE	<i>Clearance is sometimes quoted at the centre of the module table or at the torque tube. The lower edge of a tilted table lies $(W/2) \cdot \sin \theta$ below its centre, i.e., 0.79 m for a 4.6 m (two-in-portrait) table at 20°, so a 3.0 m centre height leaves only about 2.2 m at the lower edge. Because machines and people strike the lowest point, Hc is recommended to be specified and verified at the lowest point. For inter-row and vertical systems, the equivalent checks are the clear strip or lane width at machine height and the lower-edge height.</i>
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3.3.2 Machinery Envelope and Layout Rules

Table 3.4: Indicative machinery classes and minimum geometric provisions (Hc = machine height + 0.5 m, rounded up)

Class	Typical machinery	Overhead: minimum Hc	All typologies: minimum clear lane or strip
M0	Manual and animal-drawn work, power tillers, knapsack sprayers	3.0 m (absolute minimum)	≥ 2.0 m
M1	Compact and orchard tractors (≤ 30 hp), mini-harvesters	3.0-3.5 m	Implement width + 1.5 m
M2	Standard tractors (35–60 hp), mounted implements, trailers	4.0-4.5 m	Implement + 1.5 m (typically ≥ 5 m)
M3	Self-propelled combine and sugarcane harvesters	≥ 5.0 m	Header + 1.5 m (typically ≥ 6 m)

- **All typologies:** The machinery envelope is recommended to include margins of 0.5 m vertically and 0.75 m on each side, and no brace, gutter, cable, or guy wire is suggested to enter it; columns and row-end posts beside lanes are recommended to carry retro-reflective marking 0.3-2.0 m above FGL; and loaders or tipping trailers are recommended not to be raised within the array. Posts are advised to have fenders, and headlands are advised to fit the turning circle of the longest tractor-implement combination, typically 8-12 m.
- **Overhead:** Hc is recommended to be at least the maximum machine height plus 0.5 m and is advised not to be less than 3.0 m, which in practice means 4.0-4.5 m for standard tractors and at least 5.0 m where combines are used. The top edge is advised not to exceed about 6 m unless justified by the structural design, and column spacing is advised to be a multiple of the implement working width, typically about plus a safety margin, typically 12-19 m between columns and 4-6.4 m between module rows, and at least 3.3 m between columns for small machinery.

- **Inter-row:** The clear cultivated strip is recommended to be at least the widest implement plus 0.75 m on each side, measured between the outermost edges of adjacent tables, and the row pitch is recommended to meet the land-loss limit of Section 3.5.4. The lower module edge is advised to be at least 0.8 m above FGL, and at least 2.1 m where the strip beneath the tables is itself cultivated.
- **Vertical:** The clear lane is recommended to be at least the widest implement plus 0.75 m on each side, measured between module faces and posts. Rows are advised to run N-S at a pitch of 8-12 m with posts at 3-6 m, and the lower module edge is advised to be 0.6-1.0 m above FGL and above the mature crop canopy beside the row.
- **Hilly and terraced land:** Column and post heights are recommended to vary with the terrace so that the class minimum is kept on every terrace and rows are advised to follow the contours.

3.3.3 Single-Axis Trackers and Light Distribution

Trackers may be used in overhead or inter-row systems. The lower-edge height at rotation angle θ is $h_{low} = H_{axis} - (B/2) \cdot \sin \theta$, where B is the width of the panel perpendicular to the row length; θ is the angle between the width of the panel (dimension B) and the horizontal plane. With its axis at 4.5 m, a one-in-portrait (1P) overhead tracker ($B = 2.38$ m) keeps 3.47 m at 60° , whereas a two-in-portrait (2P) tracker ($B = 4.80$ m) falls to 2.42 m; keeping 3.0 m would require a 2P axis of 5.1 m and an upper edge of about 7.2 m, so 1P trackers are preferred for overhead systems [ADVISORY]. The field-operations position is recommended to be the angle that maximizes clearance for the machinery present: normally horizontal for overhead trackers (maximum H_c), and normally the steepest permitted angle for inter-row trackers (minimum projection into the lane, with the lower edge kept above crop and implements). It is recommended to be commanded before machinery enters, with interlocks and a visible status indication; agronomic tracking modes may be used within these limits.³⁴

³⁴Valle, B., Simonneau, T., Sourd, F., Pechier, P., Hamard, P., Frisson, T., Ryckewaert, M., & Christophe, A. 2017. "Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops." *Applied Energy*, 206, 1495-1507.

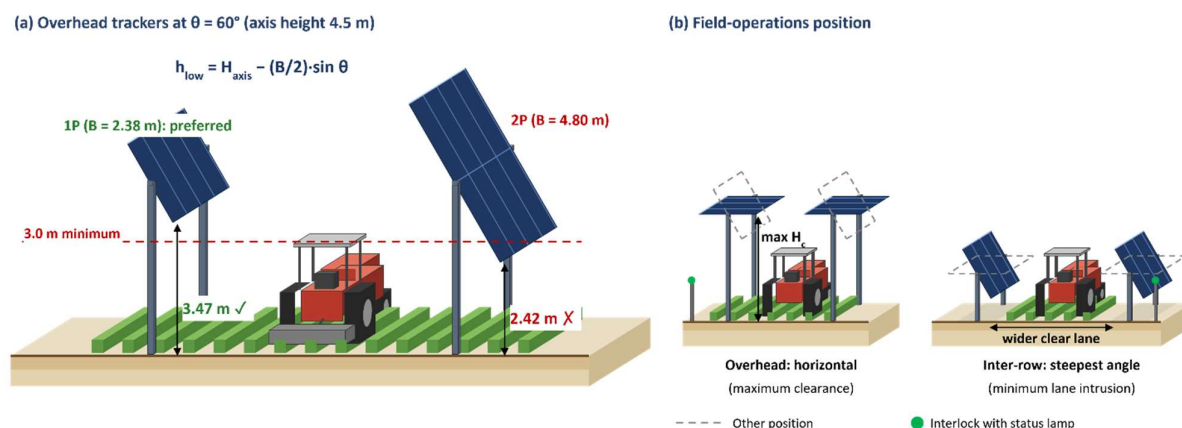


Figure 3.2: (a) lower-edge clearance of 1P and 2P overhead trackers at $\theta = 60^\circ$; (b) field-operations positions of overhead and inter-row trackers (schematic, not to scale)

A season-resolved simulation of photosynthetically active radiation (PAR) at crop height, reporting its mean fraction and spatial homogeneity, is recommended to accompany the design for every typology.³⁵ Overhead arrays cast moving shadows over the whole plot, whose homogeneity is advised to be improved by clearance, module gaps, and row orientation, and can moderate canopy temperature and water stress in dry climates.³⁶ Inter-row arrays cast persistent shade bands beside each row, so shade-tolerant crops are advised to be placed next to the rows and light-demanding crops in the mid-strip. Vertical E-W rows leave the strip almost unshaded around midday and shade it mainly in the morning and evening, while their bifacial output peaks in the morning and late afternoon, complementing conventional south-facing plants on the grid.^{37,38} GCR (light) and LLR (land lost) are recommended to both be reported; the 40% coverage ceilings of France and Italy are a useful GCR benchmark.

3.4 Structural Engineering

3.4.1 Actions and Load Combinations

The structure **is recommended** to provide a continuous load path from module to soil, designed by the limit state method of IS 800³⁹. Lateral stability is recommended to be

³⁵Santra, P., Meena, H. M., & Yadav, O. P. 2021. "Spatial and temporal variation of photosynthetic photon flux density within agrivoltaic system in hot arid region of India." *Biosystems Engineering*, 209, 74-93.

³⁶Barron-Gafford, G. A. et al. 2019. "Agrivoltaics provide mutual benefits across the food-energy-water nexus in drylands." *Nature Sustainability*, 2, 848-855. <https://doi.org/10.1038/s41893-019-0364-5>.

³⁷Riaz, M. H., Younas, R., Imran, H., Alam, M. A., & Butt, N. Z. 2021. "Module technology for agrivoltaics: Vertical bifacial versus tilted monofacial farms." *IEEE Journal of Photovoltaics*, 11(2), 469-477. Compares energy yield and light sharing of vertical bifacial and tilted monofacial AgriPV layouts.

³⁸Campana, P. E., Stridh, B., Amaducci, S., & Colauzzi, M. 2021. "Optimization of vertically mounted agrivoltaic systems." *Journal of Cleaner Production*, 325, 129091.

³⁹Bureau of Indian Standards (BIS). 2007. IS 800:2007 General Construction in Steel - Code of Practice (Third Revision). New Delhi: BIS. Table 4 gives the partial safety factors for loads (γ_f) for the limit states of strength and serviceability, including the factor of 0.9 on dead load where it contributes to stability against overturning or reduces stresses from other loads; Table 6

provided by moment frames, cantilever columns or knee braces above the machinery envelope in overhead systems; by bracing within the non-cultivable strip in inter-row systems; and by cantilevered posts or in-line bracing in vertical systems, with no guy wire or diagonal brace crossing a lane in any typology. Actions are recommended to follow Table 3.5.

Table 3.5: Design actions and typology-specific provisions

Action	Standard	Typology-specific requirement
Dead (G)	IS 875 (Part 1)	Glass-glass modules ($\approx 12\text{--}14 \text{ kg/m}^2$), structure and attachments such as trays, gutters, sensors, irrigation lines and nets
Imposed (Q)	IS 875 (Part 2)	Maintenance point load $\geq 0.9 \text{ kN}$ at the most adverse position on purlins, rails and gutters (never on modules)
Wind (W)	IS 875 (Part 3):2015	Canopy model (overhead), tilted-array model (inter-row) or free-standing wall model (vertical), as in Section 3.4.2
Seismic (E), snow (S)	IS 1893; IS 875 (Part 4)	Elevated mass on tall overhead columns (zonation in force); snow on tilted modules, and snow sliding from overhead arrays, in hill states
Accidental (A)	EN 1991-1-7 (benchmark)	Overhead columns beside lanes, and row-end posts of inter-row and vertical systems at headlands, designed for vehicle impact or protected by fenders ⁴⁰

The load combination is recommended to be as per the provision mentioned under IS 800. Recommended deflection limits are span/180 for rails and purlins (within module limits), span/240 for beams and height/150 for the drift of columns and posts **[ADVISORY]**; deflection **is recommended not to** reduce any clearance of Section 3.3.2 below its requirement.

3.4.2 Wind Actions

Design wind pressures are recommended to be determined in accordance with IS 875 (Part 3) **[ADVISORY]**.⁴¹

gives the deflection limits. In this chapter, G, Q, W, E and A correspond to the dead (DL), imposed (LL), wind (WL), earthquake (EL) and accidental (AL) loads of IS 800. See also: Bureau of Indian Standards (BIS). 2016. IS 1893 (Part 1):2016 Criteria for Earthquake Resistant Design of Structures, Part 1: General Provisions and Buildings. New Delhi: BIS, which gives the corresponding combinations with earthquake load.

⁴⁰European Committee for Standardization (CEN). 2006. EN 1991-1-7:2006 - Eurocode 1: Actions on structures - Part 1-7: General actions - Accidental actions. Brussels: CEN. Table 4.1 gives indicative equivalent static impact forces of 50 kN (cars) and 150 kN (lorries) for courtyards and parking garages.

⁴¹Bureau of Indian Standards (BIS). 2015. IS 875 (Part 3):2015 - Design Loads (Other than Earthquake) for Buildings and Structures - Code of Practice, Part 3: Wind Loads (Third Revision). New Delhi: BIS. Table 1 assigns $k_1 = 1.00$ to general structures (50-year design life) and 0.94–0.89 to “farm buildings other than residential buildings” (25-year design life), depending on the basic wind speed. Available: <https://www.bis.gov.in>. Clause 6.3 defines the design wind speed $V_z =$

Table 3.6: Illustrative wind actions per foundation for the three typologies ($p_d = 1,315 \text{ Pa}$)

Quantity	(a) Overhead	(b) Inter-row	(c) Vertical bifacial
Assumed configuration	1P rows at 20°; Hc 4.3 m; grid 12.8 m × 6.4 m; GCR 0.25 lies within 12–19 m × 4–6.4 m and GCR 0.13–0.30.	1P table at 25°; lower edge 0.8 m; posts at 5.0 m	Two modules in landscape (2.27 m); lower edge 0.8 m; posts at 3.0 m
Module area per foundation	20.5 m ²	11.9 m ²	6.8 m ²
Coefficient (illustrative)⁴²	Cp,net –1.3 (canopy)	Cp, net -1.3 (tilted row)	cf 1.8 (signboard)
Net wind force per foundation	35.0 kN	20.3 kN	16.1 kN
Lever arm; overturning moment	4.5 m; 54 kN·m	1.3 m; 11 kN·m	1.9 m; 31 kN·m
Foundations per MWp ($\approx 4,650 \text{ m}^2$ of modules)⁴³	≈ 230	≈ 390	≈ 680
Module check (rear design load 1,600 Pa)	Edge zone 3,288 Pa: exceeded	Edge zone 3,288 Pa: exceeded	2,367 Pa on either face: exceeded
Governing foundation action	Uplift and large moment	Uplift and moderate moment	Lateral load and moment

Note: Table 3.6 gives illustrative wind actions for the three typologies; it is not for design. Adopting the 25-year risk coefficient ($k_1 = 0.90$) would reduce every action by 19% and conceal the module deficiencies shown.

Vb·k1·k2·k3·k4, and Clause 7.2 defines the design wind pressure $p_z = 0.6 V_z^2$ and $p_d = K_d \cdot K_a \cdot K_c \cdot p_z$, which shall not be taken as less than 0.70 p_z.

⁴²Illustrative coefficients only: Cp, net = –1.3 (overall) and –2.5 (edge zone) are of the order given for monopitch canopies of 15–25° pitch in EN 1991-1-4 (Table 7.6), and cf = 1.8 is the EN 1991-1-4 (§7.4.3) force coefficient for signboards clear of the ground by more than a quarter of their height. Designs are recommended to use code or wind-tunnel values for the actual configuration.

⁴³Module area per MWp is calculated as $A = P/(G_{STC} \cdot \eta)$, where $G_{STC} = 1,000 \text{ W/m}^2$ is the irradiance at standard test conditions and $\eta \approx 21.5\%$ is the efficiency of a 580 Wp module of 2.382 m × 1.134 m. International Electrotechnical Commission (IEC). 2021. IEC 61215-1:2021 Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements. Geneva: IEC. See also: IEC. 2019. IEC 60904-3:2019 Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data. Geneva: IEC; and Fraunhofer Institute for Solar Energy Systems ISE. Photovoltaics Report (latest edition). Freiburg: Fraunhofer ISE, for current commercial module efficiencies.

3.4.3 Materials and Corrosion Protection

Steel is recommended to conform to IS 2062 (E250/E350), IS 1161 or IS 4923; load-bearing cold-formed members are advised to be ≥ 2.0 mm thick; aluminium (IS 8147) is recommended to be isolated from dissimilar metals; primary bolts are recommended to be galvanized class 8.8, with stainless fasteners of grade A2 in C3 and A4 in C4 or above; and welding is recommended to precede galvanizing, with no site welding of galvanized members and coating damage repaired to ASTM A780.

Corrosivity is recommended to be classified to IS 14191,⁴⁴ including the agricultural micro-environment: fertigation and sprays, ammonia from urea, manure and livestock, saline irrigation water and wet-dry cycling at the ground line. Inter-row and vertical structures lie within the splash zone of irrigation water and rain-splashed soil along their whole length, so the ground-line zone of every post is recommended to be protected as in Table 3.7.

Table 3.7: Corrosivity categories and minimum protection for a 25-year working life

Category (zinc loss)	Typical AgriPV setting	Minimum protection
C2 (0.1-0.7 $\mu\text{m}/\text{yr}$)	Dry inland, rain-fed cropping	Hot-dip galvanizing (HDG), mean $\geq 85 \mu\text{m}$ ($\approx 610 \text{ g}/\text{m}^2$)
C3 (0.7-2.1 $\mu\text{m}/\text{yr}$)	Irrigated inland plains, low-salinity water	HDG, mean $\geq 85 \mu\text{m}$
C4 (2.1-4.2 $\mu\text{m}/\text{yr}$)	Fertigation or sprinkler zones, saline water, moderately saline coast	HDG $\geq 110 \mu\text{m}$, or duplex (HDG + ISO 12944 paint); ground-line protection
C5 (4.2-8.4 $\mu\text{m}/\text{yr}$)	Highly saline coast, livestock housing, manure yards	Duplex system for C5, or stainless steel or aluminium
CX (8.4-25 $\mu\text{m}/\text{yr}$)	Splash zones, brackish spray	Site-specific corrosion study

Note: First-year zinc loss rates (IS 14191:2024). The common 80 μm galvanizing lasts 25 years only in C2-C3; in C4, first maintenance may be due within about 20 years.

Coatings are recommended to be verified to IS 4759, ISO 1461 and IS 2633; module clamping is recommended to replicate the IEC 61215 qualified configuration and, on vertical rows, is recommended to be rated for alternating loads; glass-glass modules are preferred, with a breakage-response procedure (isolation, replacement and recovery of glass from soil and crop) in the O&M manual; and modules are recommended to be handled with lifting aids or elevated platforms wherever they are mounted above arm's height.

⁴⁴International Organization for Standardization (ISO). 2012. ISO 9223:2012 - Corrosion of metals and alloys - Corrosivity of atmospheres - Classification, determination and estimation. Geneva: ISO. First-year zinc corrosion rates: C2 0.1-0.7, C3 0.7-2.1, C4 2.1-4.2, C5 4.2-8.4 and CX 8.4-25 $\mu\text{m}/\text{year}$. See also: ISO 14713-1:2017 (durability of zinc coatings).

3.5 Geotechnical, Foundation and Civil Engineering

3.5.1 Investigation and Foundation Systems

A geotechnical investigation to IS 1892 is recommended to precede foundation design, with at least two boreholes per project plus one per additional 2 ha (to ≥ 1.5 times foundation depth and ≥ 5 m), SPT (IS 2131), laboratory tests including free swell (IS 2720), soil and groundwater chemistry, soil resistivity (IS 3043), seasonal water and flood levels, and pile trials with pull-out tests where uplift governs (overhead, inter-row) and lateral tests where lateral load governs (vertical). An agronomic baseline of the topsoil (texture, organic carbon, bulk density, penetration resistance) is recommended to be recorded before construction as the reference for restoration. Foundations are recommended to be removable, as also required in Germany and Japan (Table 3.2), and strip, raft or slab foundations are recommended not to be used in the cultivable area; in expansive black cotton soils they are recommended to be anchored below the active zone, for which under-reamed piles (IS 2911, Part 3) are a proven Indian solution.

Table 3.8: Foundation systems and their use by typology

Foundation type	Suitability	Typical use	Key design and QA points
Driven steel piles (galvanized)	Most soils free of boulders; reversible	All typologies; default for inter-row and vertical rows	Driveability trials; refusal procedure; corrosion allowance
Ground screws / helical piles	Loose to medium soils; no curing; reversible	Inter-row and vertical rows; lighter overhead frames	Torque-capacity correlation; coating abrasion
Bored or under-reamed RC piles	Expansive soils; high uplift; soft rock	Overhead columns in black cotton or weak soils	IS 456 exposure; removal below tillage horizon
Precast blocks/ballast	Only where penetration is prohibited	Not recommended in cultivated land [ADVISORY]	Counted fully in land loss

3.5.2 Foundation Design and Durability

Foundations are recommended to be designed for compression, uplift, lateral load, and moment with IS 2911 factors of safety, using methods such as those of Broms (1964a, 1964b) or p-y analysis.⁴⁵ The governing action differs by typology (Table 3.6): uplift and moment for

⁴⁵Broms, B. B. 1964a. "Lateral resistance of piles in cohesive soils." Journal of the Soil Mechanics and Foundations Division, ASCE, 90(SM2), 27–63. See also: Broms, B. B. (1964b). "Lateral resistance of piles in cohesionless soils." Journal of the Soil Mechanics and Foundations Division, ASCE, 90(SM3), 123–156.

overhead columns, uplift for inter-row posts, and lateral load with moment for vertical posts; embedment is recommended to be designed and verified accordingly.

Soil within the tillage horizon, or subject to scour or shrinkage cracking, is advised to be neglected, using wettest-season parameters.

Initial compression, pull-out and lateral load tests are recommended to be made on sacrificial piles in each soil zone, and routine tests on $\geq 0.5\%$ of production piles (up to 2% in variable strata).⁴⁶

Buried steel is advised to carry a corrosion allowance, treating fertilized, irrigated soils as “polluted natural soils” (0.75 mm per face over 25 years);⁴⁷ Concrete in irrigated soil is **recommended** to meet at least the IS 456 “severe” exposure condition.⁴⁸

3.5.3 Soil Protection, Drainage and Rainwater Harvesting

Compaction by construction and farm traffic can persist for years and depress yields.⁴⁹ A Soil Protection Plan is recommended to require dry-season construction, designated temporary tracks, topsoil stripping only beneath yards and permanent tracks, decompaction verified against the baseline, and complete removal of debris such as cable ties and drilling swarf. In inter-row and vertical systems, piling and installation traffic is recommended to be confined to the future non-cultivable strips so that the cultivated strips are never trafficked.

Tilted modules in overhead and inter-row systems concentrate rainfall along their lower edges into drip-lines and rain shadows;⁵⁰ Vertical rows intercept little rain but shed wind-driven rain and runoff along the base of the row. Drainage design is recommended to preserve field drainage and control erosion along drip-lines and row bases by gutters, module gaps, tracker rain positions, mulched or grassed strips, or contour-aligned rows. Harvested water is advised to be stored for irrigation or cleaning (IS 15797)⁵¹: 1 MWp ($\approx 4,655 \text{ m}^2$ of modules) with 800 mm of rain and a runoff coefficient of 0.8 yields about $2,980 \text{ m}^3$ a year, roughly 150

⁴⁶Bureau of Indian Standards (BIS). 2013. IS 2911 (Part 4):2013 — Design and Construction of Pile Foundations — Code of Practice, Part 4: Load Test on Piles. New Delhi: BIS. Available: <https://www.bis.gov.in>.

⁴⁷European Committee for Standardization (CEN). 2007. EN 1993-5:2007 — Eurocode 3: Design of steel structures — Part 5: Piling. Brussels: CEN. Table 4-1 recommends a loss of thickness per face of 0.30 mm for undisturbed natural soils and 0.75 mm for polluted natural soils over a 25-year design working life.

⁴⁸Bureau of Indian Standards (BIS). 2000. IS 456:2000 — Plain and Reinforced Concrete — Code of Practice (Fourth Revision). New Delhi: BIS. For the “severe” exposure condition, which includes alternate wetting and drying, Tables 5 and 16 require a minimum grade of M30, a maximum water–cement ratio of 0.45, a minimum cement content of 320 kg/m^3 and a nominal cover of 45 mm.

⁴⁹Hamza, M. A., & Anderson, W. K. 2005. “Soil compaction in cropping systems: A review of the nature, causes and possible solutions.” *Soil and Tillage Research*, 82(2), 121–145. See also: Keller, T., Sandin, M., Colombi, T., Horn, R., & Or, D. (2019). “Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning.” *Soil and Tillage Research*, 194, 104293; and DIN. 2019. DIN 19639:2019-09 — Soil protection during planning and implementation of construction projects. Berlin: DIN.

⁵⁰Elamri, Y., Cheviron, B., Lopez, J.-M., Dejean, C., & Belaud, G. 2018. “Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces.” *Agricultural Water Management*, 208, 440–453. <https://doi.org/10.1016/j.agwat.2018.07.001>. See also: Cook, L. M., & McCuen, R. H. (2013). “Hydrologic response of solar farms.” *Journal of Hydrologic Engineering*, 18(5), 536–541.

⁵¹Bureau of Indian Standards (BIS). 2008. IS 15797:2008 — Roof Top Rainwater Harvesting — Guidelines. New Delhi: BIS. Available: <https://www.bis.gov.in>.

mm of supplementary irrigation over 2 ha. Equipment plinths are advised to be ≥ 0.6 m above the highest flood level.

3.5.4 Land-Loss Accounting and Site Layout

Land loss comprises the column and post footprints, the non-cultivable strips beside rows, equipment yards, permanent tracks and other exclusions. The land loss ratio (LLR), the total of these areas divided by the project area, is recommended to be calculated in the DPR and verified on the as-built layout. The LLR is advised not to exceed 10% for overhead and 15% for inter-row and vertical systems, the limits of DIN SPEC 91434⁵².

Reported land losses are about 4-8% for most overhead systems, and 7-10% for vertical systems, the width of the uncultivated strip beside each row being the decisive factor⁵³. Strip widths and row pitch are therefore recommended to be agreed with the farmer for the machinery and guidance system to be used. Tracks are advised to follow headlands with permeable surfacing, electrical equipment is advised to be grouped in one fenced yard at the field edge, and field gates are recommended to be at least 1.0 m wider than the widest machine.

