Environmental Performance and Design Considerations of Agrivoltaic Systems: A Life Cycle Perspective for Photovoltaic-Agricultural Co-Production

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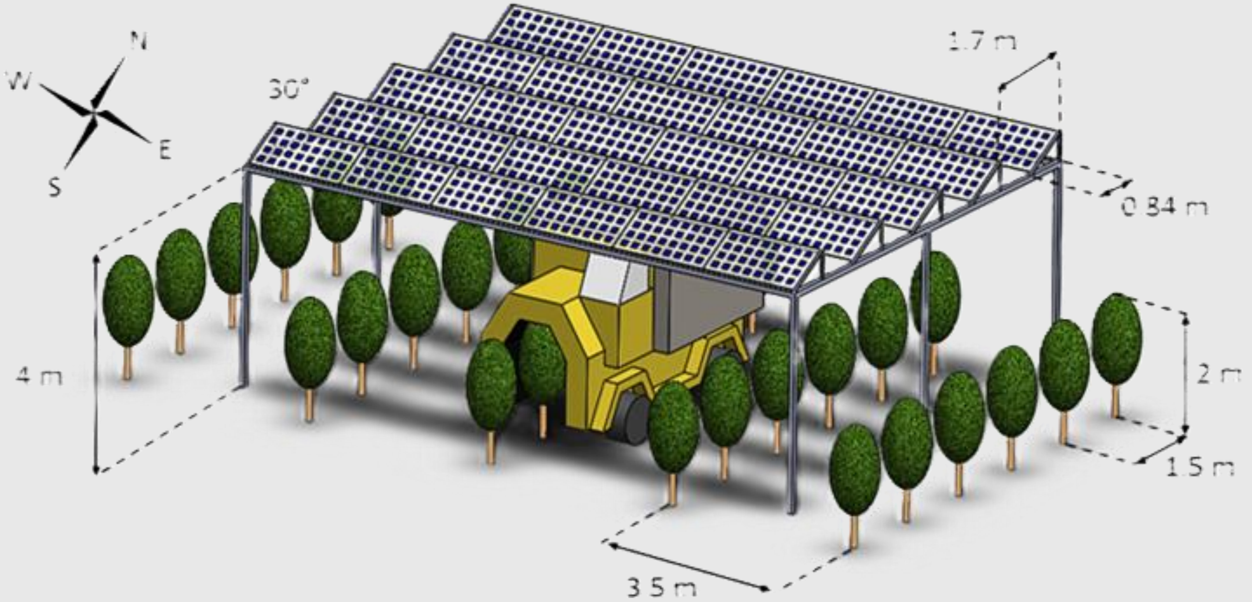
CONTENT



INTRODUCTION: Why agrivoltaics?

Global drivers:

- Global energy demand is projected to increase by ~50% by 2050.
- The European Union targets 730 GW of PV capacity by 2030.
- Global agrivoltaic capacity expanded from approximately 5 MW in 2012 to at least 14 GW by 2021 demonstrating the rapid adoption of dual land-use systems.
- Utility-scale PV requires extensive land resources.
- Increasing competition between agricultural production and utility scale PV deployment.

HOW CAN WE EXPAND SOLAR ENERGY WITHOUT SACRIFICING AGRICULTURAL LAND?

Pascaris et al. (2021); Wagner et al. (2023); DIN (2021)

Agrivoltaics as a solution

- Simultaneous production of food and electricity
- Dual land use
- Reduced land-use conflict
- Water savings: 14–29% (up to 47%)
- Enhanced crop resilience under heat and drought stress
- Supports SDGs 2, 7 and 13

Typical Land Equivalent Ratio (LER): 1.2–1.8

Maximum reported LER: 1.86 (Heggelbach, Germany)

Barron-Gafford et al. (2019); Agostini et al. (2021); Weselek et al. (2019); Ravilla et al. (2024)

Why environmental assessment?

Existing AV studies mainly focus on:

- Crop yield
- Energy production
- Economic feasibility
- Land Equivalent Ratio (LER)

Missing perspective:

- Environmental impacts
- Material demand
- Infrastructure requirements
- Design-dependent impacts

Life Cycle Assessment:

- Evaluates environmental impacts throughout the life cycle
  - Climate change
  - Resource depletion
  - Eutrophication
- Supports sustainable PV deployment.
- Enables comparison of alternative AV designs.