3.6 Electrical Engineering

3.6.1 Architecture and Key Specifications

The plant comprises bifacial modules, an inverter, an LT AC combiner, a step-up transformer, 11 kV switchgear with numerical protection and main and check metering (Figure 3.3). The inverter used in an AgriPV system can be either a central inverter or a string inverter. A central inverter has the advantage of lower cost; however, it leads to the requirement of combiner boxes and long DC cables running in the field, and a large inverter station resulting in increased land loss. String inverters may be preferred for smaller plants, up to 2 MW, if cost is not a constraint. Inverters and any combiner boxes are recommended to be mounted outside travel lanes, on columns (overhead) or on frames at row ends in the headland (inter-row, vertical), above the highest flood level [ADVISORY]. In case of a central inverter, the inverter station (inverter, transformer and RMU, usually an enclosed unit) is advised to be placed in the fenced equipment yard at the field edge, never in the cultivated area or a travel lane. The array is recommended to be designed to IS/IEC 62548-1, and connection is

⁵²Deutsches Institut für Normung (DIN). 2021. DIN SPEC 91434:2021-05 — Agri-photovoltaic systems: Requirements for primary agricultural use. Berlin: DIN. Category I (overhead) systems require a clear height of at least 2.1 m; agricultural land loss is limited to 10% for Category I and 15% for Category II (interspace) systems, and at least 66% of the reference yield must be maintained. Available: <https://www.din.de>

⁵³Bellone, Y., Santangelo, E., Assirelli, A., Zainali, S., Impollonia, G., Croci, M., Campana, P. E., & Amaducci, S. 2026. "Agricultural mechanization in agrivoltaic systems: Challenges, adaptation, and possible advancements." *Renewable and Sustainable Energy Reviews*, 229, 116661. <https://doi.org/10.1016/j.rser.2025.116661>. Table 3 compiles the buffer widths and land losses of built and simulated systems: about 4–8% for most overhead layouts (up to 17% for closely spaced ones), 7–10% for vertical layouts (22% where 1 m margins were needed on each side) and 21–30% for interspaced single-axis layouts; Section 7 notes that RTK guidance allows narrower buffer zones.

recommended to comply with the CEA Distributed Generation Connectivity Regulations⁵⁴ and the CEA Safety and Electric Supply Regulations, 2023,⁵⁵ with the injection capacity confirmed by a load-flow and voltage-rise study of the host feeder. Key specifications are given in Table 3.9.

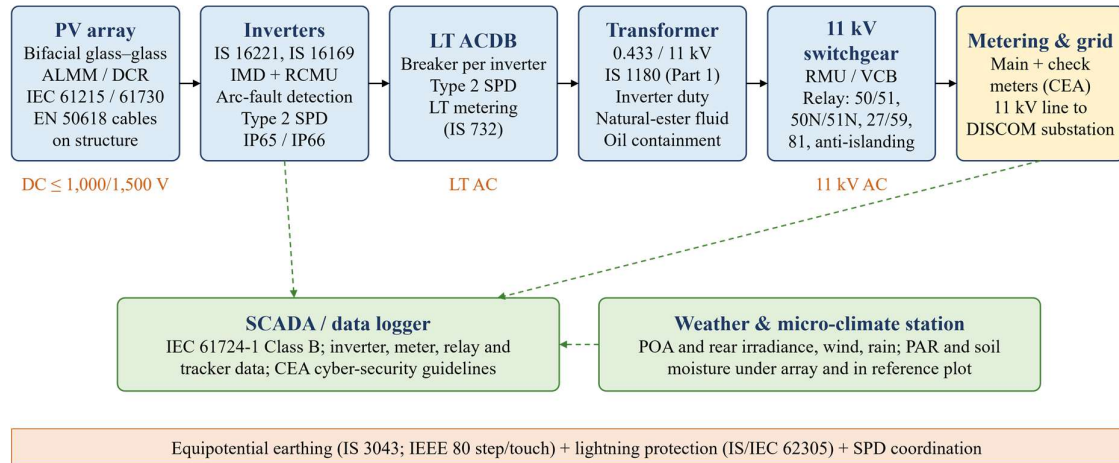


Figure 3.3: Typical single-line arrangement and monitoring architecture of a grid-connected AgriPV plant

Table 3.9: Key electrical specifications for AgriPV plants [ADVISORY]

Parameter	Specification	Reference
DC system voltage	≤ 1,000 V or 1,500 V DC; components rated accordingly	IS/IEC 62548-1
PV modules	ALMM-listed, DCR-compliant bifacial modules; glass-glass construction; bifaciality ≥ 0.70 for vertical systems	ALMM Order; IS 14286; IS/IEC 61730
Module environmental tests	Ammonia (livestock, manure), salt mist (coast, saline water), PID; sand-dust in arid zones	IS 16664/IEC 62716; IS/IEC 61701; IS 17210 (Part 1)/IEC TS 62804-1; IEC 60068-2-68
Inverters	BIS-registered; IP65 minimum, IP66 in spray zones; above HFL, outside lanes	IS 16221; IS 16169; IS/IEC 60529

⁵⁴Central Electricity Authority (CEA). 2013. CEA (Technical Standards for Connectivity of the Distributed Generation Resources) Regulations, 2013, as amended in 2019. New Delhi: CEA. The Regulations prescribe, among other requirements, harmonic limits by reference to IEEE 519, a DC-injection limit of 0.5% of rated output and protection against islanding. See also: CEA. 2006. CEA (Installation and Operation of Meters) Regulations, 2006, as amended. Available: <https://cea.nic.in>.

⁵⁵Central Electricity Authority (CEA). 2023. CEA (Measures relating to Safety and Electric Supply) Regulations, 2023. New Delhi: CEA. See also: CEA. 2022. CEA (Technical Standards for Construction of Electrical Plants and Electric Lines) Regulations, 2022. Available: <https://cea.nic.in>.

Parameter	Specification	Reference
Voltage drop	$\leq 1.5\%$ DC and $\leq 1.5\%$ LT AC at rated output	IS 732
Power quality	IEEE 519 harmonic limits; DC injection $\leq 0.5\%$; anti-islanding; PF capability 0.95 lead-lag	CEA DG Regulations; IS 16169
Protection	Type 2 SPDs (Type 1+2 with LPS); insulation and residual-current monitoring; DC arc-fault detection	IS 16463 (Part 31)/IEC 61643-312018; IS 16463 (Part 10)/IEC 61643-32; IEC 62109-2; IEC 63027
Transformer	IS 1180 (Part 1) inverter-duty; oil containment; natural-ester fluid preferred	IS 1180; IEEE 980; IS 16659/IEC 62770
Metering and monitoring	Main and check meters (CEA accuracy class, AMR); IS/IEC 61724 (Part 1) Class B + AgriPV parameters	CEA Metering Regulations; IS/IEC 61724 (Part 1)

3.6.2 Cabling, Earthing, Lightning and Fire Safety

Unlike conventional ground-mounted solar PV plants, AgriPV installations involve regular interaction of farmers, agricultural machinery and, in certain cases, livestock with PV infrastructure. Therefore, compliance with conventional electrical safety standards alone may not adequately address all the additional risks associated with dual land use.

AgriPV plants should comply with the applicable CEA (Measures Relating to Safety and Electric Supply) Regulations, 2023, as amended, and relevant BIS/IEC standards, while incorporating additional AgriPV-specific safety requirements. In particular, IEC 60364-7-705 (Electrical Installations in Agricultural and Horticultural Premises), DIN SPEC 91434 (AgriPV Systems) and DIN SPEC 91492 (AgriPV Systems - Requirements for Livestock Farming) may be considered as international references.

Cables within the cultivated area are recommended to be routed on the structure above ground: in overhead systems in trays on beams at structure level; in inter-row systems on table rails within the non-cultivable strip; and in vertical systems along the top rail or in conduit above the crop canopy, never on a lower rail within reach of crops and animals. DC cables are recommended to conform to EN 50618 or IEC 62930 with stainless-steel ties; connectors are suggested to be mated pairs of one make and type (IS 16781/IEC 62852); live DC parts are advised to be beyond arm's reach (2.5 m, IEC 60364-4-41) from the highest standing surface, such as a trailer bed or ladder; and crossings between rows are recommended to be made at headlands in ducts ≥ 0.30 m below tillage depth and ≥ 0.75 m below FGL.

Earthing is recommended to follow IS 3043, with every row, column and post bonded, long rows bonded at both ends and at intervals, and the transformer yard designed for step and

touch potentials to IEEE Std 80;⁵⁶ irrigation pipes, borewell casings and wire fences are recommended to be bonded or isolated against transferred potentials; buried conductors are suggested to lie below the tillage horizon, and copper is recommended not to touch galvanized steel underground.

Separate cable safety standards should be specified:

- DC cables: IS 17293 and IEC 62930 for solar PV DC applications.
- AC cables: IS 7098 (Parts 1 and 2), IS 694 and IS 9968 (Part 1), as applicable to voltage ratings and installation conditions.

Additionally, AgriPV-specific safety requirements covering cable protection against agricultural machinery, underground cable installation, moisture ingress, earthing, and accessibility should be incorporated.

Lightning: a risk assessment to IS/IEC 62305-2 is recommended to cover tall overhead columns and the long metallic lines of inter-row and vertical rows;⁵⁷ The structure MAY act as a natural air-termination where continuity is verified. Lightning is a leading cause of accidental deaths from natural forces in India,⁵⁸ so field work is recommended to stop in thunderstorms, and the array is recommended not to be treated as a shelter.

Fire: crop-residue burning is recommended to be prohibited within the array through the lease and is advised to be prohibited within 30 m; vegetation beneath inter-row tables is recommended to be kept short by mowing or grazing; and firebreaks, IS 2190 extinguishers, oil containment and lockable isolators are recommended to be provided, with an Emergency Response Plan stating that DC circuits stay live in daylight.

3.7 Monitoring, Commissioning and O&M

Besides energy monitoring to IS/IEC 61724 (Part 1) Class B,⁵⁹ the parameters of Table 3.10 are recommended to be measured in the array and in an identically instrumented reference plot, retained for the project life and reported to the implementing agency, as with the control zones of France and the yield reports of Japan (Table 3.2).

⁵⁶Bureau of Indian Standards (BIS). 2018. IS 3043:2018 - Code of Practice for Earthing. New Delhi: BIS. See also: Institute of Electrical and Electronics Engineers (IEEE). 2013. IEEE Std 80-2013 - IEEE Guide for Safety in AC Substation Grounding. New York: IEEE.

⁵⁷Bureau of Indian Standards (BIS). 2010. IS/IEC 62305 (Parts 1–4):2010 - Protection against Lightning. New Delhi: BIS.

⁵⁸National Crime Records Bureau (NCRB). 2023. Accidental Deaths & Suicides in India 2022. New Delhi: Ministry of Home Affairs, Government of India. Lightning is reported among the leading causes of accidental deaths due to forces of nature. Available: <https://ncrb.gov.in>.

⁵⁹International Electrotechnical Commission (IEC). 2021. IEC 61724-1:2021 - Photovoltaic system performance - Part 1: Monitoring. Geneva: IEC. Defines Class A, B, and C monitoring systems.

Table 3.10: AgriPV specific monitoring parameters

Parameter	Sensor and location	Purpose
Irradiance and wind	Front and rear pyranometers (ISO 9060 Class A/B), both faces for vertical rows; anemometer at or above top-edge height	Performance ratio; bifacial gain; tracker stow
PAR (PPFD)	Overhead: under module, gap and mid-span; inter-row and vertical: transect of ≥ 3 points across the strip (both sides of vertical rows); reference plot	Light homogeneity; crop models
Soil moisture, microclimate	Probes at 15 and 30 cm on the same transects; air temperature, humidity and rain at 2 m	Irrigation; water balance
Crop yield and quality	Harvest measurement per AgriPV strip or plot and per reference plot	Yield ratio against reference

Cyber security: Cybersecurity of grid-tied solar power plants should primarily comply with the applicable Central Electricity Authority (CEA) Cyber Security Regulations and Guidelines, supported by relevant international standards such as IEC 62443, IEC 62351, IEEE 1547.3, and ISO/IEC 27001.

Delivery is recommended to follow Figure 3.4, with hold points at design approval and before energization, under an approved Inspection and Test Plan [ADVISORY]. It is recommended to include factory checks (flash tests, EL imaging, galvanizing); pile load tests; a 100% geometry survey of the clear height of every overhead bay and of the strip or lane width and lower-edge height of every inter-row or vertical row, with no negative tolerance; commissioning tests to IS 16960 (Part 1)/IEC 62446-1, including thermography;⁶⁰ earth and relay tests; Electrical Inspector approval; a capacity test to IS/IEC TS 61724 (Part 2); and post-installation EL sampling.

The developer and farmer are recommended to agree on an annual agri-energy calendar for the Kharif, Rabi and Zaid seasons, with joint pre-sowing and post-harvest inspections, pre- and post-monsoon checks, annual thermography and structural inspection, checks after extreme events and a five-yearly structural audit. Mechanized, low-water or waterless cleaning is advised to be specified [ADVISORY]: from platforms or lanes for overhead modules, from the ground after tillage and spraying for inter-row tables, and mainly along the splash-soiled lower edge for vertical modules. No chemical unapproved for food crops is recommended to be used; fall protection (IS 3521) is recommended to be used at height, and bilingual danger notices (IS 2551) and a seasonal safety orientation for farm workers are

⁶⁰International Electrotechnical Commission (IEC). 2016. IEC 62446-1:2016+AMD1:2018 — Photovoltaic (PV) systems — Requirements for testing, documentation and maintenance — Part 1: Grid connected systems. Geneva: IEC. See also: IEC 62446-3:2017 (outdoor infrared thermography) and IEC TS 61724-2:2016 (capacity test method).

recommended. The Decommissioning and Restoration Plan is recommended to cover pile extraction, removal of concrete to ≥ 0.30 m below tillage depth, decompaction, restoration against the baseline, and recycling under the E-Waste (Management) Rules, 2022.⁶¹

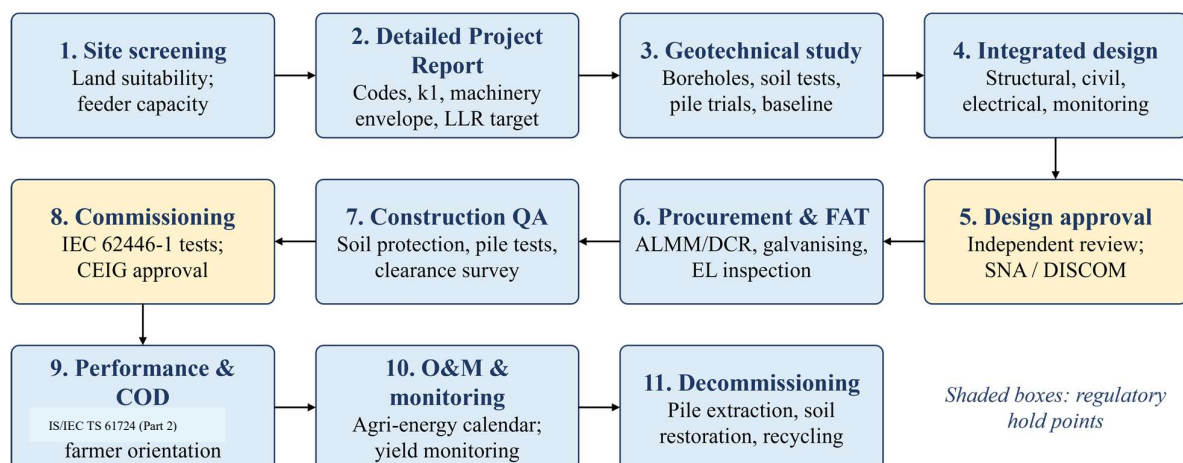


Figure 3.4: Engineering delivery workflow for AgriPV projects, with regulatory hold points

3.8 Summary Compliance Checklist

Table 3.11: Summary compliance checklist for technical appraisal by SNAs and DISCOMs

Parameter	Requirement	Section
Overhead geometry	$H_c \geq \text{machine height} + 0.5 \text{ m}$ and $\geq 3.0 \text{ m}$; top edge $\leq \approx 6 \text{ m}$	3.3
Inter-row geometry	Strip $\geq \text{implement} + 1.5 \text{ m}$; lower edge $\geq 0.8 \text{ m}$; pitch meets LLR limit	3.3
Vertical geometry	Clear lane $\geq \text{implement} + 1.5 \text{ m}$; lower edge 0.6–1.0 m; rows N–S	3.3
Trackers	Field-operations position; class clearance at all angles when occupied	3.3
Corrosion	IS 14191 incl. micro-environment; ground-line protection of all posts	3.4

⁶¹Ministry of Environment, Forest and Climate Change (MoEFCC). 2022. E-Waste (Management) Rules, 2022, as amended. New Delhi: MoEFCC. The Rules include specific provisions for solar photovoltaic modules, panels and cells. Available: <https://moef.gov.in>.

Parameter	Requirement	Section
Foundations	Removable; governing action verified by tests; tillage soil neglected	3.5
Soil and land	Soil Protection Plan; traffic in strips only; LLR 10–15%	3.5
Modules and inverters	ALMM, DCR bifacial; environmental tests; IP65/IP66	3.6
Cables and grid	Cables on structure; headland crossings; CEA DG rules; DC injection $\leq 0.5\%$	3.6
Earthing, lightning, fire	IS 3043 and IEEE 80; rows bonded; IS/IEC 62305-2; residue-burning ban	3.6
Monitoring and handover	Reference plot; PAR transects; IS 16960 (Part 1)/IEC 62446-1; 100% geometry survey; CEIG	3.7

CHAPTER 4

CROP COMPATIBILITY, AGRONOMIC PACKAGE OF PRACTICES AND AGRICULTURAL INTEGRATION STANDARDS

Agri-photovoltaics (AgriPV) is an integrated system that facilitates the harnessing of solar energy while farming continues on the same piece of land. Though the positive effect of AgriPV is very much evident in all the field and horticultural crops, the negative effect caused by shading varies significantly from one crop to another. Hence, selection of crops suitable for the AgriPV system, without considerable yield penalty, is very important. At the same time, we need to standardize the agricultural package of practices and integration of farm machinery for its effective adoption in farmers' fields.

4.1 Field Crop Suitability

The positive effect of AgriPV on crop performance in terms of favourable microclimate, reduction in evaporation losses, temperature moderation, etc., is common in all the field crops. Evapotranspiration from crops creates a cooling effect beneath the modules, boosting PV efficiency by 2%-5%. However, the negative impact of shading of solar panels on the growth and yield performance of different field crops needs to be studied and evaluated, and the final net effect will play a vital role in determining crop suitability. Crop suitability under AgriPV systems is largely determined by the capacity of plants to maintain photosynthetic activity, photosynthetic light-saturation point and shade tolerance, canopy architecture compatibility, root system interaction, water demand under altered microclimate, and land equivalent ratio (Dupraz et al., 2011).

Standard suitability assessment is advised to evaluate: i) Canopy architecture compatibility, which represents crop height relative to panel clearance and edge zones; ii) Root system interaction, which considers depth and lateral spread relative to foundation placement; iii) Growth duration alignment, which considers the matching of crop cycle to seasonal shading variation from tracking or fixed-tilt arrays; iv) Water demand under altered microclimate, where reduction of evapotranspiration occurs under partial shade that can lower irrigation requirements by 10-30% and contributes as an important factor in crop water budgeting (Omer et al., 2025).

Land Equivalent Ratio (LER) quantifies the relative productivity of land used simultaneously for crop cultivation and solar energy generation compared with the productivity achieved when these activities are carried out separately on a specific land area (Dupraz et al., 2011). Field crop suitability determinations are advised to consider a Land Equivalent Ratio of >1 for approved crop-array combinations (Valle et al., 2017).

Based on the field experiments conducted at the Centre of Excellence, ICAR-IARI, the suitable crops for AgriPV are found to be leafy vegetables like spinach, cucurbitaceous vegetables like

bottle gourd, pumpkin, and sponge gourd, which need to be further validated after completion of the second year of field study.

The following is the list of shade-tolerant field crops with higher potential under the AgriPV system in India:

- Leafy Greens & Herbs: Lettuce, spinach, kale, basil, mint, coriander.
- Root & Tuber Crops: Turmeric, ginger, potatoes, sweet potatoes, carrots, radishes.

Field crops are advised to be classified according to their photosynthetic light-saturation point and shade tolerance, since panel arrays reduce photosynthetically active radiation (PAR) by roughly 20-60% before reaching the crop canopy, which depends on the module density, height, and tracking configuration (Prakash et al., 2023).

Table 4.1: Classification of crops based on light response

Category	Representative crops	Suitability under AgriPV
High shade tolerance	Turmeric, ginger, many leafy fodder crops	High yield or yield-positive under partial shade (Sasikumar, 1989)
Moderate shade tolerance	Wheat, soybean, groundnut, potato	Moderate yield loss typically 10–25% under standard elevated racking, mitigated by row orientation and spacing (Laub et al., 2022)
Low shade tolerance (shade-sensitive)	Maize, sugarcane, sorghum	Low yield and generally unsuitable except under high-transmittance or low-density array configuration (Laub et al., 2022)

The cultivation of moderate shade tolerant and low shade tolerant crops (Table 4.1) may be encouraged in the unshaded inter-row spaces between panel arrays where light exposure exceeds 50%.

4.2 Horticultural Crop Suitability

Horticultural crops, particularly leafy vegetables, are generally well suited to AgriPV systems because of their ability to tolerate moderate shading and benefit from reduced heat stress and evaporative demand. Lettuce, spinach, amaranth, and fenugreek exhibit good shade tolerance, while tuber crops such as beetroot, radish, turmeric, and ginger show moderate to high suitability. Fruiting vegetables, including tomato, chilli, brinjal, capsicum, cucumber, and French bean, have moderate suitability, although their performance depends on cultivar and growth stage. Under moderate shading with approximately 70% of natural photosynthetically active radiation (PAR) transmission, leafy vegetables can maintain yields close to full sun conditions through increased leaf area, canopy expansion, and improved radiation

interception efficiency. In contrast, excessive shading may adversely affect flowering, fruit set, and yield in light-demanding fruiting crops.

Crop selection is therefore advised to emphasize shade tolerance, morphological plasticity, and stable productivity under intermittent radiation rather than yield potential under full-sun conditions alone. Appropriate agronomic management, including alley-based planting, adequate irrigation and nutrient supply, and suitable crop rotations, is essential for maintaining productivity. For commercial horticultural production, agriphotovoltaic designs are generally advised to aim to maintain around 70% or more of natural incoming radiation at the crop canopy, while adjustable PV panels can provide additional flexibility during radiation-sensitive growth stages.

Some horticultural crops like ginger, turmeric, coffee, and tea perform very well under shade in an AgriPV system. In their case, the whole effect of AgriPV is positive only; hence, we need to analyze its impact on the payback period. In addition, some medicinal and aromatic plants are found to be quite suitable for their cultivation under AgriPV systems, as revealed from the research study conducted by ICAR-CAZRI at Jodhpur.

The following is the list of some promising shade-tolerant horticultural crops with higher potential under AgriPV systems in India:

- Berries & Fruits: Strawberries, raspberries, blueberries, blackberries, grapes (viticulture).
- Solanaceous & Fruiting Vegetables: Bell peppers, tomatoes, chili, cherries.

4.3 Validation of Integrated Crop/Livestock/Solar System

One of the major advantages of AgriPV is the efficient recycling of farm bioresources, which allows the option of designing optimal cropping/farming / solar systems. Integrated system comparability in agriphotovoltaic research involves assessing the performance of dual-use land, where agricultural production and solar electricity generation occur simultaneously, against conventional systems in which land is allocated separately to farming and photovoltaic power generation. This comparison helps quantify the land-use efficiency and energy use efficiency associated with AgriPV development.

Two fundamental land-use configurations can be compared. In separate production systems, crop cultivation and solar electricity generation are undertaken on independent parcels of land, with one area dedicated to conventional crop production and another to PV installations. In contrast, combined AgriPV systems integrate both activities on the same land parcel, allowing crops to grow beneath or between elevated PV modules while simultaneously generating electricity.

The Land Equivalent Ratio (LER) is widely used to evaluate the combined productivity of agriphotovoltaic systems relative to separate agricultural and photovoltaic production. It can be expressed as (Dupraz et al., 2011):

$$LER = \frac{Y_{CROP,AV} + Y_{electricity,AV}}{Y_{CROP,REF} + Y_{electricity,PV}}$$

Where:

Y crop, AV = Crop yield under agriphotovoltaic conditions

Y crop, REF = Crop yield under reference farming

Y electricity, AV = electricity generation under agriphotovoltaic

Y electricity, PV = electricity generation from the reference PV system

An LER > 1 indicates that the combined system produces the equivalent output of a larger area managed as separate single-use systems (Trommsdorff et al., 2021b). Reported LER values vary substantially among agriphotovoltaic systems, depending on crop type, PV configuration, shading intensity, climate, and system design, with values exceeding 1.5 reported in several studies (Dupraz et al., 2011; Chalgybayeva et al., 2024).

AgriPV systems can be classified according to their physical configuration and compatibility with agricultural operations (Vorast, 2022; Gorjian et al., 2022). Open-field systems integrate PV arrays directly into agricultural fields, whereas greenhouse or enclosed systems incorporate PV modules into protected cultivation structures (Gorjian et al., 2021). Based on spatial arrangement, AgriPV may further be categorized as overhead systems, where elevated panels are installed above crops, and interspace systems, where PV rows are separated by cultivation corridors.

Overhead systems generally provide greater direct integration of crops and PV generation and can accommodate agricultural machinery when adequate clearance is provided. Interspace systems, including vertical or bifacial PV configurations, provide wider cultivation corridors and are particularly suitable for mechanized field crops, forage production, and grazing (Antani, 2025). The selection of configuration is therefore advised to consider crop height, machinery requirements, land availability, and the desired balance between agricultural and electricity production.

Panel density strongly influences both crop productivity and electricity generation. Full-density (FD) configurations typically transmit approximately 43-53% of incoming PAR to the crop canopy, thereby maximizing PV deployment but imposing greater radiation limitation on crops (Dupraz et al., 2011; Marrou et al., 2013c). Half-density (HD) configurations, achieved through wider panel spacing, can increase radiation transmission to approximately 70-71% of natural levels. Although HD systems may produce less electricity per unit land than FD systems, they can provide more favourable conditions for light-sensitive crops and improve the balance between agricultural and energy outputs.

AgriPV systems modify the crop microenvironment through changes in radiation, temperature, humidity, and soil-water dynamics (Hassanpour Adeg et al., 2018; Grell & Parker, 2026). Moderate shading can stimulate morphological adaptations such as increased

leaf area, thinner leaves, and faster canopy development, thereby improving radiation interception efficiency. At the same time, PV structures can reduce crop canopy temperature, transpiration demand, and soil moisture losses during periods of high atmospheric demand (Barron-Gafford et al., 2019). These microclimatic effects may provide additional protection against heat stress, drought, excessive solar radiation, and hail, although excessive shading can reduce photosynthesis and crop yield. Consequently, agriphotovoltaic system comparison is advised to consider not only crop and electricity production but also the associated microclimatic and resource-use benefits.

In addition, the integrated crop/livestock / solar systems suitable for different agro-climatic zones of India need to be tested and validated under the AgriPV system. It may also include farming systems such as rice-fish farming system, rice-water chestnut-fish farming system, rice-wheat-fish-poultry-duckery-dairy farming system suitable for both small and marginal farmers of India. In addition, sheep or poultry grazing can be well integrated, which aids in effective non-chemical weed control under solar panels.

4.4 AgriPV-Friendly Package of Practices

The package of practices needs to be standardized based on the design and proportion of space occupied by solar panels. The intercultural operations are recommended to be facilitated through advanced and small farm machinery, which requires less clearance space.

- **Irrigation Reduction:** Panels create 14%–50% shade coverage, which significantly cuts soil water evaporation and reduces total crop water demand by 15%-30%.
- **Rainwater Harvesting:** Utilize the tilted panel surface as a catchment system to divert rainwater into farm storage ponds or direct groundwater recharge structures.
- **Precision Irrigation:** Install drip or micro-sprinkler systems mapped directly to panel alignment to prevent uneven soil moistening caused by rain run-off from module edges.
- **Microclimate Benefits:** Nighttime heat retention under panels protects cold-sensitive crops from frost, while daytime shading reduces heat stress during peak thermal hours.
- **Soil Health & Tillage:** Minimal or zero-tillage approaches are recommended near panel mounting pillars to protect mechanical footings and maintain root structure stability.
- **Vertical Stacking & Micro-Zoning:** Utilize high-shade areas under modules for root crops or shade-loving spices, and lower-shade inter-row spaces for vine crops or open-ground row crops.

Spatial design standards

- Minimum inter-row spacing to be set as a function of the chosen crop's mechanization width plus a service margin (recommended minimum 0.5 m beyond implement width).
- Orientation is advised to be selected to balance shading uniformity across the crop strip.

Soil and water management

- Foundations are advised to avoid concentration of compaction in primary root zones, and standards are advised to specify maximum footprint coverage (recommended $\leq 5\%$ of cultivated area for point foundations).
- Drip or micro-irrigation systems are recommended over flood irrigation to accommodate uneven wetting patterns caused by rain shadow effects beneath panel edges.
- Soil health monitoring (organic carbon, compaction, moisture retention) is advised to be conducted at minimum annual intervals, with baseline sampling before installation.

Crop management adaptations

- Adjusted sowing windows to align crop developmental stages with periods of lower shading intensity where seasonal tilt or tracking angle changes exist.
- Modified fertilization schedules accounting for altered microclimate nutrient cycling (partial shading can slow residue decomposition rates).
- Pest and disease monitoring protocols adjusted for altered humidity and airflow patterns beneath arrays, which can elevate fungal disease risk in enclosed or low-clearance configurations.

Structural and safety practices

- Cabling, junction boxes, and inverter placement are recommended to be set back from active cultivation zones and protected against agricultural equipment contact.
- Panel edge drip-line management to prevent localized soil erosion.
- Livestock integration requires standards for panel height, fencing, and vegetation management distinct from row-crop practices.

4.5 Conceptualization and Design of Standards for Diversified Crop Matrices

Since a single AgriPV site may rotate or intercrop multiple species across seasons, standards are advised to move beyond single-crop compatibility ratings toward a matrix-based framework that allows planners to select compatible crop combinations dynamically, based on array configuration, season, and region. The standards for the scientific method of

cultivation under AgriPV are recommended to be facilitated based on the cropping system as a whole, which provides us with the necessary element of convenience.

Matrix Design Principles

The diversified crop matrix is advised to incorporate the following principles:

- Two-axis structure: Crops are advised to be evaluated against PV configurations or shading classes, with each crop-array combination assigned a suitability score based on experimental and regional evidence. Such an approach is consistent with the need to consider crop-specific shading responses and system configuration in agriphotovoltaic design (Lee et al., 2023; Marrou et al., 2013c).
- Regional calibration: Matrix scores are advised to be adjusted for agro-climatic conditions because crop responses to shading depend on radiation availability, temperature, water status, and crop-specific light requirements. Agriphotovoltaic design studies emphasize that shading and crop responses need to be evaluated according to site-specific conditions (Lee et al., 2023).
- Rotation compatibility: A secondary layer is advised to identify agronomically compatible crop sequences, including cereal-legume and diversified seasonal rotations, to maintain soil fertility and resource-use efficiency under agriphotovoltaic conditions. Such multifunctional and regenerative approaches are increasingly being incorporated into agriphotovoltaic system design.
- Dynamic updating: The matrix is advised to be periodically revised as new regional field evidence becomes available. A 2-3-year review cycle may be adopted as a proposed management framework to incorporate advances in crop performance, PV technology, and field validation.

Structural and Geometric Design Standards

Structural design is advised to ensure that PV installations do not compromise essential agricultural operations. Overhead systems are advised to provide sufficient vertical clearance according to crop and machinery requirements, while interspace systems are advised to provide adequate corridors for mechanized cultivation, haying, or grazing. DIN SPEC 91434 provides a formal framework for classifying agriphotovoltaic systems and maintaining agricultural use as the primary land function (DIN, 2021; Vorast, 2022).

Column spacing is advised to be coordinated with crop-row spacing, furrow dimensions, and machinery width. For example, 0.9-1.2 m furrow spacing for lettuce and 2.5-3.0 m planting distances for grapes have been incorporated into agriphotovoltaic structural design considerations (Lee et al., 2023). The same study emphasizes that column height and spacing are advised to allow safe operation of agricultural machinery and are advised to be adjusted according to local crop and field conditions.

Radiative Control and Panel Density

Panel density is advised to be selected according to crop radiation requirements. Full-density (FD) configurations may transmit approximately 43-53% of natural PAR, whereas half-density (HD) configurations can provide substantially greater radiation transmission and are therefore more appropriate for light-sensitive crops. Agriphotovoltaic experiments with lettuce demonstrated that crops can maintain productivity under partial shading through improved Radiation Interception Efficiency (RIE), increased leaf area, and greater leaf size (Marrou et al., 2013c).

Panel elevation and spacing are also advised to be designed to improve spatial light distribution and minimize prolonged deep-shade zones. The configuration of modules, their spacing, and their height influence both the shading ratio and the amount of radiation reaching crops; therefore, these parameters are advised to be optimized together with crop requirements.

Minimum Data Requirements for Matrix Entries

Each crop-array combination is preferably advised to be supported by at least one replicated full-season field trial comparing agriphotovoltaic and open-field conditions. Matrix entries are advised to consider:

- Shading percentage and seasonal radiation variation
- Crop yield and quality
- Water-use and microclimatic responses
- Electricity generation
- Economic performance, including LER and revenue comparisons.

Table 4.2: Suggested standards for optimal integration

Parameter	Suggested standard
Clearance Height	Minimum 3 to 4 m ground clearance to facilitate standard tractor and harvester access underneath.
Row Spacing	5 to 10 m inter-row gaps matching standard farm machinery implement widths.
Module Orientation	Vertical bifacial East-West setups or single-axis dynamic tracking systems to optimize the light penetration and energy yield.

CHAPTER 5

PERFORMANCE EVALUATION AND TESTING

5.1 Energy Performance

5.1.1 The AgriPV system is recommended to be designed to achieve optimum electrical energy generation without adversely affecting agricultural productivity. Energy performance assessment is recommended to consider site-specific meteorological data, system configuration, and operational conditions. Performance evaluation is recommended to be based on measured data and validated simulation results. The performance evaluation requirements given under IS/IEC 61724 (Part 1) are recommended to be followed, which outlines terminology, equipment, and methods for performance monitoring and analysis of photovoltaic (PV) systems. It also serves as a basis for other standards which rely upon the data collected.

5.1.2 The installed PV system is recommended to be commissioned with performance tests, including I-V curve tracing as per IS 12762 (Part 1) and efficiency measurement of power conditioners as per IS/IEC 61683.

5.2 Agricultural Performance

5.2.1 General

Agricultural performance under AgriPV systems is a critical component to ensure that integration of photovoltaic installations does not adversely affect crop production and farm viability. The dual-use of land for energy and agriculture is recommended to be optimized in such a manner that agricultural productivity is sustained or enhanced under modified microclimatic conditions created by photovoltaic panels.

The agricultural performance assessment is recommended to consider crop yield, water use efficiency, soil health, cropping intensity, and operational feasibility. These parameters are recommended to be evaluated in comparison with conventional open-field conditions under similar agro-climatic conditions.

5.2.2 Crop Yield Performance

5.2.2.1 Crop yield is the primary indicator of agricultural performance in AgriPV systems. The presence of photovoltaic panels may alter light availability, temperature, and moisture conditions, which can influence crop growth positively or negatively depending on crop type and management practices.

Crop yield under AgriPV systems is recommended to be maintained at a level that ensures economic viability of agricultural operations. In order to ensure the required balance between crop yield and energy generation, it is recommended that the yield not be lower than 80 % of that obtained under conventional open-field cultivation for the same crop and season.

5.2.2.2 Measurement and Monitoring

Crop yield is recommended to be measured using standard agronomic procedures appropriate to the crop and region, and is recommended to be expressed in kg/ha or equivalent units. Yield data are recommended to be collected for at least one complete cropping season corresponding to the crop under evaluation. For the purpose of performance assessment, AgriPV yield and baseline yield are recommended to be determined in accordance with Table 5.1.

Table 5.1: Yield Measurement and Baseline Determination Requirements

Sl. No.	Parameter	AgriPV System	Baseline (Reference)
i)	Crop type and variety	Recommended to be recorded	Recommended to be identical to the AgriPV system
ii)	Cropping season and year	Recommended to be recorded	Recommended to correspond to the same season and year
iii)	Agro-climatic conditions	Recommended to be recorded	Recommended to be comparable to AgriPV conditions
iv)	Soil and field conditions	Recommended to be recorded	Recommended to be similar to the AgriPV site
v)	Crop management practices (irrigation, inputs, etc.)	Recommended to be recorded	Recommended to be comparable to the AgriPV system
vi)	Unit of measurement	kg/ha or equivalent	Same as AgriPV system
vii)	Duration of data collection	Minimum one complete cropping season	Same as AgriPV system
viii)	Source of data	Field measurement	Farm records / nearby fields / regional data
ix)	Data documentation	Recommended	Recommended and verifiable

5.2.2.3 Additional Provisions for Baseline Determination

Baseline yield for comparison is recommended to be established using one or more of the following sources, ensuring comparability with the AgriPV system:

- Farm-level historical yield data from the same land parcel;

- Yield data from adjacent or nearby fields under similar agro-climatic and management conditions;
- Authenticated regional or district-level agricultural statistics.

Where baseline data are not directly comparable, appropriate normalization is recommended to be carried out to account for variations in agro-climatic conditions, management practices, and input use. All measurements, assumptions, methodologies, and data sources used for yield estimation and baseline determination are recommended to be documented and made available for verification.

5.2.3 Water Use Efficiency

5.2.3.1 Water use efficiency (WUE) under AgriPV systems is recommended to be maintained at a level comparable to or higher than that under conventional agricultural practices for the same crop and season. The assessment is recommended to be based on the relationship between crop yield and total water used for irrigation. Baseline water use efficiency is recommended to be determined for the same crop, season, and comparable agro-climatic and management conditions, following the principles already specified. All data related to water use and yield are recommended to be documented and made available for verification.

5.2.3.2 Measurement and Monitoring

Water use efficiency (WUE) is recommended to be determined based on the ratio of crop yield to the total quantity of water used for irrigation during the cropping period. WUE is recommended to be calculated as follows:

$$WUE = \frac{\text{Crop Yield}}{\text{Total Water Used}} \quad (\text{kg/m}^3)$$

Water usage is recommended to be measured and recorded using appropriate methods such as irrigation logs, flow meters, or other suitable measurement systems. The method adopted is recommended to ensure reasonable accuracy and consistency in measurement across the cropping period. All data related to crop yield and water usage are recommended to be recorded systematically and maintained for verification. Where estimation methods are used in place of direct measurement, the methodology and assumptions are recommended to be documented.

5.2.4 Cropping Intensity and Land Use

AgriPV systems are recommended to ensure efficient utilization of land without significant reduction in agricultural activity. Cropping intensity and cultivated area are recommended to be maintained at levels comparable to conventional agricultural practices under similar agro-climatic conditions.

Land Equivalent Ratio (LER) is an indicator of overall land use efficiency in AgriPV systems and represents the relative productivity of combined land use compared to separate agricultural and photovoltaic systems.

Assessment of cropping intensity, cultivated area, and LER is recommended to be carried out using field surveys, farm records, and energy generation records, as applicable. Geospatial techniques such as GIS may be used where appropriate.

5.2.5 Soil Health

Soil health is a critical indicator of long-term sustainability of AgriPV systems. The presence of photovoltaic structures may influence soil moisture, temperature, and biological activity, which can affect key soil properties over time. Soil parameters are recommended to be maintained within acceptable limits to ensure continued agricultural productivity.

Soil parameters under AgriPV systems are recommended to be maintained at levels comparable to baseline conditions. Baseline soil parameters are recommended to be established before installation or at the earliest feasible stage and are recommended to represent the same soil type and agro-climatic conditions.

5.2.5.1 Measurement and Monitoring

The soil parameters to be monitored are recommended to include soil pH, electrical conductivity (EC), soil organic carbon (SOC), and soil compaction (bulk density or penetration resistance).

Soil sampling is recommended to be carried out at representative locations within the cultivated area under AgriPV systems.

Monitoring is recommended to be conducted at the following frequency:

- a) Baseline measurement - before installation or at the beginning of monitoring;
- b) Subsequent measurements - at least once after each cropping season or at a minimum annually.

Soil pH, EC, and organic carbon are recommended to be determined using standard soil testing methods. Soil compaction is recommended to be measured using appropriate methods such as bulk density determination or penetrometer readings. Sampling depth, sampling procedure, and analytical methods are recommended to be consistent across monitoring periods to ensure comparability of results. All measurements, data sources, and analytical procedures are recommended to be documented and made available for verification.

5.2.6 Farm Operations Performance

Farm operations performance under AgriPV systems is recommended to ensure that routine agricultural activities such as land preparation, sowing, irrigation, intercultural, and harvesting are not significantly constrained by the presence of photovoltaic structures.

Farm operations under AgriPV systems are recommended to be carried out efficiently and are recommended not to result in significant delays, inaccessibility, or disruption to normal agricultural practices.

The following parameters are recommended to be monitored:

- a) Operational time for key farm operations - at least once per cropping season for major operations
- b) Accessible cultivated area - At least once per cropping season
- c) Cropping frequency (number of crop cycles per year) - annually

Operational time is recommended to be assessed for major farm activities such as land preparation, sowing, irrigation, interculture, and harvesting, and is recommended to be compared with baseline conditions.

Assessment is recommended to be carried out using field observations, farm records, and, where feasible, time-motion studies.

5.2.7 Data Recording and Documentation

Accurate and consistent data recording is essential for evaluation of agricultural performance under AgriPV systems. All relevant data are recommended to be recorded in a systematic manner to enable assessment, comparison with baseline conditions, and verification by competent authorities.

The following data are recommended to be recorded and maintained for each AgriPV installation:

- a) Crop yield (per crop and season);
- b) Water use, including irrigation quantity and frequency;
- c) Soil parameters, including pH, electrical conductivity, and organic carbon;
- d) Cropping pattern, including crop type and number of crop cycles;
- e) Land use details, including cultivated area and total project area;
- f) Energy generation data from the AgriPV system (where applicable).

All data are recommended to be recorded using consistent units and methods to ensure comparability over time.

Data are recommended to be recorded at appropriate intervals corresponding to the parameter being monitored, such as per cropping season, per irrigation event, or annually, as applicable. Records are recommended to include information on measurement methods, data sources, assumptions, and any deviations from standard procedures. Where digital systems are used for data recording, appropriate measures are recommended to be taken to ensure data integrity, traceability, and accessibility. Standardized formats or templates for

data recording are advised to be adopted, where available, to facilitate uniformity and ease of verification.

Record Retention

- It is recommended that all project records be retained for the entire project life.
- Longer retention periods may be adopted where required by regulatory authorities or project-specific requirements.

Compliance and Verification

- All recorded data are recommended to be made available for verification by concerned authorities or designated agencies, as required.
- Records are recommended to be complete, traceable, and supported by appropriate documentation to enable independent verification of agricultural performance under AgriPV systems.

Monitoring and data acquisition

- A data acquisition system is recommended to record, at a minimum: daily energy generation (kWh), insolation (kWh/m²), inverter performance, and string currents.
- IoT-Based Smart Agri-Photovoltaics Monitoring System Architecture.

a) Sensors Required

- i) Energy: DC string current/voltage, AC inverter output, energy meters (import/export).
- ii) Agriculture: Soil Moisture & Temperature sensors (at two depths), Ambient Temperature & Humidity under and outside the array, PAR sensors at crop canopy level, Leaf Wetness sensors.
- iii) Environment: Pyranometer (POA and GHI), Rain gauge, Wind speed/direction sensor.

b) Data logger & communication - Industrial-grade IoT gateway with 4G/5G/Wi-Fi connectivity capable of handling Modbus, RS-485, and analog protocols. Local data storage for ≥ 30 days.

c) Dashboard & analytics - A unified cloud-based dashboard is recommended to display:

- Real-time and historical energy & agricultural data.
- Automated alerts for faults (inverter trip, string failure, irrigation pump failure, soil moisture below threshold).
- Predictive insights (soiling loss alerts, irrigation scheduling recommendations, pest/disease risk indices based on microclimate).

Data governance and interoperability

The monitoring system is recommended to support open APIs [Application Programming Interfaces] (e.g., RESTful) for integration with third-party platforms (DISCOM portals, FPO management software, agricultural advisory services).

Data ownership resides with the farmer/system owner. Vendor agreements are recommended to ensure data portability and privacy.

5.2.8 Grower Skills

Effective implementation of AgriPV systems requires adequate knowledge and skills for managing both agricultural and photovoltaic components.

Growers engaged in AgriPV systems are advised to possess or be trained in the following:

- Crop management under partial shading conditions
- Efficient water and nutrient management
- Safe operation around photovoltaic structures
- Basic understanding of system layout and constraints
- Record keeping and data management

5.2.9 Disease and Insect Control

Crop protection under AgriPV systems is recommended to be carried out using appropriate integrated pest and disease management practices, considering the modified microclimatic conditions. The following is recommended to be ensured:

- Regular monitoring of pest and disease incidence
- Adoption of integrated pest management (IPM) practices
- Use of approved pesticides and biological control methods
- Avoidance of practices that may damage photovoltaic infrastructure
- Maintenance of crop health without adversely affecting system performance
- Where feasible, emphasis is advised to be placed on preventive and eco-friendly approaches for pest and disease control.

5.3 Testing Requirements

This clause specifies the testing requirements for AgriPV systems to ensure compliance with design, safety, structural integrity, electrical performance and energy performance requirements.

The components of the power plant are recommended to be tested as per the respective test requirements given under applicable standards tabulated in Annexure I.

5.3.1 During the pre-commissioning stage, all electrical installations are recommended to undergo insulation resistance (min. 1 M Ω), ground continuity (max. 1 Ω), and dielectric withstand tests as per IS/IEC 61730-2.

5.3.2 Annual inspection of structural bolt torque, galvanizing integrity, electrical safety, and irrigation system uniformity is recommended to be performed. Thermographic inspection of PV arrays is advised annually.

5.3.3 Agricultural Performance Testing

a) PAR Uniformity Test - After installation, PAR is advised to be measured at multiple points (grid pattern) under the array at solar noon on a clear day. It is recommended that the PAR availability factor be within $\pm 5\%$ of the design value across the cultivable area.

b) Microclimate Validation - Temperature and humidity are advised to be logged inside and outside the array for one full week during a peak summer and winter month. The predicted moderation effect is advised to be validated.

c) Soil Health Benchmarking - Prior to construction and following 3 years of operation, soil testing is recommended to be conducted for key parameters, including bulk density in accordance with IS 2720 series, and organic carbon, NPK status, and microbial count in accordance with relevant national standards/established testing methods.

CHAPTER 6

MICROCLIMATE, SOIL HEALTH AND LAND SUSTAINABILITY PROTOCOLS IN AGRIPV SYSTEMS

AgriPV systems provide several benefits to crops, such as improvement in microclimate and soil health, thereby generating additional net returns to the practicing farmers. The improvement in microclimate includes water conservation, soil microbial health, temperature moderation, etc.

6.1 Positive Effect of AgriPV on Evapotranspiration, Water Balance, Crop Growth and Yield

Photovoltaic modules intercept a portion of incoming solar radiation before it reaches the crop and soil surface. The resulting reduction and redistribution of radiation modifies the microenvironment beneath and between the PV structures. Under hot and water-limited conditions, moderate shading can reduce the intensity of solar loading and moderate soil and canopy temperature. Lower thermal loading can reduce atmospheric evaporative demand and prolong the residence time of water within the crop root zone.

However, the magnitude and direction of these effects depend on panel height, row spacing, tilt, orientation, crop height, season, wind regime, and agro-climatic zone. AgriPV is therefore advised to be understood not simply as a shading technology but as a radiation-mediated microclimate management system.

Table 6.1: Principal microclimatic modifications under AgriPV

Microclimatic variable	Potential AgriPV modification	Agricultural implication
Solar radiation	Partial reduction and spatial redistribution	Reduced radiation and heat load
Soil temperature	Moderation during intense solar periods	Reduced thermal stress
Air temperature	Potential moderation	Reduced heat stress
Relative humidity	May increase locally	Influences transpiration and disease risk
Soil moisture	Greater retention potential	Reduced irrigation demand under suitable conditions
Wind exposure	Locally modified	Potential reduction in wind-driven water loss
Evaporation	Potential reduction	Improved water conservation
Crop water stress	Potential reduction during hot periods	Improved crop resilience

The spatial heterogeneity of these effects is important. Areas directly below panels may experience substantially different conditions from inter-row areas. Therefore, a field-scale average may conceal important crop-level variation.

AgriPV systems create a spatially heterogeneous microclimate by modifying solar radiation, air temperature, humidity, wind, soil temperature, and soil moisture across open-field, inter-row, and under-panel zones. A recent critical review found that photosynthetically active radiation (PAR) reduction across AgriPV systems can range from about 5% to 94%, while changes in air temperature vary from cooling to slight warming depending on sensor position, system configuration, crop, and climate. The same review identified that reduced soil temperature and enhanced soil-moisture retention are relatively consistent, whereas the air temperature responses are strongly site-specific (Cosme & Vázquez y Parraguirre, 2025). These microclimatic changes directly influence the water balance of AgriPV systems. Partial shading reduces the amount of short-wave radiation reaching the soil and crop canopy, which can reduce soil evaporation as well as crop evapotranspiration. Mundu et al. (2026) identify reduced evapotranspiration, improved soil-moisture retention, and reduced crop water stress as important potential benefits, particularly in arid and semi-arid environments. However, these benefits depend on panel geometry, crop canopy, irrigation, rainfall redistribution, and the balance between shading and crop light requirements.

Field observations further demonstrate that these water-balance effects can vary spatially and may not directly translate into improved crop performance. Lower air temperature and wind speed and higher relative humidity were observed under PV conditions, with cumulative reference evapotranspiration (ET_o) during pepper and chili-pepper cycles reduced by approximately 28% and 34%, respectively, in the zone close to the PV structures relative to the open field control (Tucci et al., 2025). However, these changes were accompanied by substantial crop-specific yield responses, indicating that lower evaporative demand does not necessarily result in higher crop yield. Thus, water-saving performance is advised to be assessed together with radiation availability, crop physiology, and final yield rather than as an isolated indicator. In addition to panel-induced shading, vegetation management can further influence the water and thermal balance of AgriPV systems. The combination of vegetation and PV infrastructure can buffer soil-temperature extremes and make soil-moisture distribution more homogeneous (Choi et al., 2023). Hence, vegetation is treated as an active component of the AgriPV system rather than merely as ground cover.

These interactions compel the development of an integrated water-balance protocol based on the comparison of at least three zones: (i) full-sun control, (ii) inter-row, and (iii) under-panel. Measurements are advised to include precipitation, irrigation, soil moisture at representative root-zone depths, and actual crop evapotranspiration or crop water use. Water-use efficiency is advised to be calculated from crop yield and water consumption, while changes in soil moisture are advised to be interpreted together with rainfall and irrigation redistribution. This approach avoids attributing all observed moisture differences to shading

when panel drip-line concentration, vegetation cover, or soil compaction may also be contributing factors.

The three monitoring zones are illustrated in Figure 6.1.