Busch & Wydra (2022); Sponagel et al. (2024); ISO 14040 (2006); ISO 14044 (2006)

OBJECTIVE OF THE STUDY: To investigate how agrivoltaic design characteristics influence environmental performance from an LCA perspective.

This study aims to;

Analyzes how agrivoltaic design characteristics influence life-cycle environmental performance.

Evaluate key methodological challenges in AV-LCA:

- Functional unit
- System boundaries
- Multifunctionality

Propose a conceptual framework for future agrivoltaic LCA studies.

MATERIAL AND METHODS

- Study Approach
- Scope of the Assessment
- Agrivoltaic Design Parameters Considered in the Assessment
- Life Cycle Assessment Perspective

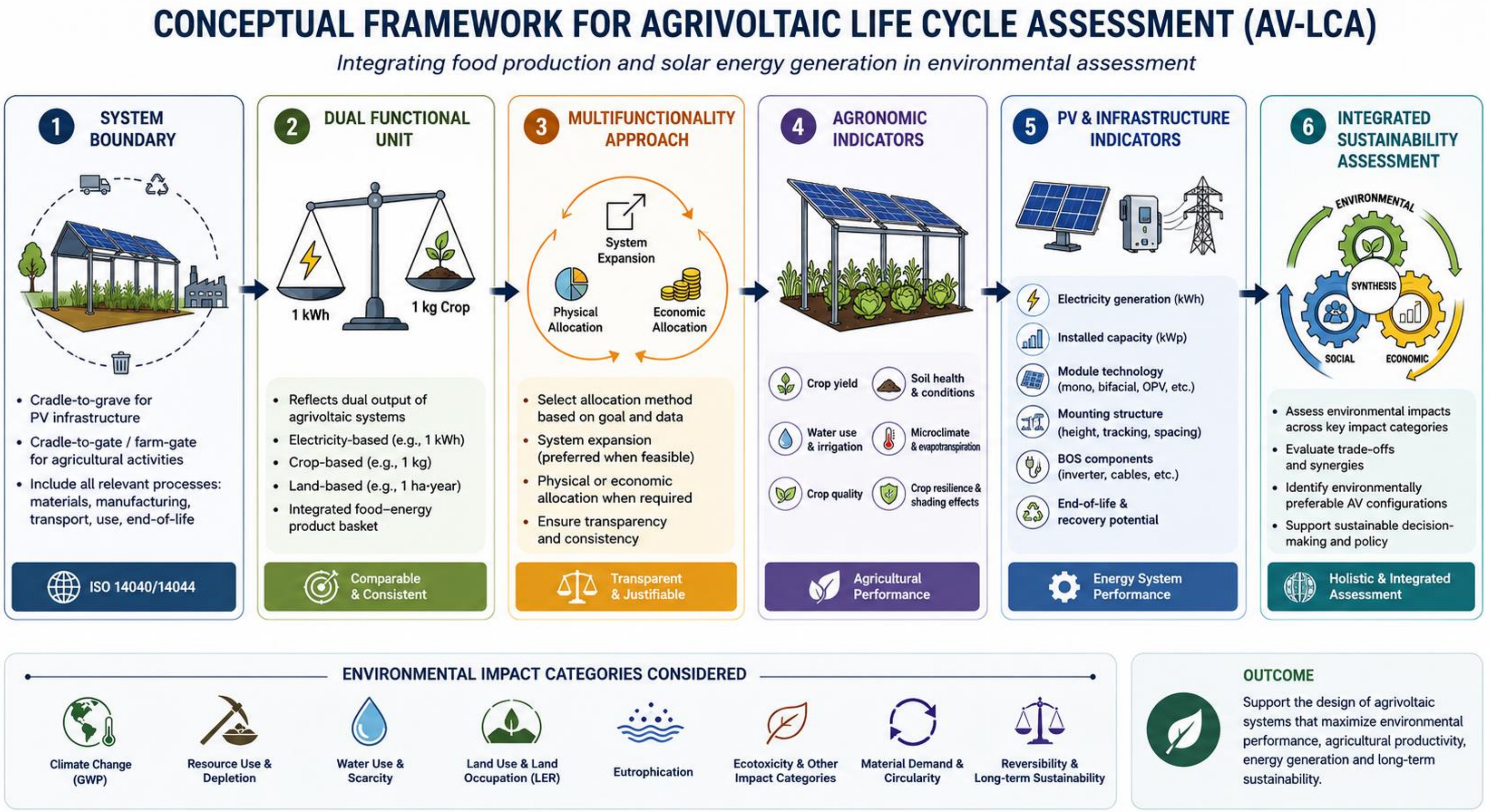


Figure 1. Conceptual framework developed in this study to guide the life cycle assessment of agrivoltaic systems.