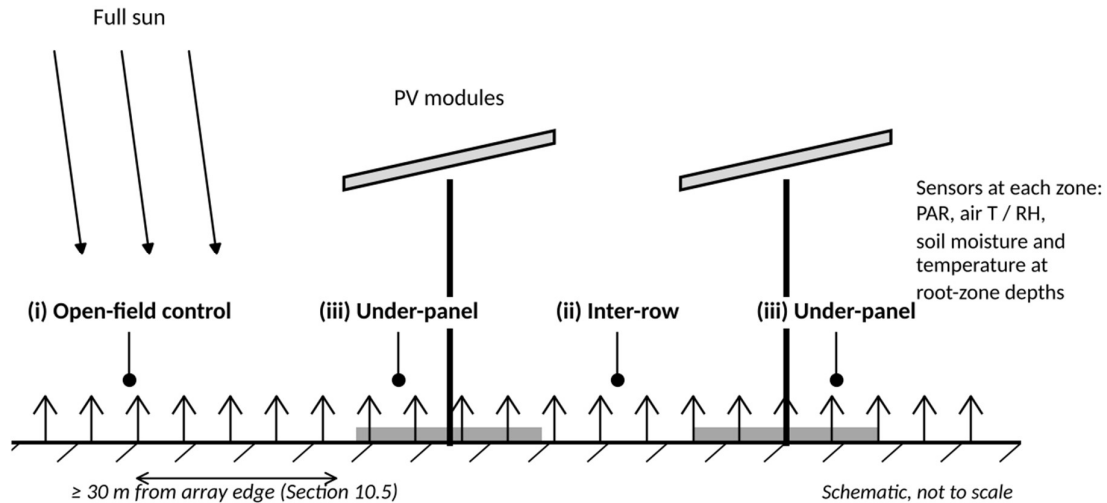


Figure 6.1: Spatial monitoring zones in an overhead AgriPV system: (i) open-field control, (ii) inter-row, and (iii) under-panel (schematic)

6.1.1 Evapotranspiration Response

Evapotranspiration (ET) represents the combined water loss from soil and vegetation. The supplied AgriPV Crop Matrix reports that reduced exposure of the ground surface to direct sunlight can reduce evapotranspiration and ground heat flux. It cites an approximate 10-30% reduction in actual evapotranspiration under conditions where light availability was approximately 50-70% of full-sun irradiation. Transpiration is a fundamental physiological process associated with carbon assimilation, nutrient transport, and plant growth. The objective is therefore advised to be optimal evapotranspiration rather than minimum evapotranspiration.

6.1.2 Field Water Balance

The field-scale water balance may be expressed as:

$$\Delta S = (P + I + CR) - (ET + R + D)$$

Where (P) is precipitation, (I) is irrigation, (CR) is capillary rise, (R) is runoff, (D) is deep drainage, and (ΔS) is change in soil-water storage. AgriPV can modify this balance through changes in ET, soil temperature, rainfall interception, and irrigation requirement. Water management is consequently advised to include soil-moisture monitoring, irrigation measurement, rainfall recording, and drainage assessment.

6.2 Negative Impact of Shading on Crop Growth and Yield

The principal trade-off in AgriPV is the reduction of radiation, which can moderate heat and water stress but may also limit photosynthesis and biomass production. Cosme and Vázquez y Parraguirre (2025) emphasize that AgriPV systems are advised not to be characterized by a single average shading value because PAR varies spatially and temporally, creating distinct environments under panels, between rows, and in open-field areas. These microclimatic differences directly affect crop water balance and productivity. Tucci et al. (2025) reported reductions in lettuce fresh weight (37%), while pepper and chili pepper yields declined by up to 51% respectively, under affected PV zones. Nevertheless, LERs of 1.60 and 1.40 for the lettuce-pepper and lettuce-chili sequences demonstrate that crop-level yield losses do not necessarily imply lower overall land productivity.

The same radiation attenuation that confers water-balance benefits can also constrain photosynthesis, biomass accumulation, and yield once shading exceeds crop-specific thresholds. Magarelli et al. (2024) reported that shading levels up to approximately 30% are generally not detrimental to fruit yield and quality, but that yield losses become evident beyond this threshold for light-demanding crop species. A large field study of rice, soybean and sweet potato under agriphotovoltaic conditions also found substantial inter- and intra-specific variation in shade tolerance, with cultivar selection, weed management and micronutrient fertilization able to partially mitigate yield penalties.

AgriPV design is therefore advised to focus on matching radiation conditions with crop requirements rather than simply maximizing or minimizing shade. Sensor-based monitoring of PAR and microclimate can identify spatial production zones, allowing shade-tolerant crops to occupy more shaded areas and light-demanding crops to be placed in higher-radiation zones (Cosme and Vázquez y Parraguirre, 2025).

The practical radiation conditions may therefore be interpreted as:

Table 6.2: Radiation conditions and AgriPV implications

Radiation condition	Physiological response	AgriPV implication
Below LCP	Insufficient net carbon gain	Unsuitable
Between LCP and LSP	Light-limited photosynthesis	Strong response to shading
Around/above LSP	Near photosynthetic saturation	Moderate shading may have limited effect

6.3 Soil Physical Properties Influenced by AgriPV

Soil is the fundamental agricultural asset within an AgriPV system. Long-term sustainability cannot therefore be assessed solely through annual crop yield and electricity generation. AgriPV can influence soil through changes in radiation, soil temperature, evaporation, soil moisture, rainfall distribution, vegetation cover, machinery traffic, irrigation, drainage and

nutrient cycling. AgriPV systems affect soil through both construction-related disturbance and long-term changes in radiation, rainfall redistribution, temperature, vegetation cover, and traffic. Construction is a particularly important phase because foundations, access roads, machinery movement, and repeated traffic can increase soil bulk density and reduce porosity and infiltration (Grahmann et al., 2026). Mundu et al. (2026) identify soil compaction as a principal environmental risk and recommend restricting heavy machinery, using low-ground-pressure equipment, maintaining vegetation cover, and adopting controlled traffic practices.

Moreover, soil temperature and moisture vary spatially under AgriPV systems. Therefore, Cosme and Vázquez y Parraguirre (2025) recommend measurements across open-field, inter-row, and under-panel zones to capture this spatial gradient. Soil-temperature responses are more consistent but vary with depth and location. Therefore, soil moisture and temperature are advised to be measured at defined root-zone depths across the three principal spatial zones. Vegetation management can moderate several of these effects. Choi et al. (2023) found higher soil moisture, carbon, and nutrients in vegetated areas compared with bare areas at a utility-scale PV facility. Hence, it can be suggested to maintain vegetation to provide soil conservation co-benefits. The result is not advised to be generalized to every climate or soil type, but it supports the principle that soil protection is advised to be integrated with PV design and vegetation management.

In the PV-agriculture treatment, fine-particle content, soil organic matter, total nitrogen, microbial abundance, microbial biomass carbon and nitrogen, and available nutrients are substantially higher than in shifting-dune controls (Ma et al., 2026). Along with this, a favourable soil hydrothermal environment and higher root biomass can be maintained under AgriPV systems. Hence, PV infrastructure can be associated with soil restoration when it is combined with active agricultural and vegetation management.

Considering these significant effects on soil properties, a land-sustainability protocol is advised to establish pre-installation baselines for bulk density, penetration resistance, aggregate stability, infiltration, soil moisture, soil temperature, pH, soil organic carbon, and major nutrients. The same variables are advised to be monitored after construction and periodically during operation. Where compaction exceeds site-specific agronomic thresholds, remediation is advised to be based on the soil type and cropping system and may include controlled subsoiling, organic amendments, or reduced traffic (Liu et al., 2026).

6.3.1 Soil Temperature and Moisture

PV shading can moderate soil temperature by reducing direct solar radiation and ground heat flux. Under hot conditions, this may reduce excessive root-zone heating. However, excessive cooling could influence germination, root development, microbial activity, and nutrient mineralization. Important observations include volumetric soil-water content, soil-water potential, irrigation depth, rainfall, drainage, infiltration rate, and moisture at multiple depths. Soil temperature is an important determinant of seed germination, root development, microbial activity, nutrient availability, and crop growth. AgriPV shading can

moderate soil temperature by reducing direct solar radiation and ground heating. This may be beneficial in hot environments where excessive soil temperature can increase water loss and impose stress on roots. However, excessive reduction in soil temperature may also influence biological and physiological processes. Therefore, soil temperature is advised to be monitored under the PV structures and compared with an open-field reference condition.

6.3.2 Soil Compaction and Structure

Construction, maintenance and repeated machinery traffic may create localized compaction, particularly around panel foundations, service corridors, access roads, turning areas and cable routes.

Table 6.3: Soil properties and recommended assessment methods

Soil property	Recommended assessment
Bulk density	Core method
Penetration resistance	Cone penetrometer
Aggregate stability	Laboratory assessment
Infiltration	Double-ring or equivalent method
Hydraulic conductivity	Field/laboratory method
Soil moisture	Sensor or gravimetric method
Soil temperature	Continuous sensing
Surface condition	Visual/photographic monitoring

Reduced radiation and soil heating can lower evaporation and allow water to remain available within the root zone for longer periods. The effect is influenced by rainfall, irrigation, soil texture, crop canopy, and drainage and panel configuration. Soil-moisture measurements are advised to be taken at representative depths and locations. Monitoring is advised to include shaded areas, inter-row areas, and reference locations so that spatial differences can be identified.

6.4 Soil Microbial Health Influenced by AgriPV

Soil microbial communities integrate changes in moisture, temperature, organic carbon, pH, nutrient availability, and vegetation inputs. Therefore, they serve as useful indicators of whether AgriPV land management is maintaining soil function. However, there is no universal conclusion related to the effect of PV shading on soil microbial health; Ma et al. (2026) reported significant biological improvement in a degraded desert setting under an AgriPV system. The study reported that total microbial abundance increased by more than tenfold, while microbial biomass carbon and nitrogen increased by approximately 10.8-13.9 and 13.4-17.1 times, respectively, relative to shifting-dune conditions. Soil organic matter and total

nitrogen also increased substantially. Correlation analysis highlighted the relationship of crop diversification with soil organic matter, total nitrogen, and microbial biomass carbon, while root biomass was associated with phosphorus variables and fungal abundance. These findings indicate that vegetation and soil inputs associated with PV development can support the soil-microbial-plant nexus.

In contrast, Yavari et al. (2022) found that PV systems can either reduce or have little effect on soil microbial activity. This highlights the importance of considering land management, as bare, compacted, vegetated, and cultivated soils may respond differently under the same PV system. Biological monitoring is therefore advised to include soil organic carbon along with functional biological indicators, such as microbial biomass carbon, soil respiration, enzyme activity, or a soil biological quality index. Where resources permit, microbial community profiling can be used to identify shifts in bacterial and fungal communities.

6.5 Criteria for Developing Protocols for Land Sustainability

As AgriPV outcomes are strongly site- and crop-dependent, a land-sustainability protocol is advised to be developed based on the pre-to-post-installation comparisons and through simultaneous assessment of agricultural, energy, soil, water, and ecological indicators during operation.

Table 6.4: Land Sustainability Protocol Criteria

Protocol component	Key indicators	Minimum monitoring requirement	References
Land-use efficiency	LER; crop yield; electricity generation	Calculate LER for each crop/design combination	Dupraz et al. (2011); Barron-Gafford et al. (2019)
Microclimate	PAR; air temperature; RH; wind speed; soil temperature	Open-field, inter-row and under-panel zones, defined sensor heights/depths	Omer et al. (2025); Barros et al. (2026)
Water balance	Rainfall; irrigation; soil moisture; ET ₀ /ET _c ; water use efficiency	Root-zone moisture estimation, quantify irrigation supply and ET observation	Marrou et al. (2013a)
Soil physical condition	Bulk density; penetration resistance; infiltration; aggregate stability	Baseline before construction, measurement during operation and repeated post-installation measurements	Hassanpour Adeg et al. (2018); Liu et al. (2023)

Protocol component	Key indicators	Minimum monitoring requirement	References
Soil chemical condition	SOC; pH; N, P, K; electrical conductivity	Baseline and periodic laboratory analysis	Liu et al. (2023b)
Soil biological quality	Microbial biomass/respiration; enzymes; soil-fauna indicators	At least one functional biological indicator	Barros et al. (2026)
Hydrology and erosion	Runoff pathways; infiltration; sediment movement; ground cover	Site drainage survey, event-based observations on vulnerable sites	Barron-Gafford et al. (2019); Liu et al. (2023a)
Biodiversity	Vegetation cover; plant functional groups; pollinators/soil fauna	Seasonal survey of managed and reference zones	Walston et al. (2016); Hernandez et al. (2014)
Reversibility	Foundation type; soil disturbance; land restoration plan	Document construction footprint and decommissioning provisions	Hernandez et al. (2019)

6.6 Optimal Design for Suitability of Intercultural Operations

AgriPV structures are recommended to accommodate agricultural machinery and manual operations while maintaining a favourable microclimate. Structural design is therefore advised to be developed jointly with crop selection and farm operations rather than after the PV layout has been fixed (Al-Quraan et al., 2022). Clearance height is advised to be determined from the tallest equipment and mature crop canopy expected in the production system. Row spacing is advised to be compatible with the actual working width, turning requirements, and safety envelope of the farm machinery. The design is also advised to avoid placing foundations in primary wheel tracks and is advised to provide unobstructed headlands at row ends. These measures reduce operational inefficiency and limit repeated traffic-induced compaction.

Panel height and row spacing also control the spatial distribution of radiation and rainfall. Wider spacing can reduce sharp contrasts between under-panel and inter-row conditions, while higher structures can increase the usable agricultural envelope. However, increased structural dimensions also increase capital requirements, so design is advised to be based on a multi-objective assessment of crop productivity, electricity generation, machinery access, soil protection, and water management. Vertical or narrow-footprint bifacial configurations represent an alternative where machinery access between module rows is more important

than clearance beneath the panels. Their suitability is advised to be assessed using the same criteria: crop radiation requirements, farm machinery width, field slope, rainfall redistribution, and expected energy production. No single geometry is advised to be treated as universally optimal. Moreover, Costa et al. (2026) demonstrate that panel height, tilt angle, and PV-covered area can be optimized by accounting for the hourly and seasonal distribution of shading, crop-specific radiation responses, electricity generation, and farm energy demand. Their framework also considers crop rotation and soil-fertility effects, highlighting that system design is advised to be evaluated over the complete annual production cycle rather than for a single crop or season.

An integrated design workflow can therefore be summarized as: (1) characterize baseline soil, hydrology and climate; (2) define crop and machinery requirements; (3) simulate seasonal radiation and PAR distribution; (4) select panel height, orientation, row spacing and tracking strategy; (5) evaluate water balance and runoff pathways; (6) design construction and vegetation-management controls; and (7) establish the monitoring network before commissioning. AgriPV performance is inherently heterogeneous, and that heterogeneity is advised to be measured and managed rather than averaged away.

The design of an AgriPV system is advised to ensure that photovoltaic structures do not interfere with routine agricultural operations. Unlike conventional solar parks, AgriPV systems are recommended to simultaneously accommodate crops, farm machinery, workers, and PV infrastructure. Therefore, panel height, row spacing, support-column arrangement, orientation, and access pathways are advised to be made compatible with the crop geometry and machinery used on the farm (Toledo & Scognamiglio, 2021).

The layout of the AgriPV system is advised to be based on the maximum operating dimensions of the machinery and implements used for the selected crops. The important dimensions to be considered are tractor width and height, implement width and operating height, turning radius, sprayer boom dimensions, crop height at maturity, harvesting requirements, and operator safety. The minimum vertical clearance of panels is advised to accommodate the maximum crop and machinery height with an appropriate safety margin, while horizontal spacing between support columns is advised to provide adequate machinery clearance and manoeuvrability.

AgriPV systems have been found to impose spatial and operational constraints on mechanized field operations. Field efficiency may decrease because of reduced operating speeds, restricted manoeuvrability, and a mismatch between implement working width and the available operating space. Additional constraints may arise during headland turning and from the management of uncultivated areas closer to support structures. The structural arrangement of AgriPV systems can also influence machinery pathways, requiring field operations to follow the PV-row orientation rather than the natural orientation of the field. Therefore, PV orientation, row spacing, implement working width, headland dimensions, and machinery manoeuvrability are advised to be considered jointly during system design (Bellone et al., 2026).

AgriPV row spacing is advised to be determined according to agricultural machinery requirements rather than solely to maximize PV capacity. Support columns are preferably advised to be positioned between crop rows or outside principal machinery pathways. The layout is advised to avoid columns within crop rows, narrow passages, obstruction of sprayer booms, and interference with harvesting equipment.

The system is suggested to permit major agricultural operations, including seedbed preparation, sowing, weeding, intercultivation, earthing-up, fertilizer and pesticide application, irrigation-system maintenance, harvesting, and transportation, without causing accidental damage to PV structures.

Spraying requires particular attention because adequate horizontal and vertical clearance is required for boom sprayers. The AgriPV design is advised to consider boom width and height, crop canopy height, turning space, and electrical safety. Adequate headland space is advised to be provided at the ends of PV rows for tractor turning, implement alignment, entry and exit, crop transport, and PV maintenance. The required turning area is recommended to be based on the turning radius of the largest implement used on the farm. Crop-row and PV-array orientation is advised to be considered jointly because it influences radiation distribution, shade movement, crop growth, machinery movement, irrigation, and drainage. Agronomic and machinery requirements are therefore advised to be optimized simultaneously. For smallholder conditions in India, AgriPV systems are advised to be compatible with commonly available tractors, power tillers, and small farm machinery. Simple structural arrangements, minimum column obstruction, accessible irrigation and drainage systems, and convenient crop-transport pathways are advised to be prioritized.

An AgriPV system is advised to be considered suitable for intercultural operations when:

- Major agricultural machinery can operate without structural interference.
- Crop establishment and maintenance can be performed efficiently.
- Mechanical weeding and fertilizer application remain feasible.
- Spraying can be conducted safely.
- Harvesting and crop transportation are not restricted.
- Irrigation and drainage infrastructure remain accessible.
- Soil compaction from machinery traffic is minimized.
- PV maintenance can be undertaken without damaging crops.

Thus, AgriPV is advised to be designed as an integrated agricultural production and renewable-energy system, rather than as a conventional PV installation placed over agricultural land.

CHAPTER 7

WATER MANAGEMENT, IRRIGATION EFFICIENCY AND DRAINAGE SPECIFICATIONS IN AGRIPV SYSTEMS

Water management is a critical component of AgriPV systems because photovoltaic structures modify the spatial and temporal distribution of rainfall, solar radiation, evapotranspiration, soil temperature, and soil moisture. Partial shading can reduce atmospheric evaporative demand and crop water consumption, while panel surfaces may alter rainfall interception and redistribution (Elamri et al., 2018; Omer et al., 2025). Consequently, irrigation and drainage strategies developed for conventional open-field agriculture may not always be directly applicable to AgriPV systems. An integrated water management approach is therefore recommended to optimize crop production, photovoltaic performance, and water use efficiency while preventing waterlogging, localized drought, and uneven soil-moisture conditions.

7.1 Water Balance Components

The water balance of an AgriPV field is advised to account for all major water inputs, storage components, and losses within the crop root zone. The basic soil-water balance can be expressed as:

$$\Delta S = P + I + CR - R - D - ET$$

Where ΔS is the change in soil-water storage, P is precipitation, I is irrigation, CR is capillary rise, R is surface runoff, D is deep percolation or drainage, and ET is crop evapotranspiration.

In AgriPV systems, precipitation is advised not to be assumed spatially uniform. PV modules can intercept rainfall and redistribute it toward specific locations, producing concentrated water inputs along panel edges or beneath drainage points. The magnitude of this redistribution depends on panel inclination, module width, row spacing, rainfall intensity, wind conditions, and the presence of gutters or collection systems. Therefore, rainfall measurements are preferably advised to be collected at representative locations, including open areas, beneath panels, between panel rows, and near panel drip edges, where appropriate.

Soil-water storage is another important component because the modified microclimate beneath PV modules can alter the duration and magnitude of soil-moisture availability (Elamri et al., 2018). Shading can reduce soil surface temperature and evaporation, potentially increasing the residence time of water in the root zone. At the same time, uneven rainfall redistribution may produce localized wet and dry zones. Monitoring soil moisture at multiple depths is therefore important for identifying spatial differences in water availability.

7.2 Water Use Efficient Practices under AgriPV

Efficient irrigation in AgriPV systems is advised to be based on crop water demand, soil-water status, and the spatial distribution of shading and rainfall rather than applying a uniform irrigation schedule throughout the field. Drip irrigation is particularly suitable because it delivers water directly to the crop root zone and can be integrated with PV support structures without significantly interfering with agricultural operations.

Under AgriPV conditions, irrigation can potentially be reduced where shading substantially decreases crop water demand. However, irrigation is advised not to be reduced solely on the basis of panel coverage. Field measurements of soil moisture, crop water status, and actual evapotranspiration are advised to be used to determine the appropriate irrigation schedule (Bernal-Basurco et al., 2026). This is particularly important because spatially heterogeneous rainfall and shading can create differences in water demand within the same field.

Several practices can improve water-use efficiency under AgriPV systems:

- Drip and subsurface irrigation to minimize conveyance, evaporation, and runoff losses.
- Soil-moisture-based irrigation scheduling using sensors or water-balance approaches.
- Deficit irrigation during less sensitive growth stages, where agronomically appropriate.
- Mulching and residue retention to further reduce soil evaporation.
- Rainwater harvesting and storage from suitable PV surfaces or associated infrastructure.
- Variable-rate irrigation, where spatial differences in crop water demand are sufficiently large to justify differential application.
- Irrigation during cooler periods, where operationally feasible, to reduce evaporative losses.
- Integration of soil-moisture monitoring with weather and crop-growth information for adaptive irrigation scheduling.

The combination of PV shading and efficient irrigation can be particularly beneficial in water-limited and semi-arid regions, where reductions in evaporative demand can improve crop water availability during periods of high atmospheric stress.

7.3 Potential for Enhancing Water-Use Efficiency through AgriPV

One of the important potential benefits of AgriPV systems is improved water-use efficiency (WUE). AgriPV systems can improve WUE through several interacting mechanisms. Partial shading reduces incoming radiation and can moderate crop canopy temperature, thereby lowering atmospheric evaporative demand. Reduced soil surface temperature can also decrease direct soil evaporation. At the same time, improved soil-water retention may increase the fraction of stored water available for crop uptake. These effects can be particularly valuable during periods of extreme heat or water scarcity.

However, the relationship between shading and WUE is not linear. Excessive shading may reduce photosynthesis and biomass accumulation more strongly than it reduces water consumption, ultimately lowering WUE. Therefore, the objective is not to maximize shading but to identify an appropriate radiation-water balance for the target crop. Recent field evidence from a hyper-arid environment showed reduced irrigation demand and improved WUE under AgriPV conditions, while tomato experiments demonstrated that combining AgriPV with regulated deficit irrigation can influence irrigation water productivity (Islam et al., 2026; Bernal-Basurco et al., 2026). The potential improvement in WUE is consequently advised to be evaluated using paired comparisons between AgriPV and open-field controls. Measurements are advised to include precipitation, irrigation, soil moisture, evapotranspiration, crop yield, and biomass. A standardized experimental water-balance protocol is ideally advised to compare at least three spatial environments:

- Full-sun control
- Inter-row area
- Under-panel area

The use of multiple water-productivity indicators is preferable because irrigation savings alone do not necessarily indicate improved agricultural productivity. An effective AgriPV system is ideally advised to achieve stable or improved crop production with reduced irrigation demand and/or lower evapotranspiration losses. AgriPV systems may also provide opportunities for integrated water management through rainwater collection. Water intercepted by PV modules can potentially be directed to storage structures or strategically redistributed to cultivated areas. Such systems are advised to be designed carefully because uncontrolled concentration of runoff at panel edges may cause soil erosion, ponding, nutrient movement, or localized waterlogging.

7.4 Drainage Specifications for Varying Soil Types

Drainage design in AgriPV systems is advised to account for changes in rainfall distribution and localized runoff caused by PV panels, along with soil texture, infiltration capacity, slope, groundwater conditions, and rainfall intensity. Sandy soils generally require limited drainage but may need measures such as mulching and controlled runoff to reduce rapid water loss and nutrient leaching. Loamy soils usually provide a good balance between water retention and drainage, although surface grading or shallow drains may be needed to prevent localized ponding. Clay and heavy soils are more prone to waterlogging and may require surface or subsurface drainage, raised beds, and field grading, with drain spacing based on hydraulic conductivity, groundwater conditions, and desired water-table depth. On sloping or erosion-prone land, contour drainage, vegetated waterways, grassed channels, and erosion-control structures can reduce concentrated runoff from PV panel edges. Overall, drainage is advised to be integrated with PV layout and crop management to remove excess water while conserving root-zone moisture and supporting groundwater recharge.

7.5 Recommended Water-Management Framework for AgriPV Systems

For reliable assessment and management, AgriPV water studies are advised to integrate hydrological, agronomic, and energy measurements. A standardized field protocol is advised to include:

- Rainfall at representative open and PV-influenced locations
- Irrigation quantity and timing
- Soil moisture at multiple root-zone depths
- Reference evapotranspiration
- Actual crop evapotranspiration
- Runoff and drainage
- Groundwater level, where relevant
- Crop yield and biomass
- Water-use efficiency and water productivity
- Electricity generation

The resulting water balance can then be coupled with crop and energy production to evaluate the overall performance of the system. Such an integrated approach is essential for determining whether AgriPV provides genuine water-saving and water-productivity benefits, rather than merely shifting water availability spatially within the field. Sensor-based monitoring of soil moisture, temperature, radiation, and plant conditions can support adaptive resource management in AgriPV systems (De Francesco et al., 2025).

CHAPTER 8

OPERATION AND MAINTENANCE REQUIREMENTS

8.1 Operation and Maintenance Requirements for Photovoltaics (PV)

This clause specifies the requirements for operation and maintenance of photovoltaic systems installed in AgriPV projects.

The standard IS 16960 (Part 2) is advised to be followed for operation and maintenance of the PV power plant.

8.1.1 PV panels are recommended to be cleaned regularly to minimize soiling losses, typically once every 15 days in summer and once a month in winter, or when soiling causes > 5% output loss. Water-efficient methods (e.g., automated cleaning system, robotic cleaners, osmotic water) are recommended. Cleaning methods are recommended as follows:

- a) Water-Efficient Robotic Cleaning - Recommended for large arrays. Robots are advised to use < 2 L of water per panel per cleaning. Water is advised to be deionized or of low TDS (< 50 ppm) to prevent staining.
- b) Manual Cleaning - If done, use soft brushes or silicone blades. Never use abrasive materials or high-pressure jets (> 35 bar), which damage the anti-reflective coating.
- c) Frequency - Based on soiling rate. Typical: Bi-weekly in dry seasons (Mar-Jun, Oct-Nov), monthly in monsoon and winter.

8.1.2 Inspections - Quarterly visual inspections of modules (for cracks, snail trails), structures (for corrosion, loose bolts), and electrical connections. Vegetation under the array is recommended to be managed to prevent panel shading and fire hazards. Annual thermographic inspection of PV arrays is advised.

8.1.3 Vegetation Management - Growth under and around the array is recommended to be managed to prevent shading of panels and to maintain fire safety clearances.

- a) Underneath the Array - Grow low-maintenance, shallow-rooted cover crops (e.g., clover, creeping thyme) to prevent dust, suppress weeds, and enhance soil health. Mow 2-3 times a year.
- b) Perimeter - Maintain a clear, gravel-based firebreak of minimum 3 m width around the entire array.
- c) Not recommended - Deep-rooted plants or trees near foundations. Use of broad-spectrum herbicides is discouraged; prefer mechanical weeding near structures.

8.1.4 Record Keeping - A logbook is recommended to be maintained for all operation and maintenance activities, failures, and corrective actions.

8.1.5 Comprehensive Operation and Maintenance Documentation

The Operation and Maintenance manual is recommended to include:

- a) As-Built Drawings: Electrical single-line diagrams, structural drawings, layout with GPS coordinates of foundations.
- b) Spare Parts List: With part numbers and minimum stocking levels.
- c) Troubleshooting Guide: For common alarms and faults.
- d) Safety Procedure Manual: Specifically, for working in an agricultural-electrical hybrid environment.

8.2 Operation and Maintenance Requirements for Agricultural Systems

AgriPV systems may influence crop productivity, PV module performance and local microclimatic conditions due to shading effects, dust accumulation and changes in soil moisture and temperature conditions.

The operation and maintenance requirements specified in section 8.2.1 to 8.2.8 are advised to be followed to address these aspects and to ensure efficient agricultural and PV system operation.

8.2.1 Crop Selection and Management

The following aspects are recommended to be considered during crop selection and management:

- Crop selection is recommended to consider the shading effects of the AgriPV system on the ground surface. Shade-tolerant crops may be preferred based on light availability during different periods of the day and seasons of the year.
- Crops recommended for the respective agro-climatic zones are recommended to be selected to obtain optimum yield.
- Cash crops may be preferred to improve economic returns from agricultural activities.
- Crop height is recommended to be selected such that shading of PV modules does not occur during any period of the year. Tall crops, such as sugarcane, banana, mango and guava, may be avoided for low mounting PV structures.
- Selection of perennial crops and shrubs is recommended to consider possible interference of roots with the PV structure.

8.2.2 Irrigation Water Management

The following aspects are recommended to be considered during irrigation water management:

- Irrigation planning is advised to consider the microclimatic conditions created by the PV installation.

- Pressurized irrigation systems, such as drip and sprinkler irrigation, may be preferred. Care is suggested to be taken to ensure that irrigation water does not affect electrical connections and inverter installations, particularly when sprinkler irrigation is used.
- Rainwater harvesting from PV modules into a water reservoir may be adopted. The harvested water may be utilized for supplemental irrigation and cleaning of PV modules.
- Automated irrigation systems based on soil moisture monitoring may be preferred as they are more suitable to improve crop water productivity.
- Deficit irrigation approaches may be adopted to improve water productivity in AgriPV systems established in hot and dry agro-climatic regions.

8.2.3 Soil Health Management

The following aspects are recommended to be considered during soil health management:

- Soil nutrient content is recommended to be managed through regular monitoring of soil health parameters and soil testing.
- Fertilizers and manures are recommended to be applied in accordance with the recommended package of practices for the respective agro-climatic zones to meet crop nutrient requirements.
- Soil organic carbon content is recommended to be maintained through the addition of organic manures and compost.
- Soil biological activity is recommended to be monitored regularly as prolonged shading may influence soil health.
- Controlled traffic farming may be adopted to minimize soil compaction caused by PV support structures.

8.2.4 Agronomic Management

The following aspects are recommended to be considered during agronomic management:

- Standard agronomic practices for the selected crop and agro-climatic zone are recommended to be followed as per IS 15930 (part 1).
- The cropping layout is recommended to permit access for agricultural machinery.
- Cereal and legume rotations may be adopted for maintaining soil health and crop productivity.
- Continuous use of heavy machinery is recommended to be avoided to minimize soil compaction.
- Drought-tolerant crops may be preferred in hot and dry agro-climatic regions.

8.2.5 Livestock Integration

The following aspects are recommended to be considered during livestock integration:

- Livestock integration may be adopted for recycling of outputs from livestock and agricultural systems.
- Suitable precautions are recommended to be taken to protect wiring and low-hanging PV components from damage by livestock.

8.2.6 Cleaning and Soiling Management

The following aspects are recommended to be considered during cleaning and soiling management:

- PV modules are recommended to be periodically cleaned to minimize the effects of dust, pollen and soil particle accumulation arising from agricultural activities.
- The frequency of cleaning is recommended to depend on local dust conditions, crop residue and rainfall.
- Water-efficient cleaning methods may be adopted.

8.2.7 Coordination of Agricultural and PV Operations

The following aspects are recommended to be considered during coordination of agricultural and PV operations:

- PV maintenance activities and agricultural operations are recommended to be scheduled to minimize interference.
- Appropriate safety measures are recommended to be followed for agricultural workers operating under elevated PV modules, particularly during the monsoon season.
- Legal and contractual arrangements relating to revenue sharing, liability, insurance and regulatory compliance may be established between the relevant stakeholders.

8.2.8 Safety and Regulatory Requirements

The following aspects are recommended to be considered during safety and regulatory compliance:

- The AgriPv system is recommended to comply with applicable agricultural, electrical and environmental requirements.
- Appropriate worker protection measures are suggested to be provided for personnel working under elevated PV installations.
- Necessary permits and approvals are advised to be obtained, wherever applicable.

CHAPTER 9

STANDARD DESIGN CONFIGURATIONS AND TECHNICAL BENCHMARKING FOR DIFFERENT AgriPV MODELS

9.1 Introduction

AgriPV systems occupy a much wider design space than conventional ground-mounted photovoltaic installations. Each design choice - module technology, mounting height, row spacing, tilt angle, tracking mode, and array orientation - is recommended to satisfy two coupled but sometimes competing objectives: maximizing electricity yield and preserving (or enhancing) agricultural productivity. The absence of a single "best" architecture means that standardization is recommended to be parametric rather than prescriptive, anchored to a set of measurable geometric and performance indicators.

Two Indian macro-indicators frame the benchmarking problem. First, India receives between 4 and 7 kWh m⁻² day⁻¹ of global horizontal irradiation, equivalent to roughly 2,300-3,200 sunshine hours per year across the major agricultural states of Maharashtra, Gujarat, Rajasthan, Haryana, Punjab, and Andhra Pradesh (Ghamari et al., 2026). Second, a 50 MWp AgriPV plant in Maharashtra has demonstrated a competitive levelized cost of electricity of ₹2.02/kWh, while grape-farm installations have shown more than a 15-fold increase in economic value per hectare relative to open-field viticulture (Malu et al., 2017). These findings are reinforced by a growing body of Indian field trials reporting land-equivalent ratios of roughly 1.6-1.73 for tomato and turmeric (Abubakar et al., 2025; Patel et al., 2024; Giri et al., 2022) and cost-competitive designs (LCOE ≈ ₹3.17/kWh) in the hot arid zone (Poonia et al., 2021). Together, these data points establish that a viable Indian AgriPV design is recommended to be technically robust, financially competitive, and agriculturally non-detrimental. However, sites below 4 kWh m⁻² day⁻¹ are advised to be excluded at the screening stage when carrying out AgriPV projects to ensure proper crop yields.

This chapter, therefore, combines an evidence-based benchmarking framework with a normative set of design and structural requirements.

At least 85-90% of the total AgriPV project area is recommended to remain cultivable and accessible for agricultural operations. Areas rendered unavailable for cultivation by foundations, equipment yards, permanent access tracks and other exclusions are recommended to be limited to an LLR of 10-15% of the total project area, so that the installation remains, in substance, for an agricultural operation.

9.2 Taxonomy and Classification of AgriPV Systems

A widely adopted classification distinguishes four top-level AgriPV prototypes (Miljkovic et al., 2024; Asa'a et al., 2024), and recent reviews confirm that mounting height, inter-row spacing, tilt, and panel technology are the decisive levers that differentiate them and govern the energy–agriculture trade-off (Sarr et al., 2023; Mahim et al., 2025):

- **Stilted/elevated (overhead) systems:** modules are mounted on tall structures (typically ≥ 3 m clearance) so that conventional tractor-mounted implements can pass beneath. This is the only configuration that preserves full mechanization of farming.
- **Inter-row systems:** modules are installed at low or medium height between cultivated rows, as in the Malu et al. grape-farm analysis, where polycrystalline modules (Trina Solar TSM-310-PD14, 310 W, 15.7 % efficiency, $1956 \times 992 \times 40$ mm) were placed between existing trellises on a 1-acre ($4,046 \text{ m}^2$) plot, yielding 32 modules per row $\times$ 17 rows (Malu et al., 2017).
- **Greenhouse-integrated systems:** semi-transparent modules replace portions of the cladding, reducing incoming photosynthetically active radiation by 5 % - 94 % depending on cell density and orientation (Ghosh, 2023). These are particularly relevant for horticultural and high-value vegetable production.
- **Vertical/bifacial systems:** modules are oriented east–west in a vertical configuration, distributing light homogeneously across the day and being most appropriate for permanent crop species. Katsikogiannis et al. showed that E-W vertical bifacial arrays increased specific yield by 13 % over conventional monofacial arrays, while an E-W "wings" topology raised land productivity by 50 % even when AC electrical yield dropped 33 % (Katsikogiannis et al., 2022).

For the purposes of a normative Indian standard, these models map onto two clear-height-based system types, which determine how much of the ground area counts as agriculturally usable:

9.2.1 Overhead AgriPV System (Category I)

An Overhead AgriPV System (Category I) is recommended to be characterized by an installation with a clear height of not less than 3 m that permits agricultural use beneath the system. The solar modules may be mounted at different angles and positions and may partially or completely cover the agriculturally usable area. The agriculturally unusable area is recommended to be limited to (a) the area occupied by the installation, and (b) areas that are no longer available for conventional agricultural activities during the course of field-farming operations.

9.2.2 Interspace AgriPV System (Category II)

An Interspace AgriPV System (Category II) is recommended to be characterized by an installation in which the area between the rows and under the panels is utilized for agricultural purposes. Vertical bifacial systems are included in Category II. A distinction is recommended to be made between: (a) systems in which the solar modules are permanently installed at a specified angle on one or two stilts; and (b) systems in which the solar modules are mounted vertically or are adjustably mounted (tracking) on a stilt. For the purposes of agricultural land-use assessment, the area beneath solar modules having a clear height of less than 2.0 m is recommended to be considered as land not usable for agricultural activities.

9.2.3 Agricultural Use Categories

Based on the specifications for eligible agricultural land, AgriPV systems of both types may be further classified into the following use categories: (a) permanent and perennial crops; (b) annual and multi-year crops; (c) permanent grassland for mowing; and (d) permanent grassland used as pasture. The overall classification adopted in this handbook is summarized in Figure 9.1.

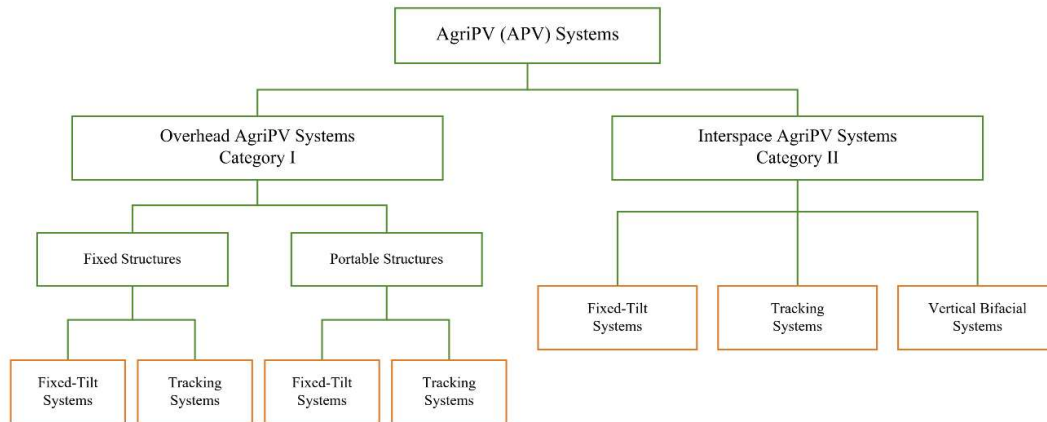


Figure 9.1: Classification of AgriPV systems

9.3 System Layout and Configuration Optimization

The system layout and configuration are suggested to be designed to ensure optimal agricultural productivity, electrical energy generation, operational safety, and long-term structural reliability, and are recommended to allow simultaneous agricultural operations and power generation without significant compromise to either function. As a minimum, the configuration is advised to consider crop type and growth pattern, agricultural machinery movement, soil characteristics, water availability, and site topography.

The following design parameters are recommended to be considered for configuration optimization:

- **Ground Coverage Ratio (GCR):** suggested to be the primary design variable, defined as the ratio of PV module (panel) area to total ground area. The final GCR value is recommended to be justified with reference to the target photosynthetically active radiation (PAR) availability factor for the selected crop.
- **Inter-row spacing (pitch):** for overhead tilted configurations, the minimum pitch is advised to be determined to ensure that inter-row shading on crops remains within acceptable limits during the critical growth period.

- **Tilt angle:** for fixed-tilt systems in India (latitudes 8°N to 37°N), the tilt angle is recommended to equal the optimal tilt for the PV module to achieve optimal annual energy yield.
- **Azimuth (orientation)** - for fixed-tilt systems, the azimuth is normally suggested to be oriented towards true south (180°).

NOTE - A simplified rule for the minimum pitch is: Minimum Pitch $\geq$ Panel Height/tan (Sun Altitude at critical time).

9.4 Standard Configuration Types

The selection of configuration is recommended to be based on crop type, local latitude, agro-climatic zone, mechanization requirements, and project objectives. Three configuration types are recommended based on PV panel arrangement. The normative geometric requirements below are complemented by the benchmarking parameters in Section 9.5.

9.4.1 Elevated Fixed-Tilt Systems

These systems are typically recommended to be south-facing and latitude-tilt oriented. The lower end of the tilt is the front elevation; the upper end is the rear elevation.

- **Front elevation:** advised to be a minimum of 3 m above ground level, as this determines the crop height that can be grown underneath the panels.
- **Rear elevation:** recommended to be between 2.5 m and 4.0 m and is typically recommended to be higher than the front elevation by 50 %-100 % based on the latitude tilt.
- **Tilt angle:** recommended to be the local latitude $\pm 15^\circ$ with a south-facing orientation for maximum energy generation.
- **Row spacing:** recommended to be at least 5 m to 8 m.
- **Ground Coverage Ratio:** the panel area occupied is advised to be around 30-40 % (open area $\approx$ 60-70 %) to provide adequate, shadow-free sunlight for all types of crops; the range may vary depending on crop and site-specific conditions.

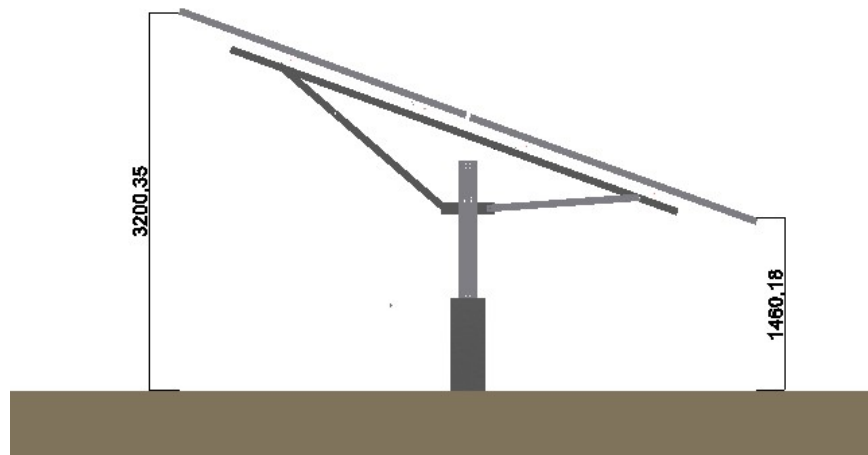


Figure 9.2: Elevated fixed-tilt system (front and rear elevation)

9.4.2 Vertical Bifacial Systems

These systems are recommended to consist of East-West oriented panels. Vertical east-west bifacial arrays distribute light more homogeneously across the day, ease machinery movement, and resist soiling; modelling and field studies show they can match or exceed the combined food-energy output of conventional tilted arrays for appropriate crops and densities (Riaz et al., 2021b; Campana et al., 2021).

- **Elevation** - for East-West orientation, the elevation is advised to be a minimum of 1 m above ground.
- **Tilt angle** - the panels are recommended to be oriented at approximately 90° (vertical), with the front face facing east and the back face facing west consistently within each series connection. To balance evening energy yield, up to 50 % of the strings may have the front face facing west.
- **Shading** - in the East-West orientation, the minimum non-shading duration is recommended to be at least 6 hours per day.
- **Row spacing** - calculated as $(\text{Height of structure} + \text{Height of panel}) \times 2$.
- **Ground Coverage Ratio** - the panel area occupied is advised to be around 30-40 % (open area $\approx$ 60-70 %) to obtain adequate shadow-free sunlight for at least 4 hours for all crop types.

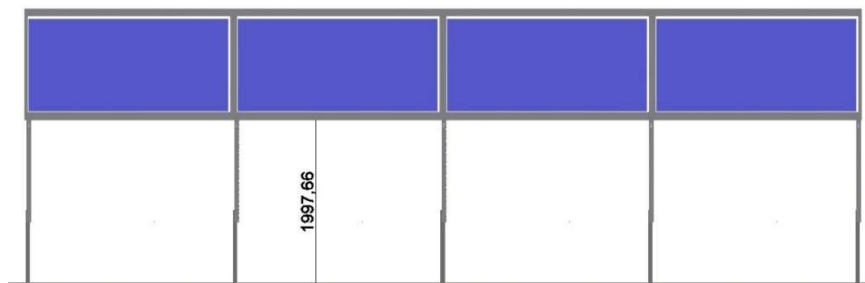


Figure 9.3: Vertical bifacial (East-West) system

9.4.3 Single-Axis Tracking Systems

These systems are recommended to feature a North-South tracker axis with a $\pm 60^\circ$ rotation range. Trackers allow dynamic management of the shading pattern, but land productivity is governed chiefly by row spacing and orientation rather than by clearance height, and dense tracker layouts can impose substantial energy and crop trade-offs for shade-intolerant species (Berrian et al., 2025).

- **Elevation** - advised to be a minimum of 3 m above ground.
- **Row spacing** - calculated as (Height of structure + Length of panel) $\times$ 2.
- **Ground Coverage Ratio** - the panel area occupied is advised to be around 30-40 % (open area $\approx$ 60-70 %) to ensure at least 4 hours of shadow-free sunlight for all crop types.

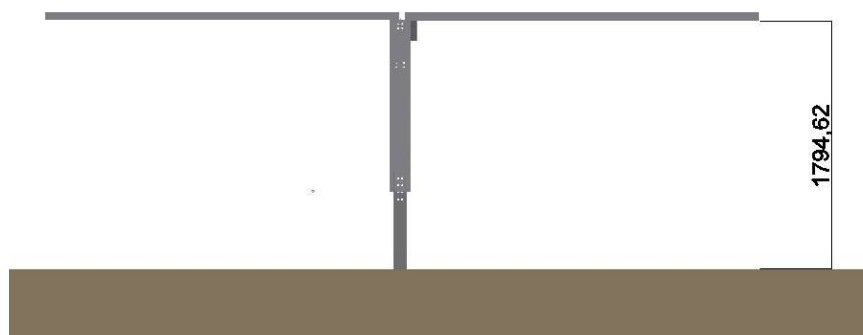


Figure 9.4: Single-axis tracking system

9.5 Standard Geometric Parameters

Geometric parameters govern the trade-off between shading (affecting crops) and insolation (affecting modules), and they form the primary axis of any benchmarking exercise (Weselek et al., 2019; Weselek et al., 2021). The ranges below represent international and Indian

reference practice for elevated AgriPV and are advised to be read together with the normative configuration requirements of Section 9.4.

Table 9.1: Standard geometric parameters for elevated AgriPV

Parameter	Symbol	Typical range for elevated AgriPV	Reference
PV module row width	W_{row}	1.85 – 3.40 m	Trommsdorff et al. (2021a); Weselek et al. (2019)
Inter-row distance	D_{row}	5.0 – 6.3 m	Trommsdorff et al. (2021a)
Vertical clearance	H_v	≥ 3 m	
Pillar spacing along row	$P_{\parallel}$	5.0 m	
Pillar spacing perpendicular to row	$P_{\perp}$	7.0 m	
Ground Coverage Ratio	$A_{\text{AgriPV}} / A_{\text{ground}}$	0.30 – 0.40 (Italy caps at 40 %; Indian pilots 25–35 %)	Dupraz (2023)
Module tilt	θ	20° (fixed, SW) for elevated; 90° (vertical) for bifacial	Katsikogiannis et al. (2022); Trommsdorff et al. (2021a)
Birds-eye coverage rate	C_{bird}	≈ 37.1 % in Trommsdorff 2021	Trommsdorff et al. (2021a)

The Trommsdorff Maharashtra feasibility study (100 ha; four crop candidates: cotton, soybean, tomato, banana) used a 370 Wp bifacial monocrystalline module (992 × 2,000 mm, 70 % bifaciality, 20 % assumed ground albedo), 20 modules per string, 10 strings per inverter, a 67.3 kW DC / 60 kW AC inverter, yielding a 4 m clearance and 5 m row distance (Trommsdorff et al., 2021a). The German reference design at Lake Constance elevates modules on steel columns with a 20° tilt, 3.4 m row width, 6.3 m inter-row distance, and 5 m clearance (Weselek et al., 2019).

Mazzeo et al. showed that across GCR values from 0.2 to 0.6, the Land Equivalent Ratio ranged from 2.05 (low GCR) to 1.04 (high GCR) for lettuce, turnip, and maize - confirming that design parameters are decisive determinants of dual-land-use productivity (Mazzeo et al., 2025).

9.6 Module Technology Selection

Crystalline silicon (c-Si) remains the default technology across virtually all Indian pilot installations, with bifacial modules gaining ground because of their higher ground-reflected contribution (Panda et al., 2024). Key decisions include:

- **Mono- vs. poly-crystalline** - monocrystalline modules show higher efficiency (~19-21 %) and better temperature coefficients, preferred in land-scarce installations; polycrystalline (15.7 % in the Malu grape-farm case (Malu et al., 2017)) remains cost-competitive in larger arrays.
- **Bifaciality factor** - Trommsdorff assumed 70 % bifaciality with a 20 % albedo (Trommsdorff et al., 2021a), broadly consistent with Indian dry-soil conditions; concrete or white-mulched reflective surfaces can push this assumption higher.
- **Semi-transparent modules** - appropriate when sunlight transmission is recommended to exceed ~50 % for shade-intolerant crops; transparent, semi-transparent and vertical bifacial designs are well-matched to shade-intolerant cropping, while opaque modules are reserved for shade-tolerant crops (Asa'a et al., 2024).
- **Spectral-shifting and wavelength-selective panels** - emerging technologies that convert wavelengths poorly used by photosynthesis into photosynthetically useful bands; flagged in the Asa'a et al. review as a future direction (Asa'a et al., 2024).
- **Qualification testing** - light-soaking, hot-spot endurance and bypass-diode thermal testing are required under any IEC 61215 / IEC 61730 baseline; India-specific operation above the IEC's 40 °C ambient reference is recommended to qualify IEC TS 63126 (Kempe et al., 2021).