Study approach & Scope of the assessment

A STRUCTURED LITERATURE SYNTHESIS WAS CONDUCTED TO IDENTIFY ENVIRONMENTAL HOTSPOTS, DESIGN-RELATED TRADE-OFFS, AND METHODOLOGİCAL CHALLENGES IN AGRIVOLTAIC LCA.

Study approach	Literature-based environmental assessment
	Review of published AV-LCA studies
	ISO 14040/14044-compliant studies
	Technical guidelines and methodological frameworks
Scope of the assessment	PV infrastructure
	Agricultural operations
	Land-use indicators
	Environmental hotspots
	Agrivoltaic design configurations

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ISO 14040; ISO 14044; DIN SPEC 91434; Wagner et al. (2023)

Agrivoltaic design parameters

Table 1. Agrivoltaic design parameters considered in the environmental assessment

Design parameter	Key design characteristics	Environmental implications
Mounting height	Minimum clearance: 2.1 m (DIN SPEC 91434)Typical practical height: 4–5 m	Agricultural compatibility, higher steel demand
Row spacing	Typical installation density: 500–800 kWp ha^{-1}	Crop light availability, lower PV capacity density
Tracking systems	Fixed / single-axis / dual-axis	Light management, operational flexibility
Structural materials	Steel and aluminum support structures	Embodied carbon, material demand
Foundation systems	Concrete vs. screw anchors / piles	Soil disturbance, end-of-life recoverability

AGRIVOLTAIC DESIGN PARAMETERS DIRECTLY DETERMINE AGRICULTURAL FUNCTIONALITY, MATERIAL DEMAND, AND LIFE-CYCLE ENVIRONMENTAL PERFORMANCE.

DIN (2022); *Ott et al. (2020)*

Life cycle assessment perspective

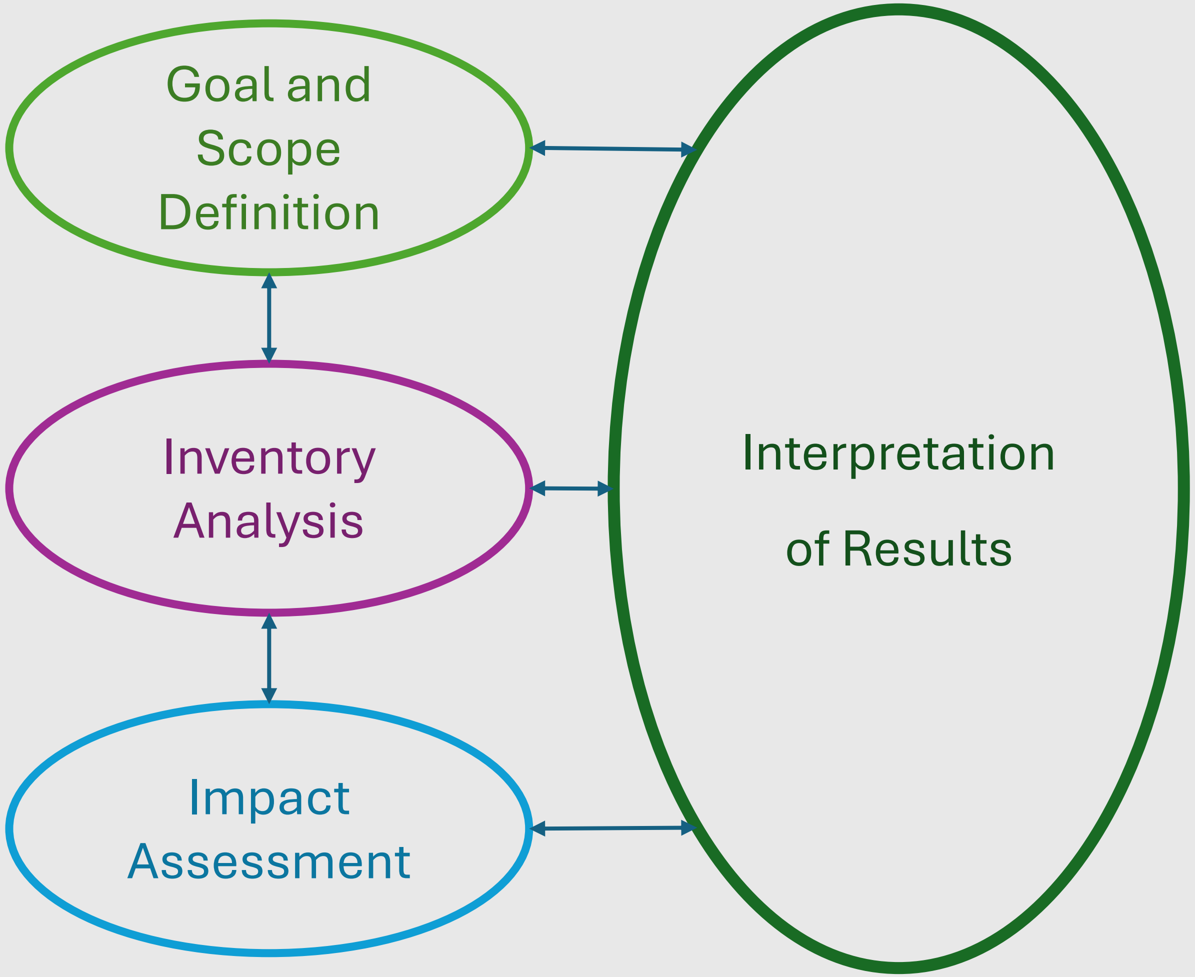

Figure 2. LCA methodology (ISO 14044, 2006)

Key methodological choices:

System boundary

Functional unit

Allocation method

End-of-life

**Preferred approach for multifunctional AV systems: System expansion (ISO 14044)

METHODOLOGICAL CHOICES STRONGLY INFLUENCE LCA OUTCOMES.

RESULTS AND DISCUSSION

- Agrivoltaic System Design Configurations
- Material Requirements and Environmental Implications
  - Structural Steel Requirements
  - Aluminum and Lightweight Structural Solutions
  - Foundation Systems and Land Disturbance
  - Balance-of-System Components and Operational Infrastructure
  - Material Demand as a Design Trade-Off
- Environmental Hotspots Reported in Previous Studies
- Land-Use Efficiency and Environmental Trade-Offs
- Methodological Challenges in Agrivoltaic LCA
  - Functional Unit Selection
  - Allocation Issues
  - System Boundary Definition
- Implications for Sustainable Agrivoltaic Deployment

Agrivoltaic system design configurations

- Agrivoltaics system design
  - Elevated open-field (Overhead crop cultivation)
  - Vertical bifacial (East–west configuration)
  - PV greenhouse (Controlled environment)

AGRIVOLTAIC PERFORMANCE DEPENDS ON SYSTEM CONFIGURATION RATHER THAN INSTALLED PV CAPACITY ALONE.

Weselek et al. (2019); Amaducci et al. (2018); Scognamiglio et al. (2020).

Elevated open-field systems

HIGHER MATERIAL DEMAND
+
REDUCED IRRIGATION DEMAND
+
IMPROVED CROP RESILLIENCE

Characteristics:

- Elevated PV above crops
- Microclimate modification
- Dynamic shading
- Compatible with farm machinery

Environmental Implications:

- Lower evapotranspiration
- Improved soil moisture
- Reduced heat stress
- Steel demand: ~36.23 kg m^{-2}
- Climate impact: +12% vs. conventional PV
- Mineral & metal resource use: +14%

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Barron-Gafford et al. (2019); Busch & Wydra (2022); Krexner et al. (2024)

Vertical bifacial systems

**Reduced structural material demand compared with elevated systems

Characteristics:

- Vertical east–west oriented modules
- Bifacial PV technology
- High field accessibility
- Morning–afternoon electricity generation profile

Environmental Implications:

- Reduced permanent shading
- Improved agricultural accessibility
- More balanced daily electricity generation
- Trade-off between PV density and crop productivity