9.7 Crop-Specific Design Compatibility and Crop Segregation

Shade tolerance is the single most important agronomic parameter that couples to geometric design. A synthesis of experimental evidence yields the following compatibility matrix, which can be used as a benchmark for Indian pilots (Laub et al., 2022):

Table 9.2: Crop shade response and indicative design parameters

Crop group	Shade response	Indicative design parameters
Leafy greens (lettuce, spinach), turmeric, coriander	Positive yield response under 15-30 % shade; lettuce adapts by increasing leaf area	Vertical E-W bifacial, GCR 25-35 %
Tomato	Highest yield under moderate shading; reduced sunscald; lower ascorbic acid and carotenoid content	Semi-transparent greenhouse-integrated modules, 30-50 % transmittance
Potato	Tuber number and total yield decrease under shading; in high-radiation zones, time-of-day shading can be beneficial	Dynamic/trackable modules with morning/afternoon intermittent shade

Crop group	Shade response	Indicative design parameters
Kiwi	Highest fruit yield under moderate shading; reduced heat stress, increased storage quality	Stilted, GCR 30-40 %, ≥ 4 m clearance
Coffee	Highest yields under moderate shade	Stilted with high clearance under multi-tier canopy
Grape	Shade-intolerant; yields fall with reduced direct insolation; tolerant only at very low GCR (~10-12 %)	Inter-row linear modules between trellises, no shade on canopy
Wheat, rice (reproductive stage), cotton	Wheat grain yield can fall by up to 51 % under shade; rice and cotton lint yield fall under shade during reproductive/ripening stages	Generally unsuitable for elevated AgriPV; only possible with very wide row spacing and tracking
Maize, grain legumes	Strong yield losses even at low shade levels	Not recommended for canopy-overcrop AgriPV; suitable for inter-row alley configuration

The grape case reinforces the need for design tailored to crop physiology: shade-tolerant crops effectively convert panel-density gains into revenue without incurring agricultural yield penalties, while shade-intolerant crops tolerate a much narrower design envelope (Malu et al., 2017). The broader evidence base supports this stratification: meta-analyses find that most crops tolerate up to ~15 % radiation reduction with a less-than-proportional yield decline, that berries and fruity vegetables can benefit from up to 30 % shade, and that maize and grain legumes lose yield even at low shade (Laub et al., 2022; Hermelink et al., 2024). Even shade-intolerant staples can be viable in favourable designs; stilt-mounted corn showed a small yield gain under low module density (Sekiya & Nagashima, 2019), while high-value perennials such as kiwifruit retain yield and increase water productivity at ~19% coverage (Jiang et al., 2022). Conversely, six-year rice trials show a ~23 % grain-yield reduction under 27 % ground cover, with losses greatest in wet years, underscoring that cereals demand very low coverage (Thum et al., 2025).

All configuration types are recommended to be able to accommodate variable crop heights based on the growing pattern of a particular agro-climatic zone. The structure elevation is recommended to be selected to accommodate the crop-height brackets in Table 9.3.

Table 9.3: Typical mature plant-height ranges of selected crops

Sl. No.	Crop height range (m)	Representative crops (height range, m)
1	0.3 - 1.0	Pulses (gram 0.4-0.8, green gram 0.4-0.8, black gram 0.4-0.8), groundnut (0.3-0.5), onion (0.4-0.6), tomato (0.5-1.0), potato (0.5-0.8), millets - bajra (~1.0), ragi (0.5-1.0)
2	1.0 - 2.0	Maize (1.5-2.5), arum/arvi (1.0-2.0), sorghum/jowar (1.0-3.0), chickpea/gram (0.6-1.2), mustard (1.0-1.5), okra/bhindi (1.0-2.0), brinjal (0.5-1.5), chilli (0.5-1.5), papaya - young plants (1.0-2.0)
3	2.0 - 3.0	Sugarcane (2.0-4.0), banana (2.0-3.0), cotton (1.5-2.5), pigeon pea (2.0-3.0), sunflower (1.5-2.5), turmeric (0.5-1.0; foliage up to 2.0), soybean (0.5-1.5)
4	3.0 - 4.0	Bamboo (3.0-20.0), tall sorghum varieties (up to 3.0), tall maize hybrids (~3.0), tall jowar varieties (2.0-4.0), teff (limited suitability)

NOTE - Heights indicated are typical mature plant heights under normal agronomic conditions and are recommended to be adapted to local varieties and practices.

9.8 Detailed Layout Requirements

9.8.1 Structural Geometry

- **Table length** - the length of a table is recommended to be determined based on ease of operation and maintenance; a typical arrangement is approximately 18 panels in a two-portrait configuration across three rows.
- **Inter-row spacing** - the gap between rows of tables, measured centre-to-centre, is recommended to be a minimum of 1.5 times the width of the table. (Example: two modules in portrait mode, each 2.5 m wide, give a table width of 5.0 m and a minimum inter-row spacing of $5.0 \times 1.5 = 7.5$ m.)
- **Pathways** - the gap between the edges of panels of two adjacent rows is recommended to have a minimum width of 3 m, to permit movement of tractors or other mechanized devices and for operation and maintenance.
- **Edge setbacks** - recommended setbacks at the edges are advised to be at least equal to the pathway width.

9.8.2 Panel Arrangement and Cabling

It is recommended that 16 to 24 modules be arranged per table in pairs of two in portrait mode for all configuration types. For conventional PV systems, all electrical cables are advised

to be buried at least 1.5 m below ground. Array electrical design is recommended to comply with IS/IEC 62548 (PV array design), IS 1893 (seismic design) and IS 3043 (earthing); IS/IEC 61701 (salt-mist) and IEC 62759 (bifacial qualification) are recommended where applicable. In the case of AgriPV systems, to eliminate risks during deep tillage (30-90 cm) and avoid soil compaction in root-zone areas, above-ground routing is recommended. A site-specific geotechnical report (SBC validation) and a shading analysis (LiDAR/drone survey) are advised to be undertaken.

9.9 Structural Design and Safety Considerations

The structural design of AgriPV systems is recommended to ensure safety, durability, serviceability, and compatibility with agricultural activities under site-specific environmental conditions, and is recommended to safely support the PV modules and associated equipment in accordance with the applicable Indian Standards. The most under-regulated failure mode for AgriPV structures is wind loading: structural columns in elevated systems are particularly vulnerable to wind loads, and the safety margin is highly sensitive to column spacing (Lee et al., 2023; Gautam et al., 2024). Indian practice is recommended to confirm to IS 875 (Part 3): 2015 for wind loads, which defines basic wind-speed zones from 33 m/s to 55 m/s, the latter applying to coastal regions where many large Indian solar farms are sited.

Table 9.4: Structural design loads and applicable standards for AgriPV systems

Sl. No.	Load type	Design considerations	Applicable standard
1	Dead load (DL)	Self-weight of PV modules, mounting structures, foundations, cables, junction boxes and other permanent components	IS 875 (Part 1)
2	Live load (LL)	Maintenance personnel, access requirements, temporary equipment and other imposed loads during O&M	IS 875 (Part 2)
3	Wind load (WL)	Wind pressure and uplift forces on elevated PV modules and support structures	IS 875 (Part 3)
4	Seismic load (EQ)	Earthquake forces based on project seismic zone and structural configuration	IS 1893 (Part 1)
5	Snow load (SL)	Snow-accumulation loads, where applicable based on project location	IS 875 (Part 4)
6	Crop-related operational loads	Loads from crop-support systems, irrigation pipelines, maintenance, agricultural equipment, and harvesting operations	Site-specific

Key structural design parameters, drawn from Indian studies and international codes, are: basic wind speed (zone-specific, 33–55 m/s), combined with snow and seismic loads; net

wind-pressure coefficients that depend on tilt angle (10°–50° studied for Indian conditions (Agarwal et al., 2020)) and on edge effects, which are not fully captured by ASCE 7-10 or IS 875 for solar arrays and can lead to significant underestimation of peak pressures (Anantharam & Manju, 2022; Aly, 2026); pillar spacing along the row, where narrower spacing improves wind safety but raises cost and reduces crop accessibility (the Trommsdorff design compromised at 5 m (Trommsdorff et al., 2021a; Lee et al., 2023)); and panel spacing on raised structures, shown by CFD simulation to be a key factor in lowering wind loads (Gautam et al., 2024). Open-jet wind-tunnel testing and CFD are recommended for India-specific prototypes.

A consistent finding across combined wind-tunnel, CFD, and finite-element studies is that the windward (first) row and the edge and corner modules carry the largest aerodynamic loads, with peak pressure coefficients typically arising under oblique ($\approx 45^\circ/135^\circ$) winds (Debnath et al., 2025; Wittwer et al., 2022; Browne et al., 2020). Compilations of wind-tunnel data further show that code definitions of a "rigid" array (e.g., ASCE 7) can misrepresent multi-row and flexible structures, so vortex-shedding and dynamic resonant effects are advised to be considered explicitly for elevated AgriPV tables (Yemenici & Aksoy, 2021). These results support reinforcing edge modules and validating India-specific geometries experimentally rather than relying on code coefficients alone.

Additional structural requirements are recommended to apply. The selected configuration (fixed-tilt, adjustable-tilt, tracking or vertical bifacial) is recommended to provide adequate ground clearance for crop growth and machinery movement, and column and support spacing are recommended to minimize obstruction to agricultural operations. Deflection of structural members under design loads is recommended to comply with IS 800 and IS 456, and the system is recommended to be designed to avoid excessive vibration that may cause fatigue failure over the design life.

Table 9.5: Structural design parameters for AgriPV systems

Sl. No.	Parameter	Requirements
1	Ground clearance	Minimum clearance is recommended to be determined by crop type, crop height, and cultivation method, and is recommended to conform to the Category I / Category II requirements of Clauses 9.2.1-9.2.2. For mechanized farming, the clearance is recommended to accommodate the height of agricultural machinery and ensure adequate ventilation and sunlight penetration for crops.

Sl. No.	Parameter	Requirements
2	Row spacing	For Category II (interspace) systems, row spacing is typically advised to be about 3 m to facilitate machinery movement and minimize shading. A minimum safety margin of 1 m is recommended to be maintained on either side of the supporting structure to prevent contact between machinery and PV components, for both Category I and Category II systems.
3	Foundations	A Soil Investigation Report is recommended for projects exceeding 1 acre, conforming to IS 2131 and IS 2911 (Part 1/Sec 1), and is recommended to determine safe bearing capacity, soil strata, groundwater table, and corrosion potential. Isolated footings are recommended to be used for stable soil with high SBC; pile foundations for soft/expansive soils or high water tables (IS 2911, Parts 1-4). Foundations are recommended to resist wind uplift via adequate embedment, footing mass or anchoring (including helical anchors), transfer all loads without excessive settlement, and include corrosion protection for embedded components (see IS 2914).
4	Materials	Structural members are recommended to be of structural steel (IS 2062 Part 1), aluminium or other corrosion-resistant materials; foundation concrete to IS 456; reinforcement steel to IS 1786. All components are advised to have a minimum protective coating life of 15 years, with hot-dip galvanizing (minimum 550 g/m ²) preferred and conforming to IS 4759. Fasteners and bolts are recommended to be corrosion-resistant and compatible with adjoining materials to prevent galvanic corrosion (IS 1367, IS 4759).

For elevated AgriPV modules mounted at ≥ 4 m clearance, a minimum factor of safety of 1.5 against yield stress (using von Mises equivalent stress per distortion-energy theory) is recommended for the load combinations specified in IS 875 combined with IS 1893 (seismic) where applicable.

9.10 Benchmarking Performance Indicators

Four quantitative indicators form the standard reference framework for AgriPV performance benchmarking (Dinesh & Pearce, 2015; Zahrawi & Aly, 2024):

- **Land Equivalent Ratio (LER)** - $LER = (Y_{crop,AV} / Y_{crop,farm}) + (Y_{e,AV} / Y_{e,PV})$. $LER > 1$ indicates that combined land use is more productive than separate use; reported values in Indian pilots often exceed 1.5 with shade-tolerant crops, $GCR \approx 25\text{--}35\%$, and revised feed-in tariffs of $\sim ₹4/\text{kWh}$. A high LER can, however, mask crop losses offset by energy revenue - a critical limitation for policy benchmarking (Sharma et al., 2026).

- **Ground Coverage Ratio (GCR)** - A_{PV} / A_{ground} . Italy limits GCR to $\leq 40\%$ to preserve agricultural viability; Indian recommendations for suggestive field crops are 30-40 % (the range may vary depending on crop and site-specific conditions). High GCR increases energy yield but suppresses crop yield, except for shade-tolerant species (Dupraz, 2023).
- **Yield Energy per Land** - annual energy output per hectare (MWh/ha).
- **Yield Agriculture per Land** - crop yield per hectare (kg/ha).

Simulation and field evidence consistently place LER above 1 across a wide range of configurations, with sun-tracking and higher panel density raising the energy term (and thus LER) at the expense of the crop term (Amaducci et al., 2018), and GCR emerging as a simple, controllable proxy for crop potential - a GCR below $\sim 25\%$ is generally required to keep relative crop yield above 80 % (Dupraz, 2023; Mazzeo et al., 2025).

Table 9.6: Indicative benchmark values for Indian AgriPV contexts

Configuration	Indicative LER	Indicative GCR	Indicative crop-yield impact
Stilted over shade-tolerant crops (vegetables, turmeric)	1.5 - 2.0	25 - 35 %	0 % to +20 %
E-W vertical bifacial over permanent crops	1.2 - 1.5	35 - 50 %	-10 % to 0 %
Inter-row modules over grape trellis	1.1 - 1.3	10 - 15 %	-5 % to 0 % (trellis spacing > 1.8 m)
High-density canopy-overcrop (GCR > 50 %)	0.8 - 1.0	> 50 %	Wheat/maize yield losses 30–60 %

9.11 Reference Benchmark Designs in India

(i) Maharashtra 50 MWp elevated system: Configured with GCR $\approx 30\%$, a polycrystalline-monocrystalline mix, 4 m clearance, and 5 m row distance. Demonstrated an LCOE of ₹2.02/kWh, farmer-income uplift of 9–10 $\times$ over conventional farming under farmer-centric models, LER often > 1.5 with shade-tolerant crops, and feed-in-tariff sensitivity of up to $\pm 20\%$ revenue impact (Sharma et al., 2026).

(ii) Maharashtra 100 ha Trommsdorff feasibility design: Bifacial 370 Wp monocrystalline modules, 992 $\times$ 2,000 mm, 70 % bifaciality, 20 % albedo; module row width 1.85 m; row distance 5.0 m; vertical clearance 4.0 m; pillar spacing 7 m $\times$ 5 m; coverage 37.1 %; 20 modules/string; 10 strings/inverter; 67.3 kW DC / 60 kW AC. Crop analysis prioritized cotton (high shading benefit, low irrigation, high know-how, medium profit margin) and soybean (high know-how, low investment) over tomato and banana (Trommsdorff et al., 2021a).

(iii) Grape-farm inter-row design: Trina Solar 310 W polycrystalline modules (15.7 % efficiency, 1956 × 992 × 40 mm) mounted at canopy height between trellises on a 1-acre plot (side 63.6 m), 32 modules × 17 rows. Inter-trellis spacing of 1.8 m kept module shade off the grape canopy for most of the year, increasing economic value by more than 15× over conventional grape cultivation (Malu et al., 2017).

9.12 Recommended Indian Standard Configurations

Synthesizing the above evidence, three reference designs can be proposed for handbook adoption, each calibrated to a crop-climate archetype.

Table 9.7: Recommended Indian standard AgriPV reference configurations

Configuration	Crop	GCR	Clearance	Row spacing	Module	Expected LER
Elevated stilt, fixed tilt, SW orientation	Turmeric / leafy vegetables/coriander	30 %	4.0 m	5.0 m	370 Wp bifacial mono	1.5 - 1.8
Inter-row, canopy height	Grape (trellis)	12 %	canopy-height	1.8 m	310 Wp poly	1.1 - 1.3
Vertical E–W bifacial	Pulses/cotton (rain-fed)	35 %	n/a (vertical)	7.0 m	400 Wp bifacial	1.2 - 1.5

Each configuration is advised to be evaluated against the IEC TS 63126 high-temperature regime, given that modules in many Indian agricultural regions operate above the IEC 61215 reference ambient temperature of 40 °C (Kempe et al., 2021).

CHAPTER 10

FRAMEWORK FOR DATA COLLECTION, MONITORING, REPORTING AND VERIFICATION

10.1 Purpose and Relationship with Other Chapters

This chapter provides the operational framework for monitoring, reporting and verification (MRV) of AgriPV performance. Chapter 5 establishes agricultural performance requirements, baseline principles, documentation and testing provisions. This chapter explains how project teams are suggested to collect the supporting evidence, manage its quality, prepare comparable reports, and enable independent verification. Its summary tables retain the principal indicators needed for field implementation.

The monitoring plan is recommended to be read with Chapter 3 for engineering and sensor placement requirements; Chapters 4 and 6 for crop and soil responses; Chapter 7 for water management; Chapter 8 for operation and maintenance; and Chapter 11 for certification and independent assessment.

AgriPV assessment requires both automated measurements and field observations. Reviews identify hybrid acquisition as the predominant approach and highlight gaps in calibration, maintenance, power supply, and communications metadata (De Francesco et al., 2025; Sara et al., 2025). The monitoring plan is therefore recommended to cover energy, crop, water, and operational evidence collectively, rather than relying on electricity output alone.

10.2 Energy Performance Measurement

Energy-performance requirements and testing principles are recommended to be applied in accordance with Chapter 5, Section 5.1, and Annexure I. The project is recommended to maintain measured records of generation, irradiation, inverter operation, and availability sufficient to reproduce its performance calculations. The installed DC capacity, AC capacity, meter boundary, array orientation, module technology, commissioning date, and energy model version are recommended to be recorded.

Daily and monthly records are recommended to include AC generation and export, relevant DC measurements, irradiation, module temperature, inverter downtime, and grid curtailment. Performance Ratio (PR), including any project-specific Agri-Photovoltaic Performance Ratio (APR), is recommended to state the calculation method and reference basis. An APR is recommended not to be reported as a separate indicator unless its difference from conventional PR is defined. The annual PR/APR criterion is ≥ 0.75 .

Land Equivalent Ratio (LER) is recommended to be calculated from comparable agricultural and electricity production ratios for the same area and assessment period. LER is recommended to be >1 . Recommended targets are recorded in Tables 10.3 and 10.8.

LER = (AgriPV crop yield/reference crop yield) + (AgriPV electricity yield/reference PV electricity yield). Each ratio is recommended to use consistent units, area, and duration. The reference PV arrangement and any simulation assumptions are recommended to be disclosed. For multiple crops, the annual aggregation method and individual crop results are recommended to be reported; incomplete crop seasons are recommended not to be presented as final annual LER.

The project is also recommended to compare measured shading with the design model. Where Specific Shadow Capacity (SSC) or Shadow Coverage Index (SCI) is used, the variable, spatial weighting, time basis, and calculation are recommended to be defined. SCI deviations greater than 10% are advised to trigger agronomic review; the report is recommended to state whether the deviation is relative or expressed in percentage points.

10.3 Agricultural Baselines and Field Measurements

The requirements in Sections 5.2.2-5.2.6 are recommended to govern crop yield, irrigation water productivity, land use, soil health and farm operations. The following protocols specify the evidence needed to assess these requirements. Each project is recommended to identify its crop blocks and reference plots before monitoring begins and maintain comparable management records.

10.3.1 Crop Yield and Reference Plots

Use the baseline-selection and normalization provisions in Sections 5.2.2.2–5.2.2.3 and Table 5.1*. A contemporaneous open-field control with the same crop and cultivar is preferred. Where nearby fields, historical farm records or authenticated regional statistics are used, document their comparability, sources and any normalization for weather, soil, management or input differences.

Table 10.1: Evidence to accompany crop yield comparisons

Record	Implementation requirement
Crop block and control	Map boundaries, measured area, cultivar, planting/harvest dates and reference-source identity.
Management and conditions	Record irrigation, fertilizer, crop protection, soil conditions and weather for both treatments; explain material differences.
Harvest measurement	Record harvest method, sampling or whole-block measurement, marketable yield, quality and moisture basis where relevant.
Comparison period and units	Use at least one complete cropping season; report kg/ha or crop-appropriate equivalent, with the same area and unit basis in the control.
Verification evidence	Retain field sheets, weighed quantities, plot areas, photographs where useful, calculations and baseline authentication.

*Report relative crop yield as $100 \times \text{AgriPv yield/reference yield}$.

10.3.2 Irrigation Water Productivity

Follow Section 5.2.3 for irrigation-water measurement and WUE calculation, and Chapter 7 for the wider water balance. Record irrigation by block and event, using meter readings or a documented estimation method. Pair seasonal irrigation volume with yield from the same crop area and period. Record rainfall separately.

Table 10.2: Water measurement and reporting

Indicator	Calculation or evidence	Reference
Irrigation WUE	Crop mass (kg) / irrigation volume (m ³); report the crop area and period.	≥baseline WUE
Irrigation saving	100 × (reference volume - AgriPV volume) / reference volume, for comparable crop area and period.	≥10% desirable; not mandatory
Measurement quality	Meter identity, readings, calibration or estimation assumptions; note recycled or harvested-water contributions.	Same method/basis for reference and AgriPV

10.3.3 Land Use and Cropping Continuity

Survey the total project area and all areas made unavailable for cultivation, including foundations, equipment yards, permanent tracks, and other exclusions. At least 85-90% of the total project area is recommended to remain cultivable and accessible for agricultural operations. Suitable cultivable land beneath modules is recommended to be included; shading or module coverage alone is recommended not to be counted as land loss.

Distinguish land available for cultivation from land actually cropped in each season. Record fallow periods and rotation plans so that seasonal fallow is not automatically reported as permanent infrastructure-related land loss. Report GCR separately from cultivable-area retention.

Table 10.3: Land use and cropping indicators

Indicator	Reference	Required evidence
Cultivable-area retention	≥85-90% of the total project area; excluded area (LLR) 10-15%.	As-built map, measured areas and exclusions register.
Cropping intensity	≥80% regional baseline.	Seasonal cropped areas, annual crop calendar, formula and regional baseline source.
LER	>1 recommended.	Crop and energy ratios over a common complete assessment period.

10.3.4 Soil Health

Apply the sampling, methods and comparison principles in Section 5.2.5. Establish baseline soil condition before installation or at the earliest feasible stage. Repeat measurements after cropping seasons or at least annually, using consistent locations, depths and methods. Record amendments, digging, traffic and drainage changes that could explain results.

Table 10.4: Soil evidence and comparison limits

Variable	Evidence	Comparison limit
pH	Laboratory method, depth and sample location.	Within ± 0.5 of baseline
Soil organic carbon	Consistent analytical method and reporting basis.	$\geq 90\%$ baseline
Electrical conductivity	Method, units, irrigation-water context and crop-specific agronomic limit.	No significant increase
Compaction	Bulk density or penetrometer protocol, depth and soil moisture at testing.	No significant increase

The monitoring plan is recommended to define how significance is assessed for salinity and compaction, with reference to crop and regional agronomic conditions. Seasonal laboratory sampling and continuous soil-temperature/moisture probes serve different purposes and are recommended to have separate records.

10.3.5 Farm Operations

Use Section 5.2.6 for operation-time, accessibility and cropping-frequency assessment. Observe land preparation, sowing, irrigation, interculture and harvest, recording equipment, implement width, work area, turning time, obstruction and unusual delays. Compare operation time for equivalent tasks and areas.

Table 10.5: Farm operations reporting

Indicator	Reference	Measurement cadence
Operation time	$\leq 120\%$ baseline	Major operations at least once per crop season
Area accessibility	$\geq 90\%$ cultivated area	Field assessment at least once per crop season
Cropping continuity	At least one crop cycle/year	Annual crop calendar; record interruptions and reasons

10.4 Monitoring Domains and Variables

The project monitoring schedule is recommended to connect meteorological, electrical, and agricultural observations. Coupled assessment supports interpretation of crop-energy-water trade-offs (Warmann et al., 2024). Every variable is suggested to have a defined unit, sensor or field method, location, sampling interval, aggregation period, and quality flag.

Meteorological measurements include GHI and plane-of-array irradiation, crop-canopy PAR/PPFD, air temperature and RH under and outside the array, wind, and rainfall. Record sensor height and exposure. DNI or diffuse-irradiance data, where used, are advised to identify their instrument or derivation method. Specify whether light measurements are instantaneous PPFD, integrated DLI, or a percentage relative to the open-field reference.

Electrical measurements include string current/voltage where available, inverter input/output and alarms, AC energy, module temperature, soiling observations, export and curtailment. Agricultural records include soil moisture/temperature, crop growth stage, plant height, biomass where measured, final yield and quality, irrigation and crop-protection activities. Separate measured observations from model estimates.

10.5 Spatial Sampling and Reference Locations

Overhead arrays are recommended to be characterized at representative under-module, edge/gap, and inter-row locations. Interspace and vertical layouts require transects that capture the row-adjacent and mid-strip conditions; vertical layouts require observations on both sides. Reference plots are recommended to be free from array shading and comparable in crop, soil, and management.

For an approximately 1 ha overhead installation with 4 m clearance, the illustrative monitoring arrangement places an open-field control at least 30 m from the array edge, with module-edge, module-centre and inter-row centreline measurements. This distance is an example; final placement is recommended to be justified by seasonal shade geometry and local obstructions. Record coordinates and photographs, and use consistent sampling depths in treatment and control.

Enhanced pilots may add canopy-top profiles at the height of 1, 2 and 3 m where appropriate, together with more stations across crops and treatments. High-resolution Indian pilots provide examples of distributed half-hourly microclimate monitoring (Trommsdorff et al., 2021a). Such profiles supplement the minimum schedule and are recommended not to replace representative spatial sampling.

10.6 Time Resolution and Acquisition

Automated meteorological, soil and energy observations are normally advised to be logged at 15-30 minute intervals. The selected interval is recommended to preserve diurnal variation and support applicable metering/reporting requirements. Diagnostic measurements may be

stored at one-minute or shorter intervals and aggregated for routine reporting. Record whether each stored value is a mean, total, minimum, maximum, or instantaneous reading.

Manual measurements are recommended to follow crop stages and farm events: sowing, growth observations, irrigation, treatment, and harvest. A hybrid system of automatic logging and targeted field measurement is recommended (Sara et al., 2025; Weselek et al., 2021). Reports are recommended to identify complete crop seasons and incomplete monitoring periods.

10.7 Sensors, Communication and Implementation

Use the minimum acquisition and architecture requirements in Section 5.2.7 rather than a separate parallel equipment specification. The implementation schedule is recommended to identify sensor models, serial numbers, calibration dates, accuracy basis, power supply, logger channels and maintenance responsibility. The following stack provides indicative pilot specifications for procurement and placement review.

Table 10.6: Pilot sensor schedule

Variable	Sensor or arrangement	Indicative specification
GHI/irradiation	Thermopile pyranometer; appropriate arrangement for the measured irradiance component.	$\pm 2\%$; declared classification
PAR/PPFD	Quantum sensor at crop level.	$\pm 5\%$
Air temperature/RH	Temperature/RH sensors with documented exposure and height.	$\pm 0.3^{\circ}\text{C}$ / $\pm 3\%$ RH
Soil temperature/moisture	TDR/FDR or equivalent at 15cm and 30 cm below ground level,	$\pm 0.5^{\circ}\text{C}$ / $\pm 3\%$ VWC
Wind	Anemometer; record mast and array-top height.	± 0.3 m/s; 4 m in the pilot example
Module temperature	Back-of-module temperature sensor.	$\pm 1^{\circ}\text{C}$
DC & AC monitoring	String-level current/voltage or power measurement.	Class 0.5 in the pilot schedule
Network/logger	LoRaWAN, cellular, or suitable wired connection.	Size for actual channels/intervals; pilot budget ≤ 2 MB/day

The gateway is recommended to implement the local buffer specified in Section 5.2.7 (at least 30 days), recover interrupted transmissions, and preserve raw timestamps and units. Record outages, replacements, recalibration, power-supply autonomy, and communications

reliability. The dashboard is recommended to support combined crop/energy records, defined KPI calculations and alerts, with farmer/system-owner access and data portability. Digital twins, UAVs and predictive models may supplement but are recommended not to replace minimum observations (Edirisinghe et al., 2026; Chen et al., 2024).

10.8 Crop Records, Training and Plant Health

Crop selection is recommended to follow Chapter 1 eligibility provisions and the agronomic guidance in Chapters 4 and 6. This chapter does not establish a second crop-suitability list. Record the selected crop, cultivar, permitted layout, and any required approval, and verify their performance against the declared light and management conditions. For crops restricted beneath modules, identify whether cultivation is in inter-row areas or supported by an approved exception.

Table 10.7: Crop and management records

Record group	Information to retain
Crop identity and calendar	Crop/cultivar, block, sowing/harvest, stages, rotation and reference plot.
Light and microclimate	Canopy PPFD/DLI where available, shade fraction, reference readings, temperature/RH and measurement timing.
Inputs and plant health	Irrigation, nutrients, pest/disease observations, treatment dates/products and affected areas.
Harvest and quality	Crop area, yield, sampling/measurement, quality attributes and losses.
Farmer training and safety	Training in partial-shade management, record keeping and safe working around PV equipment.

Training and plant-protection principles in Sections 5.2.8-5.2.9 are recommended to be applied. Field records are advised to link crop-health observations to the modified microclimate and management response. Crop suitability depends on location, season, and crop physiology; species-specific DLI is useful evidence where available (Widmer et al., 2024). It is not a substitute for applicable eligibility conditions.

10.9 Verification and Corrective Action

Verification is recommended to distinguish owner/operator checks from independent assessment. The operator is suggested to review automated alerts and field sheets, reconcile meter and dashboard totals, and issue traceable daily/monthly exports. The independent inspection arrangements in Chapter 11 are suggested to be used for site audits, calibration review, raw-data sampling, and independent checks of weather and crop-yield measurements.

Remote sensing and UAV observations may corroborate crop area, crop identity, phenology, and spatial patterns, but the report is recommended to state model validation and uncertainty before treating derived yield as a measured result (Khanal et al., 2020; Moretta et al., 2025). Separate remote evidence from ground-truth harvest data.

For each nonconformity, record the affected indicator and period, evidence, likely cause, corrective action, responsible person, and follow-up result. Carbon-credit or environmental-attribute claims require their applicable scheme-specific baseline, additionality, and accounting evidence; ordinary handbook compliance is recommended not to itself be reported as credit eligibility.

10.10 Commissioning and Periodic Verification Records

AgriPV validation is recommended to compare measured PAR with the design at mapped sample points, including a clear-day solar-noon check within $\pm 5\%$ of design. Record the fraction, time, and spatial comparison basis; seasonal light assessment remains necessary. Log temperature/RH against the control for a full week in peak summer and winter conditions, and link the results to crop and weather conditions rather than assuming cooling is guaranteed.

Undertake a three-year soil benchmarking check alongside routine seasonal/annual soil monitoring. Select analytical methods appropriate to each soil property, consistently with Section 5.2.5. The integrated 72-hour trial is recommended to document expected PV output for the actual weather and operating conditions, observed output ($>95\%$ of the stated expectation), programmed irrigation operation, monitoring/transmission, and safety-test evidence.

Periodic records are recommended to include annual structural-fastener, corrosion, electrical-safety, and irrigation checks. Thermography is advised annually; event- or fault-triggered inspections are also recommended to be recorded. Inspection frequencies are recommended to be reconciled with the applicable engineering and O&M schedule.

10.11 Reporting and Baseline Disclosure

Daily operations reports are recommended to summarize generation, weather, alarms, and data outages. Monthly performance reports are recommended to provide PR/CUF, irradiation, availability/curtailment, irrigation, crop stage, and anomalies, with submission to the designated agency under the project reporting arrangements. Seasonal reports are recommended to record completed crop-yield and water-productivity comparisons.

The annual MRV report is recommended to consolidate electricity, completed crop seasons, yield/quality, land availability and cropping intensity, water productivity, soil/farm-operation outcomes, corrective actions, and independent audit evidence. Include the three linked elements: the open-field agricultural baseline; reference PV yield from measured data or the

stated simulation; and LER derived from the two ratios. Report grievances and scheme-specific carbon information where applicable.

Identify crop blocks and the total project boundary in every report. Give energy in kWh or MWh with capacity and area basis, yield in kg/ha, irrigation in m³, and water productivity in kg/m³. Per-hectare values are recommended to identify their denominator; monthly energy totals are recommended not to be mixed with seasonal crop totals without labelling the assessment period.

10.12 Data Quality, Access and Retention

Implement the recording, traceability and access principles in Section 5.2.7. Use a data dictionary covering timestamps/time zone, units, locations, calibrations, logger intervals, raw/aggregated values, missing-data flags and model versions. Document anomaly detection, any gap-filling and corrections. Preserve original observations and the correction history; estimated values are recommended to remain distinguishable from measurements.

Retain calibration certificates, placement records, sensor changes, power/network outages, field sheets, baseline evidence, verification reports and approvals. Provide secure, role-based access and exportable records to the owner and authorized verifier; vendor arrangements are recommended to support privacy and portability.

Project records are recommended to be retained for the entire project life. The record custodian and retention schedule are advised to be stated.

10.13 MRV Reporting Card

Use the following card for monthly operations and attach seasonal/annual indicators when their assessment periods are complete. Unavailable or incomplete indicators are recommended to be marked accordingly, with reasons, rather than entered as zero. Detailed field and audit records are recommended to support the summary.

Table 10.8: MRV summary reporting card

Indicator and period	Target or reference	Result and evidence
Generation - monthly/annual	Weather-adjusted yield model; report kWh/MWh and area/capacity basis.	Value; model/meter record
PR/APR - monthly/annual	≥0.75; declared formula and irradiation reference.	Value; period; quality flags
CUF - declared period	≥17%; disclose location, capacity, and period.	Value; denominator
PAR reduction - crop stage/season	15–35%; configuration/crop dependent.	Value; canopy/reference; timing

Indicator and period	Target or reference	Result and evidence
Soil moisture - monthly/seasonal	Crop/root-zone reference; state %VWC and depth.	Value; depth; location
Crop yield - complete crop season	Normal $\geq 80\%$ baseline; identify any approved deviation.	kg/ha; cultivar; harvest/control
Irrigation productivity - crop season	$\geq$ baseline WUE, kg/m ³ .	Yield/irrigation volume; method
Cultivable area - as-built/annual	$\geq 85-90\%$ total project area.	Area; exclusions map
LER - complete annual assessment	>1 recommended.	Crop/PV ratios; period
Data completeness - each variable/period	$\geq 95\%$.	Valid/expected records; gaps

CHAPTER 11

RECOMMENDATIONS ON STANDARDIZATION, QUALITY CONTROL AND CERTIFICATION MECHANISM FOR AGRIPV SYSTEMS IN INDIA

11.1 The Standardization Imperative

The absence of cohort-specific standards is the single most important non-financial barrier to Indian AgriPV deployment. As Lee et al. noted, it is rare for actual end-users and farmsteads to adopt AgriPV systems owing to a lack of standardized models and design criteria (Lee et al., 2023). Indian policies still treat AgriPV as a derivative of either GM-PV systems (governed by IEC standards adopted through BIS) or of protected cultivation (governed by agricultural and horticultural norms), with neither lineage addressing the integrated system. The Indian agriphotovoltaic sector is constrained by definitional ambiguities, inadequate financial instruments, and institutional fragmentation (Sharma et al., 2026), with the absence of a nationally accepted standard as the central manifestation of these constraints. This is not unique to India: systematic reviews of agriphotovoltaic policy find the field fragmented across the energy, agriculture, and land-use sectors, with a lack of dedicated definitions and integrated frameworks identified as the primary barrier to scaling (Pascaris, 2021; Alves et al., 2025). Analysts consistently recommend that clearly defining and categorizing the technology, and developing agriphotovoltaic-specific standards, are prerequisites for accelerated deployment (Jamil et al., 2022).

11.2 Existing Standards Landscape

11.2.1 International Electrotechnical Commission (IEC)

The IEC's TC82 maintains nearly 80 standards applicable to PV and operates five working groups. The most relevant for Indian AgriPV are:

- **IS 14286 (Part 1)/IEC 61215-1; IS 14286 (Part 2)/IEC 61215-2** - Crystalline silicon terrestrial photovoltaic modules - Design qualification and type approval. Specifies 19 qualification tests, including visual inspection, maximum-power determination, insulation, thermal cycling, humidity-freeze, mechanical load, hail, hot-spot endurance, UV preconditioning, bypass-diode thermal test, and wet leakage current.
- **IEC 61730-1 / 61730-2** - Photovoltaic module safety qualification - providing construction requirements (Part 1) and testing requirements (Part 2).
- **IEC TS 63126** - Guidelines for qualifying PV modules, components and materials for operation at high temperatures - explicitly developed to address hotter climates and thermally restrictive installations, replacing legacy "open-rack" / 40 °C ambient condition. India is a primary driver region for this technical specification (Kempe et al., 2021).
- **IEC 62108** - Concentrator photovoltaic modules and assemblies - Design qualification and type approval.

11.2.2 Bureau of Indian Standards (BIS)

Relevant standards include IS 14286 (crystalline silicon PV modules), IS/IEC 61730 (safety), IS/IEC 62108, and structural loading codes. For AgriPV-specific certification (e.g., structures, mounting on stilts, shading compliance), Indian Standards do not yet exist in a stand-alone form; current practice treats elevated AgriPV support structures as buildings for the purposes of IS 875 (Sarkar et al., 2021). International precedent for a dedicated instrument now exists - Germany's pre-standard DIN SPEC 91434 for agriphotovoltaic and the DIN SPEC 91492 specification for AgriPV with animal husbandry provide a template for a defined, certifiable system category that Indian standardization can adapt (Trommsdorff et al., 2025). BIS is currently developing an IS Standard on Agri-Photovoltaics (AgriPV) Farming Production System.

11.3 Identified Standards Gaps for AgriPV

A recent PRISMA review of 249 studies confirms that, despite the technical and environmental maturity of agriphotovoltaic (LER typically 1.2-1.8), large-scale deployment remains constrained chiefly by institutional barriers - the lack of dedicated regulatory frameworks and fragmented agriculture-energy policy (Martínez-Hernández et al., 2026). Against that backdrop, six gaps stand out as priorities for India-specific standardization:

- **Crop-compatibility envelope** - IEC standards address PV modules only; they do not define the agronomic envelope within which the structure is recommended to operate. Italy's 40% GCR cap is a useful reference but not directly transferable to India's broader crop base.
- **Wind load on elevated AgriPV structures** - ASCE 7-10 and IS 875 recommendations are very conservative in some cases and may not reflect experimentally measured demands; existing codes underestimate peak pressures on PV array edges. Updated wind-tunnel / CFD-derived pressure coefficients are recommended for elevated Indian AgriPV geometries (Anantharam & Manju, 2022; Aly, 2026).
- **High-temperature operation** - Indian cell operating temperatures routinely exceed 40 °C; qualification to IEC TS 63126 is advised for Indian installations (Kempe et al., 2021).
- **Crop-specific shading data and yield baselines** - without a national database of "expected yield under X % shade" for key Indian crops (rice, wheat, cotton, soybean, sugarcane, mango, grape, turmeric, vegetables), MRV cannot be reliably interpreted.
- **Structural durability under agricultural operations** - tractor collisions, pesticide drift, irrigation wetting, and harvest machinery impose additional loads not captured by IS 875 design assumptions.
- **End-of-life and recycling** - existing PV standards do not establish the reverse-logistics chain required when modules on farmer-owned land reach end-of-life; India-specific regulation under the E-Waste Rules is largely untested for AgriPV.

11.4 Recommended Certification Scheme

A three-tier certification scheme is recommended for India.

Tier 1 - Module-level certification (existing): PV modules are recommended to remain certified to BIS-adopted IEC 61215, IEC 61730, IEC TS 63126 (where applicable) through any of the NABL-accredited facilities. This tier is already operational.

Tier 2 - AgriPV system-level certification (new): A new BIS standard, proposed as Agriphotovoltaic Systems: Design, Performance and Safety Requirements, is being recommended.

Tier 3 - Project-level certification (new): Project-level certification is recommended as the operational vehicle through which individual installations receive an "AgriPV Mark" (analogous to the BIS ISI Mark).

The certification pathway is:

- **Pre-construction registration** with the State Nodal Agency or Central Agency.
- **Design review** by an empanelled Third-Party Inspection Agency (TPIA) against the upcoming standards.
- **Pre-commissioning inspection** - the TPIA verifies module traceability, structural integrity, clearance compliance, and metering/SCADA conformance.
- **First-year MRV audit** - independent verification (see Chapter 10) of declared crop yield and electricity generation against the baseline.
- **Annual surveillance audit** - TPIA visits, recalibration, and a data audit on a 10 % sample.
- **Triennial recertification** - full performance test including IEC 61215 retests for a sample of modules.

The Indian agriphotovoltaic sector's definitional ambiguity (Sharma et al., 2026) is best resolved by embedding the operational definition in this Tier 3 project-level certificate.

11.5 Quality Control Mechanisms

A complementary set of quality-control mechanisms is recommended:

- **Vendor qualification** - module, inverter, and mounting-structure vendors are recommended to be approved models; Tier 1 BIS/IEC module certification is a precondition but not sufficient for AgriPV projects where structural and agronomic integration is in scope.
- **Factory Acceptance Test** - recommended for elevated support structures and inverter-MPPT combinations.

- **Site Acceptance Test** - including a torque audit on structural fasteners, insulation test per IEC 61730, IV-curve tracing of installed modules, and clearance / shading as-built verification.
- **In-process inspection** - during erection, the inspection agency is recommended to verify clearance height with reference to the cleared crop canopy at maturity (e.g., ≥ 4.0 m for tractor access, ≥ 4.0 m for high-clearance cotton/turmeric).
- **Periodic retesting** - module IV-curve tracing at Year 2, Year 5 and Year 10; thermal-imaging inspection for hot-spots; and a structural fastener audit after each named cyclone or wind event exceeding the design basic wind speed.

11.6 Institutional Framework

The successful implementation of large-scale PV technology requires quality certification and standards (Sarkar et al., 2021). For AgriPV specifically, co-management is recommended:

- **BIS** - Responsible for the AgriPV-specific IS standard and accredits test labs.
- **MNRE / SECI** - Responsible for the operational certification pathway; chairs a standing AgriPV Standards Committee.
- **Ministry of Agriculture & Farmers' Welfare** - responsible institution for the agronomic verification protocol; co-chairs the Standards Committee; designates ICAR / State Agricultural Universities as third-party agronomic auditors.
- **CEA** - responsible for grid-side electrical safety and connectivity provisions.
- **State Nodal Agencies / DISCOMs** - operational registration authority.
- **Empanelled Inspection Agencies** - independent third-party inspection agencies accredited by the competent Authority.

11.7 Concluding Recommendations

The Indian AgriPV sector can achieve its full potential and fully justify the optimistic estimates that $LER > 1$ is achievable with the right crop-design-policy harmony only if a coherent standards-based ecosystem is in place. The recommended package is: (i) integrate IEC TS 63126:2020 high-temperature qualification into Indian BIS module certification; (ii) develop a dedicated standard as a Tier 2 system standard with an $LER > 1$ and a 40 % GCR upper bound; (iii) implement the AgriPV Mark as a Tier 3 project-level certification; and (iv) anchor the entire framework to a layered, MRV-disciplined, audit-grade data-collection methodology. Doing so will resolve the definitional ambiguity that currently constrains farmer-centric AgriPV models, protect farmers against inferior installations, and provide the regulatory certainty that institutional and financial partners need to scale up AgriPV deployment. Global reviews reach the same conclusion: standardized modelling, policy coherence, and harmonized definitions are now the critical enablers for scaling AgriPV as a cornerstone of climate-resilient land use (Mehta et al., 2025).

Annexure I

Table I.1: Applicable Standards for Major Components of AgriPV Systems

Sl. No.	Name of component	Applicable standards
1.	PV module	IS 14286-1 IS 14286-1-1 IS 14286-1-2 IS 14286-1-3 IS 14286-1-4 IS 14286-2 IS/IEC 61730-1 IS/IEC 61730-2
2.	Inverter	IS 16221 (Part 2)/ IEC 62109-2 IS/IEC 61683 IS 16169: 2019/ IEC 62116 IS 17980: 2022/IEC 62891
3.	Battery	IS 16270
4.	Module mounting structure	IS 2062/IS4759
5.	Cables	IEC 60227/IS 694, IEC60502/IS 1554 (Part 1&2) IEC 60947 DC cables (solar PV): IS 17293; IEC 62930 AC cables (as applicable to voltage ratings and installation conditions): IS 7098 (Parts 1 and 2); IS 694; IS 9968 (Part 1)

For testing of a PV power plant, the following standards can be followed:

Table I.2: Standards for Testing of the PV Power Plant

Sl. No.	Standard	Title
1.	IS/IEC 61724 (Part 1)	Photovoltaic system performance - Part 1: Monitoring
2.	IS/IEC TS 61724 (Part 2)	Photovoltaic system performance - Part 2: Capacity evaluation method
3.	IEC 61724-3	Photovoltaic system performance - Part 3: Energy evaluation method

Sl. No.	Standard	Title
4.	IS 16960 (Part 1)/IEC 62446-1	Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid-connected systems - Documentation, commissioning tests and inspection

References

All sources are listed once below. Letters after the year (a, b, c) distinguish works by the same first author in the same year.

Literature

- Abubakar, S. I., et al. (2025). Model-based optimization of a 10-kWp agrivoltaic system with semi-transparent and bi-facial panels for enhanced crop yield, energy production, and land-use efficiency. *IEEE Access*.
- Agarwal, A., Irtaza, H., & Ahmad, M. J. (2020). Numerical analysis of the ground-mounted solar PV panel array mounting systems subjected to basic wind for optimum design. *Canadian Journal of Civil Engineering*, 48(6), 656-668. <https://doi.org/10.1139/cjce-2019-0280>
- Al-Quraan, A., Al-Mahmodi, M., Alzaareer, K., El-Bayeh, C., & Eicker, U. (2022). Minimizing the utilized area of PV systems by generating the optimal inter-row spacing factor. *Sustainability*, 14(10), 6077.
- Alves, A., et al. (2025). The policy landscape of agrivoltaics: A systematic review. *Energy, Sustainability and Society*.
- Aly, A. M. (2026). Optimizing agrivoltaic systems for global sustainability: A structural and wind dynamics approach to resilience and performance. *Frontiers in Horticulture*, 4. <https://doi.org/10.3389/fhort.2025.1677480>
- Amaducci, S., Yin, X., & Colauzzi, M. (2018). Agrivoltaic systems to optimize land use for electric energy production. *Applied Energy*, 220.
- Anantharam, T., & Manju, R. (2022). Influence of wind characteristics and other parameters on module mounting structures. *International Journal of Advanced Research in Science, Communication and Technology*, 322–327. <https://doi.org/10.48175/ijarsct-5030>
- Antani, E. M. (2025). *Technical and environmental feasibility of agrivoltaics in Finland* [Bachelor's thesis, Sustainable Solutions Engineering].
- Asa'a, S.-N., et al. (2024). A multidisciplinary view on agrivoltaics: Future of energy and agriculture. *Renewable and Sustainable Energy Reviews*, 200, 114515. <https://doi.org/10.1016/j.rser.2024.114515>
- Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., & Macknick, J. E. (2019). Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nature Sustainability*, 2, 848–855. <https://doi.org/10.1038/s41893-019-0364-5>
- Barros, J. S. G., Barros, T. A. S., Miele, M. J., Oleto, R. C. V., & Teruel, B. (2026). Agrivoltaic systems: Systematic review and meta-analysis relating energy, soil, and crop parameters. *Annual Review of Environment and Resources*, 51 (in press). <https://doi.org/10.1146/annurev-environ-121224-073319>

- Bellone, Y., Santangelo, E., Assirelli, A., Zainali, S., Impollonia, G., Croci, M., Campana, P. E., & Amaducci, S. (2026). Agricultural mechanization in agrivoltaic systems: Challenges, adaptation, and possible advancements. *Renewable and Sustainable Energy Reviews*, 229, 116661. <https://doi.org/10.1016/j.rser.2025.116661>
- Bernal-Basurco, C., Sánchez-Piñero, M., Centeno, A., Martín-Palomo, M. J., Hernández-Montes, E., Castro-Valdecantos, P., Moratiel, R., Peco, J. D., Moriana, A., Pérez-López, D., & Corell, M. (2026). Regulated deficit irrigation based on plant water status and agrivoltaic systems as possible improvements on water resources management in tomato. *Agricultural Water Management*, 327, 110281. <https://doi.org/10.1016/j.agwat.2026.110281>
- Berrian, D., et al. (2025). Performance of land productivity with single-axis trackers and shade-intolerant crops in agrivoltaic systems. *Applied Energy*.
- Böhm, J., et al. (2024). Key advantages of agrivoltaic systems in Germany. *AgriVoltaics Conference Proceedings*, 2. <https://doi.org/10.52825/agripv.v2i.1005>
- Broms, B. B. (1964a). Lateral resistance of piles in cohesive soils. *Journal of the Soil Mechanics and Foundations Division, ASCE*, 90(SM2), 27–63.
- Broms, B. B. (1964b). Lateral resistance of piles in cohesionless soils. *Journal of the Soil Mechanics and Foundations Division, ASCE*, 90(SM3), 123-156.
- Browne, M., et al. (2020). A wind load design method for ground-mounted multi-row solar arrays based on a compilation of wind tunnel experiments. *Journal of Wind Engineering and Industrial Aerodynamics*, 205.
- Campana, P. E., Stridh, B., Amaducci, S., & Colauzzi, M. (2021). Optimization of vertically mounted agrivoltaic systems. *Journal of Cleaner Production*, 325, 129091.
- Centre of Excellence for AgriPv (CoE-AgriPv), ICAR-Indian Agricultural Research Institute, New Delhi, and National Institute of Solar Energy, Gurugram. (n.d.). Centre of Excellence for AgriPv. <https://coeagripv.iari.res.in>
- Centre of Excellence for AgriPv, ICAR-Indian Agricultural Research Institute. (2026a). *AgriPv for achieving net zero emission targets, energy security and enhancing farmers' income in India: A white paper*.
- Centre of Excellence for AgriPv in India, ICAR-Indian Agricultural Research Institute. (2026b). *AgriPv: For net zero emission, energy security, and enhancing farmers' income - Guidelines*.
- Centre of Excellence for AgriPv, ICAR-Indian Agricultural Research Institute. (2026c). *Crop matrix for AgriPv system in India*.
- Chalgynbayeva, A., Balogh, P., Szöllősi, L., Gabnai, Z., Apáti, F., Sipos, M., & Bai, A. (2024). The Economic Potential of Agrivoltaic Systems in Apple Cultivation—A Hungarian Case Study. *Sustainability*, 16(6), 2325. <https://doi.org/10.3390/su16062325>

- Chatzipanagi, A., Taylor, N., & Jaeger-Waldau, A. (2023). *Overview of the potential and challenges for agri-photovoltaics in the European Union* (JRC Science for Policy Report). Publications Office of the European Union.
- Chen, J., et al. (2024). Agrivoltaics: A digital twin to learn the effect of solar panel coverage on crop growth. In *ICSEE 2024*.
- Choi, C. S., Macknick, J., Li, Y., Bloom, D., McCall, J., & Ravi, S. (2023). Environmental co-benefits of maintaining native vegetation with solar photovoltaic infrastructure. *Earth's Future*, 11, e2023EF003542. <https://doi.org/10.1029/2023EF003542>
- Cook, L. M., & McCuen, R. H. (2013). Hydrologic response of solar farms. *Journal of Hydrologic Engineering*, 18(5), 536–541.
- Cosme, I., & Vázquez y Parraguirre, S. (2025). Deconstructing agrivoltaic microclimates: A critical review of inherent complexity and a minimum viable monitoring framework. *Agronomy*, 15(12), 2829. <https://doi.org/10.3390/agronomy15122829>
- Costa, M., Del Papa, G., Sgambato, D., & Palombo, A. (2026). Integrated optimization of agrivoltaic systems for the highest crop yield and energy production. *Energy*, 142188.
- De Francesco, C., Centorame, L., Toscano, G., & Duca, D. (2025). Opportunities, technological challenges and monitoring approaches in agrivoltaic systems for sustainable management. *Sustainability*, 17(2), 634. <https://doi.org/10.3390/su17020634>
- Debnath, K., et al. (2025). Wind pressure characterization on ground-mounted solar PV systems: A combined experimental and numerical study. *Case Studies in Thermal Engineering*.
- Dinesh, H., & Pearce, J. M. (2015). The potential of agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, 54, 299-308. <https://doi.org/10.1016/j.rser.2015.10.024>
- Doedt, C., Tajima, M., & Iida, T. (2024). Agrivoltaics in Japan: A legal framework analysis. *AgriVoltaics Conference Proceedings*, 1. <https://doi.org/10.52825/agripv.v1i.533>
- Dupraz, C. (2023). Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity. *Agroforestry Systems*, 98(8), 2679–2696. <https://doi.org/10.1007/s10457-023-00906-3>
- Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., & Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimizing land use: Towards new agrivoltaic schemes. *Renewable Energy*, 36(10), 2725-2732. <https://doi.org/10.1016/j.renene.2011.03.005>
- Edirisinghe, E., et al. (2026). A digital twin-enabled framework for agrivoltaic system design, simulation, monitoring and control. *Machines*.
- Elamri, Y., Cheviron, B., Lopez, J.-M., Dejean, C., & Belaud, G. (2018). Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. *Agricultural Water Management*, 208, 440–453. <https://doi.org/10.1016/j.agwat.2018.07.001>

- Fraunhofer Institute for Solar Energy Systems ISE. (2021). *APV-RESOLA: Agrivoltaics - Research on optimizing land use solutions*. Fraunhofer ISE.
- Fraunhofer Institute for Solar Energy Systems ISE. (2022). *Agrivoltaics: Opportunities for agriculture and the energy transition - A guideline for Germany* (updated edition, April 2022). Fraunhofer ISE. <https://www.ise.fraunhofer.de>
- Gautam, S., Das, D. B., & Saxena, A. K. (2024). Impact of solar panel spacing on wind load in an elevated solar panel structure. *Discover Mechanical Engineering*, 3(1). <https://doi.org/10.1007/s44245-024-00081-4>
- Ghamari, M., Ramasamy, M., & Sundaram, S. (2026). Agrivoltaics in India: A promising nexus of solar energy and agriculture for sustainable development. *Solar Energy*, 309, 114438. <https://doi.org/10.1016/j.solener.2026.114438>
- Ghosh, A. (2023). Nexus between agriculture and photovoltaics (agrivoltaics, agriphotovoltaics) for sustainable development goals: A review. *Solar Energy*, 266, 112146. <https://doi.org/10.1016/j.solener.2023.112146>
- Giri, N., et al. (2022). Agrivoltaic system: Experimental analysis for enhancing land productivity and revenue of farmers. *Energy for Sustainable Development*, 70.
- Gomez-Casanovas, N., et al. (2023). Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production. *Cell Reports Physical Science*, 4(8), 101518.
- Gorjian, S., Bousi, E., Özdemir, E., et al. (2022). Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology. *Renewable and Sustainable Energy Reviews*, 158, 112126.
- Grahmann, K., Reis dos Santos Bastos, T., Donat, M., Rohlmann, L., & Reckling, M. (2026). Construction-induced soil compaction in agri-photovoltaic systems: Evidence from an Arenosol. *Scientific Reports*, 16(1), 25529.
- Grell, K. B., & Parker, S. S. (2026). Regenerative agrivoltaics: Challenges and opportunities in Southern California's Inland Empire region. *Energy Nexus*, 21, 100661.
- Hamza, M. A., & Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes, and possible solutions. *Soil and Tillage Research*, 82(2), 121-145.
- Hassanpour Adeg, E., Selker, J. S., & Higgins, C. W. (2018). Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS ONE*, 13(11), e0203256. <https://doi.org/10.1371/journal.pone.0203256>
- Hermelink, M. I., et al. (2024). Berry shade tolerance for agrivoltaics systems: A meta-analysis. *Scientia Horticulturae*, 333.
- Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., Barrows, C. W., Belnap, J., Ochoa-Hueso, R., Ravi, S., & Allen, M. F. (2014). Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews*, 29, 766–779. <https://doi.org/10.1016/j.rser.2013.08.041>

- Hernandez, R. R., Armstrong, A., Burney, J., Ryan, G., Moore-O’Leary, K., Diédhiou, I., Grodsky, S. M., Saul-Gershenz, L., Davis, R., Macknick, J., et al. (2019). Techno-ecological synergies of solar energy for global sustainability. *Nature Sustainability*, 2, 560–568. <https://doi.org/10.1038/s41893-019-0309-z>
- ICAR. (2025). German delegation explores Indo-German collaboration during visit to ICAR-IARI. <https://www.icar.gov.in>
- IEA PVPS Task 13. (2025). *Dual land use for agriculture and solar power production: Overview and performance of agrivoltaic systems* (Report T13-29-2025). International Energy Agency Photovoltaic Power Systems Programme. <https://iea-pvps.org>
- India Agrivoltaics Alliance (IAA). (2024). *Business models of agrivoltaics and its potential socio-economic impacts* (Version 1.0, 16 July 2024). IAA Secretariat/NSEFI. <https://indiaagripv.org>
- Islam, S., Islam, N., Sabeeh, S., Abudayyeh, A., Gari, A. A., & Alkhawlan, Q. (2026). Agrivoltaics improve energy-water and land use efficiency in hyper-arid regions. *Sustainable Production and Consumption*, 68, 306–320. <https://doi.org/10.1016/j.spc.2026.08.014>
- Jamil, U., et al. (2022). Energy policy for agrivoltaics in Alberta, Canada. *Energies*, 15(22).
- Jiang, S., et al. (2022). Effects of different photovoltaic shading levels on kiwifruit growth, yield and water productivity under ‘agrivoltaic’ system in Southwest China. *Agricultural Water Management*, 269.
- Katsikogiannis, O. A., Ziar, H., & Isabella, O. (2022). Integration of bifacial photovoltaics in agrivoltaic systems: A synergistic design approach. *Applied Energy*, 309, 118475. <https://doi.org/10.1016/j.apenergy.2021.118475>
- Keller, T., Sandin, M., Colombi, T., Horn, R., & Or, D. (2019). Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil and Tillage Research*, 194, 104293.
- Kempe, M., Holsapple, D., Whitfield, K., & Shiradkar, N. (2021). Standards development for modules in high-temperature micro-environments. *Progress in Photovoltaics*, 29(4), 445–460. <https://doi.org/10.1002/pip.3389>
- Khanal, S., KC, K., Fulton, J. P., Shearer, S. A., & Özkan, E. (2020). Remote sensing in agriculture—Accomplishments, limitations, and opportunities. *Remote Sensing*, 12(22), 3783. <https://doi.org/10.3390/rs12223783>
- Laub, M., Pataczek, L., Feuerbacher, A., Zikeli, S., & Högy, P. (2022). Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: A meta-analysis. *Agronomy for Sustainable Development*, 42(3). <https://doi.org/10.1007/s13593-022-00783-7>
- Lee, S., Lee, J. H., Jeong, Y., Kim, D., Seo, B. H., Seo, Y. J., Kim, T., & Choi, W. (2023). Agrivoltaic system design for sustainability and smart farming: Agronomic aspects and design criteria

- with safety assessment. *Applied Energy*, 341, 121130. <https://doi.org/10.1016/j.apenergy.2023.121130>
- Liu, H., Wu, C., Yu, Y., Zhao, W., Liu, J., Yu, H., et al. (2023a). Effect of solar farms on soil erosion in hilly environments: A modeling study from the perspective of hydrological connectivity. *Water Resources Research*, 59, e2023WR035067. <https://doi.org/10.1029/2023WR035067>
- Liu, T., Yu, L., Wu, X., Qi, W., Zheng, Q., Wu, H., et al. (2026). Releasing the compound potential of abandoned cropland through recultivation, afforestation, and photovoltaic solutions. *Resources, Conservation and Recycling*, 227, 108760.
- Liu, Z., Peng, T., Ma, S., Qi, C., Song, Y., Zhang, C., Li, K., Gao, N., Pu, M., Wang, X., Bi, Y., Na, X., et al. (2023b). Potential benefits and risks of solar photovoltaic power plants on arid and semi-arid ecosystems: An assessment of soil microbial and plant communities. *Frontiers in Microbiology*, 14, 1190650. <https://doi.org/10.3389/fmicb.2023.1190650>
- Ma, M., Yang, F., Zheng, X., Yang, X., Mamtimin, A., Zhou, C., Li, C., Huo, W., Zheng, X., Wang, T., He, P., & Gong, Q. (2026). Integrated photovoltaic-agriculture systems enhance soil health in desert ecosystems: Evidence from microbial biomass and nutrient synergies. *Scientific Reports*, 16, 472. <https://doi.org/10.1038/s41598-025-29815-4>
- Macknick, J., et al. (2022). *The 5 Cs of agrivoltaic success factors in the United States: Lessons from the InSPIRE research study* (Technical Report NREL/TP-6A20-83566). National Renewable Energy Laboratory. <https://www.nrel.gov>
- Magarelli, A., Mazzeo, A., & Ferrara, G. (2024). Fruit crop species with agrivoltaic systems: A critical review. *Agronomy*, 14(4), 722.
- Mahim, T. M., et al. (2025). Review of the challenges and prospects in agrivoltaics. *Advanced Energy and Sustainability Research*.
- Malu, P. R., Sharma, U. S., & Pearce, J. M. (2017). Agrivoltaic potential on grape farms in India. *Sustainable Energy Technologies and Assessments*, 23, 104–110. <https://doi.org/10.1016/j.seta.2017.08.004>
- Marrou, H., Dufour, L., & Wery, J. (2013a). How does a shelter of solar panels influence water flows in a soil–crop system? *European Journal of Agronomy*, 50, 38–51. <https://doi.org/10.1016/j.eja.2013.05.004>
- Marrou, H., Guilioni, L., Dufour, L., Dupraz, C., & Wery, J. (2013b). Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? *Agricultural and Forest Meteorology*, 177, 117–132. <https://doi.org/10.1016/j.agrformet.2013.04.012>
- Marrou, H., Wery, J., Dufour, L., & Dupraz, C. (2013c). Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. *European Journal of Agronomy*, 44, 54–66.

- Martínez-Hernández, C., et al. (2026). Efficiency, sustainability and governance of agrivoltaic systems: A PRISMA-based systematic review of global evidence (2010–2025). *Energies*.
- Mazzeo, D., Zio, A. D., Pesenti, C., & Leva, S. (2025). Optimizing agrivoltaic systems: A comprehensive analysis of design, crop productivity, and energy performance in open-field configurations. *Applied Energy*, 390, 125750. <https://doi.org/10.1016/j.apenergy.2025.125750>
- Mehta, K., et al. (2025). Agrivoltaics around the world: Potential, technology, crops and policies to address the energy-agriculture nexus for sustainable and climate-resilient land use. *Energies*.
- Miljkovic, N., et al. (2024). Advancing agrivoltaics through a systematic design framework: Guidelines for integration and informed decision-making [Preprint]. <https://doi.org/10.21203/rs.3.rs-4791170/v1>
- Moretta, M., et al. (2025). Towards crop monitoring in agro-photovoltaic systems: An image-driven modeling approach for fAPAR-derived biomass estimation. *European Journal of Agronomy*, 170, 127748. <https://doi.org/10.1016/j.eja.2025.127748>
- Mundu, M. M., Sempewo, J. I., Mahoro, G. B., Sankarapandian, V., & Uti, D. E. (2026). Environmental impacts of Agri-Photovoltaics systems on local ecosystems. *Food and Energy Security*, 15, e70186. <https://doi.org/10.1002/fes3.70186>
- Omer, A. A. A., Li, M., Zhang, F., Hassaan, M. M. E., El Kolaly, W., Zhang, X., Lan, H., Liu, J., & Liu, W. (2025). Impacts of agrivoltaic systems on microclimate, water use efficiency, and crop yield: A systematic review. *Renewable and Sustainable Energy Reviews*, 221, 115930. <https://doi.org/10.1016/j.rser.2025.115930>
- Panda, S., Kumar, R., Panda, B., Panda, B., & Raj, A. (2024). Combining solar panels with plants for sustainable energy and food production: State of the art. *International Journal of Applied Power Engineering*, 13(2), 434-441. <https://doi.org/10.11591/ijape.v13.i2.pp434-441>
- Pascaris, A. S. (2021). Examining existing policy to inform a comprehensive legal framework for agrivoltaics in the U.S. *Energy Policy*, 159.
- Patel, U., et al. (2024). Techno-economic analysis of agrivoltaic system for affordable and clean energy with food production in India. *Clean Technologies and Environmental Policy*.
- Poonia, S., et al. (2021). Techno-economic evaluation of different agri-voltaic designs for the hot arid ecosystem in India. *Renewable Energy*, 184.
- Prakash, V., Lunagaria, M. M., Trivedi, A. P., Upadhyaya, A., Kumar, R., Das, A., et al. (2023). Shading and PAR under different density agrivoltaic systems, their simulation and effect on wheat productivity. *European Journal of Agronomy*, 149, 126922.
- Pulipaka, S., & Peparthy, M. (2021). *Agrivoltaics in India: Overview of operational projects and relevant policies*. National Solar Energy Federation of India (NSEFI).

- Riaz, M. H., Younas, R., Imran, H., Alam, M. A., & Butt, N. Z. (2021a). Module technology for agrivoltaics: Vertical bifacial versus tilted monofacial farms. *IEEE Journal of Photovoltaics*, 11(2), 469-477.
- Riaz, M. H., et al. (2021b). The optimization of vertical bifacial photovoltaic farms for efficient agrivoltaic systems. *Solar Energy*, 230.
- Santra, P., Meena, H. M., & Yadav, O. P. (2021). Spatial and temporal variation of photosynthetic photon flux density within agrivoltaic system in hot arid region of India. *Biosystems Engineering*, 209, 74-93.
- Santra, P., Pande, P. C., Kumar, S., Mishra, D., & Singh, R. K. (2017). Agri-voltaics or solar farming: The concept of integrating solar PV-based electricity generation and crop production in a single land use system. *International Journal of Renewable Energy Research*, 7(2), 694–699.
- Sara, P., José, S. A., Luís, F., & Pedro, H. (2025). Review of sensor technologies for monitoring agrivoltaic systems. In *Proceedings of EU PVSEC 2025*. <https://doi.org/10.4229/eupvsec2025/4dv.1.15>
- Sarkar, S., Bhaskar, M. S., Rao, K. U., Prema, V., Almakhlles, D., & Subramaniam, U. (2021). Solar PV network installation standards and cost estimation guidelines for smart cities. *Alexandria Engineering Journal*, 61(2), 1277–1287. <https://doi.org/10.1016/j.aej.2021.06.098>
- Sarr, A., et al. (2023). Agrivoltaic, a synergistic co-location of agricultural and energy production in perpetual mutation: A comprehensive review. *Processes*, 11(12).
- Sasikumar, B. (1989). *Screening of varieties of ginger and turmeric for shade tolerance* [Master's thesis, Kerala Agricultural University].
- Sekiyama, T., & Nagashima, A. (2019). Solar sharing for both food and clean energy production: Performance of agrivoltaic systems for corn, a typical shade-intolerant crop. *Environments*, 6(6).
- Sharma, L., Banerjee, B., & Basu, S. (2026). Beyond the energy-agriculture binary: How agriphotovoltaics can transform India's rural economy through PM KUSUM. *International Journal of Inventive Engineering and Sciences*, 13(1), 30–38. <https://doi.org/10.35940/ijies.b1056.13010126>
- Solaracks. (2026). *Agrivoltaics mounting structures: Design guide*. <https://www.solaracks.com>
- SolarPower Europe. (2023). *Agrisolar best practices guidelines* (Version 2.0). SolarPower Europe.
- SurgePV. (2026). *Agrivoltaics: How solar and farming work together - Technical guide*. <https://www.surgepv.com>
- TERI. (2025). *Agri-photovoltaics potential in India: Pathways for sustainable energy–food solutions*. The Energy and Resources Institute.

- Thum, C. H., et al. (2025). Impacts of agrivoltaic systems on microclimate, grain yield, and quality of lowland rice under a temperate climate. *Field Crops Research*.
- Toledo, C., & Scognamiglio, A. (2021). Agrivoltaic systems design and assessment: A critical review, and a descriptive model towards a sustainable landscape vision (three-dimensional agrivoltaic patterns). *Sustainability*, 13(12), 6871.
- Trommsdorff, M., Vorast, M., Durga, N., & Padwardhan, S. M. (2021a). Potential of agrivoltaics to contribute to socio-economic sustainability: A case study in Maharashtra/India. *AIP Conference Proceedings*, 2361, 040001. <https://doi.org/10.1063/5.0054569>
- Trommsdorff, M., Kang, J., Reise, C., Schindele, S., Bopp, G., Ehmann, A., Weselek, A., Högy, P., & Obergfell, T. (2021b). Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany. *Renewable and Sustainable Energy Reviews*, 140, 110694. <https://doi.org/10.1016/j.rser.2020.110694>
- Trommsdorff, M., et al. (2025). Legislation on agrivoltaics in Germany: Changes and complements towards a comprehensive legal framework. *AgriVoltaics Conference Proceedings*.
- Tucci, V., Montesano, F. F., Altieri, G. M., Bari, G., Tarasco, E., Zito, F., Strazzella, S., & Stellacci, A. M. (2025). Microclimatic parameters, soil quality, and crop performance of lettuce, pepper, and chili pepper as affected by modified growing conditions in a photovoltaic plant: A case study in the Puglia Region (Italy). *Agronomy*, 15, 2035. <https://doi.org/10.3390/agronomy15092035>
- Valle, B., Simonneau, T., Sourd, F., Pechier, P., Hamard, P., Frisson, T., Ryckewaert, M., & Christophe, A. (2017). Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. *Applied Energy*, 206, 1495-1507.
- Vorast, M. (2022). *Challenges for agrivoltaics in the international context* [Master's thesis, University of Graz].
- Walston, L. J., Rollins, K. E., LaGory, K. E., Smith, K. P., & Meyers, S. A. (2016). A preliminary assessment of avian mortality at utility-scale solar energy facilities in the United States. *Renewable Energy*, 92, 405–414. <https://doi.org/10.1016/j.renene.2016.02.041>
- Warmann, E., et al. (2024). Agrivoltaic system design tools for managing trade-offs between energy production, crop productivity, and water consumption. *Environmental Research Letters*.
- Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., & Högy, P. (2019). Agrophotovoltaic systems: Applications, challenges, and opportunities. A review. *Agronomy for Sustainable Development*, 39(4). <https://doi.org/10.1007/s13593-019-0581-3>
- Weselek, A., Bauerle, A., Hartung, J., Zikeli, S., Lewandowski, I., & Högy, P. (2021). Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop

- rotation in a temperate climate. *Agronomy for Sustainable Development*, 41(5). <https://doi.org/10.1007/s13593-021-00714-y>
- Widmer, J., Christ, B., Grenz, J., & Norgrove, L. (2024). Agrivoltaics, a promising new tool for electricity and food production: A systematic review. *Renewable and Sustainable Energy Reviews*, 192, 114277.
- Wittwer, A. R., et al. (2022). Wind loading and its effects on photovoltaic modules: An experimental–computational study to assess the stress on structures. *Solar Energy*, 240.
- Yadav, D., Babu, S., Rathore, S. S., & Rana, D. S. (2025). Agri-photovoltaics: Integrating agricultural production and energy generation for sustainable resource use. *Indian Journal of Agronomy*, 70 (6th IAC Special Issue), S79–S87.
- Yavari, R., Zaliwciw, D., Cibin, R., & McPhillips, L. (2022). Minimizing environmental impacts of solar farms: A review of current science on landscape hydrology and guidance on stormwater management. *Environmental Research: Infrastructure and Sustainability*, 2, 032002. <https://doi.org/10.1088/2634-4505/ac76dd>
- Yemenici, O., & Aksoy, Ö. (2021). An experimental and numerical study of wind effects on a ground-mounted solar panel at different panel tilt angles and wind directions. *Journal of Wind Engineering and Industrial Aerodynamics*, 213.
- Zahrawi, A. A., & Aly, A. M. (2024). A review of agrivoltaic systems: Addressing challenges and enhancing sustainability. *Sustainability*, 16(18), 8271. <https://doi.org/10.3390/su16188271>

Standards, Regulations and Policy Instruments

- AFNOR Certification. (2022). “*Projet agrivoltaïque*” label criteria. <https://www.afnor.org>
- Bureau of Indian Standards (BIS). (2000). *IS 456:2000 - Plain and reinforced concrete - Code of practice* (Fourth Revision).
- Bureau of Indian Standards (BIS). (2007). *IS 800:2007 - General construction in steel - Code of practice* (Third Revision).
- Bureau of Indian Standards (BIS). (2008). *IS 15797:2008 - Rooftop rainwater harvesting - Guidelines*.
- Bureau of Indian Standards (BIS). (2010). *IS/IEC 62305 (Parts 1-4):2010 - Protection against lightning*.
- Bureau of Indian Standards (BIS). (2013). *IS 2911 (Part 4):2013 - Design and construction of pile foundations - Code of practice, Part 4: Load test on piles*.
- Bureau of Indian Standards (BIS). (2015). *IS 875 (Part 3):2015 - Design loads (other than earthquake) for buildings and structures - Code of practice, Part 3: Wind loads* (Third Revision).
- Bureau of Indian Standards (BIS). (2016). *IS 1893 (Part 1):2016 - Criteria for earthquake-resistant design of structures, Part 1: General provisions and buildings*.

- Bureau of Indian Standards (BIS). (2018). *IS 3043:2018 - Code of practice for earthing*.
- Central Electricity Authority (CEA). (2006). *CEA (Installation and Operation of Meters) Regulations, 2006*, as amended. <https://cea.nic.in>
- Central Electricity Authority (CEA). (2013). *CEA (Technical Standards for Connectivity of the Distributed Generation Resources) Regulations, 2013*, as amended in 2019. <https://cea.nic.in>
- Central Electricity Authority (CEA). (2022). *CEA (Technical Standards for Construction of Electrical Plants and Electric Lines) Regulations, 2022*. <https://cea.nic.in>
- Central Electricity Authority (CEA). (2023). *CEA (Measures relating to Safety and Electric Supply) Regulations, 2023*. <https://cea.nic.in>
- Deutsches Institut für Normung (DIN). (2019). *DIN 19639:2019-09 - Soil protection during planning and implementation of construction projects*.
- Deutsches Institut für Normung (DIN). (2021). *DIN SPEC 91434:2021-05 - Agri-photovoltaic systems: Requirements for primary agricultural use*. <https://doi.org/10.31030/3257526>
- European Committee for Standardization (CEN). (2006). *EN 1991-1-7:2006 - Eurocode 1: Actions on structures - Part 1-7: General actions - Accidental actions*.
- European Committee for Standardization (CEN). (2007). *EN 1993-5:2007 - Eurocode 3: Design of steel structures -Part 5: Piling*.
- Institute of Electrical and Electronics Engineers (IEEE). (2013). *IEEE Std 80-2013 - IEEE guide for safety in AC substation grounding*.
- International Electrotechnical Commission (IEC). (2014). *IEC 62817:2014 - Photovoltaic systems - Design qualification of solar trackers*.
- International Electrotechnical Commission (IEC). (2016). *IEC 62446-1:2016+AMD1:2018 - Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems*.
- International Electrotechnical Commission (IEC). (2019). *IEC 60904-3:2019 - Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*.
- International Electrotechnical Commission (IEC). (2021a). *IEC 61215-1:2021 - Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements*.
- International Electrotechnical Commission (IEC). (2021b). *IEC 61215-2:2021 - Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures*.
- International Electrotechnical Commission (IEC). (2021c). *IEC 61724-1:2021 - Photovoltaic system performance - Part 1: Monitoring*.

- International Organization for Standardization (ISO). (2012). *ISO 9223:2012 - Corrosion of metals and alloys - Corrosivity of atmospheres - Classification, determination and estimation*.
- Ministero della Transizione Ecologica (MiTE). (2022). *Linee Guida in materia di Impianti Agrivoltaici* [Guidelines on agrivoltaic installations]. <https://www.mase.gov.it>
- Ministry of Agriculture, Forestry and Fisheries (MAFF), Japan. (2013, amended 2021). *Guidelines on solar sharing* (Noushin Article 2131, April 2013; Notification No. 2 Noushin Article 3854, March 2021). <https://www.maff.go.jp>
- Ministry of Environment, Forest and Climate Change (MoEFCC). (2022). *E-Waste (Management) Rules, 2022*, as amended. <https://moef.gov.in>
- Ministry of New and Renewable Energy (MNRE). (2017). *Solar Photovoltaics, Systems, Devices and Components Goods (Requirements for Compulsory Registration) Order, 2017*, as amended. <https://mnre.gov.in>
- Ministry of New and Renewable Energy (MNRE). (2019). *Approved Models and Manufacturers of Solar Photovoltaic Modules (Requirements for Compulsory Registration) Order, 2019*, as amended. <https://mnre.gov.in>
- National Crime Records Bureau (NCRB). (2023). *Accidental deaths & suicides in India 2022*. Ministry of Home Affairs, Government of India. <https://ncrb.gov.in>
- République française. (2023). *Loi n° 2023-175 du 10 mars 2023 relative à l'accélération de la production d'énergies renouvelables (Loi APER)*.
- République française. (2024). *Décret n° 2024-318 du 8 avril 2024 relatif au développement de l'agrivoltaïsme et aux conditions d'implantation des installations photovoltaïques sur des terrains agricoles, naturels ou forestiers*. <https://www.legifrance.gouv.fr>



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