LOWER LAND USE CONFLICT

+

IMPROVED FIELD ACCESSIBILITY

+

MORNING-AFTERNOON ELECTRICITY GENERATION

Riaz et al. (2021); Katsikogiannis et al. (2022); Busch & Wydra (2022)

Photovoltaic greenhouses

**Balance electricity generation and photosynthetically active radiation (PAR).

Characteristics:

- PV integrated into greenhouse
- Controlled environment
- Crop-specific light management

Environmental Implications:

- Renewable electricity generation
- Reduced cooling demand
- Lower building energy demand
- Higher PV coverage reduces PAR availability
- PV coverage-crop productivity trade-off

RENEWABLE ELECTRICITY
+
CONTROLLED ENVIRONMENT
+
PV COVERAGE PAR TRADE-OFF

Castellano et al. (2008); Touil et al. (2019); Ravishankar et al. (2020)

Material requirements and environmental implications

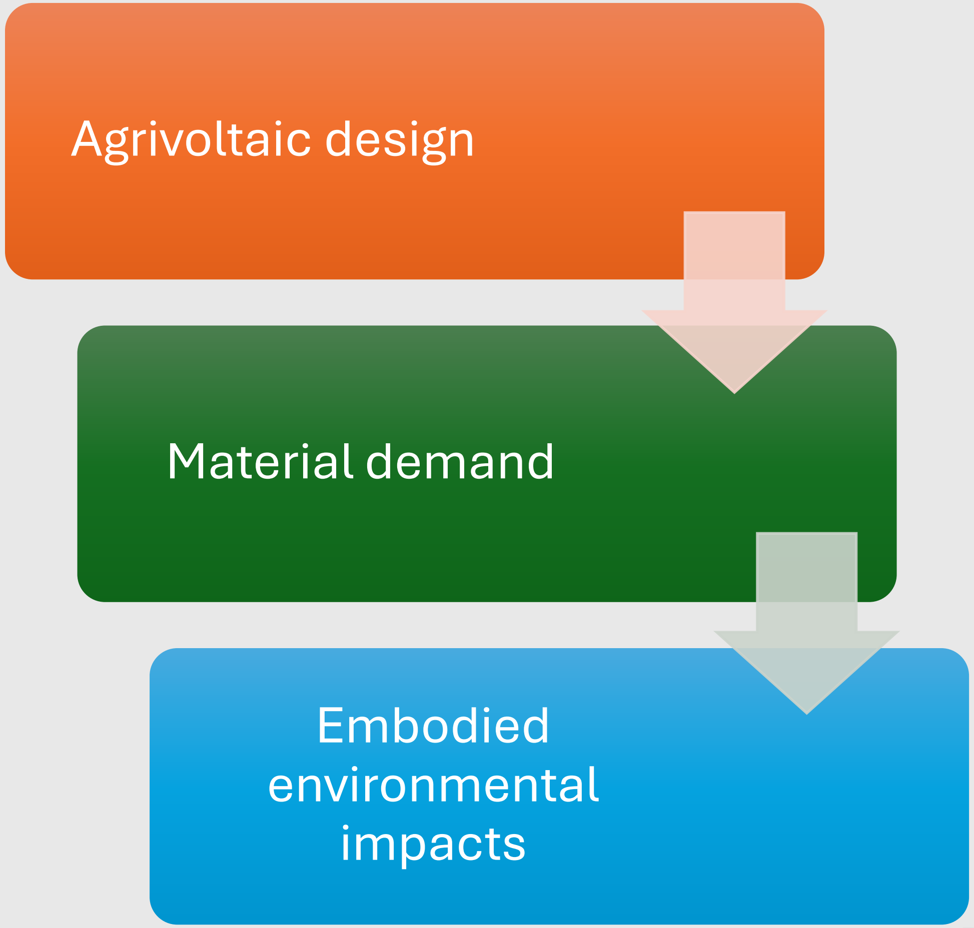

Table 1. Required materials for agrivoltaics and related environmental concerns

Material	**Main environmental concern**
Steel	Climate change, Resource use
Aluminum	Manufacturing energy
Concrete	Embodied carbon
BOS	Resource depletion, Ecotoxicity

MATERIAL DEMAND IS A PRIMARY DRIVER OF LIFE-CYCLE ENVIRONMENTAL IMPACTS.

Busch & Wydra (2022); Krexner et al. (2024); Ravilla et al. (2024)

Structural materials

Table 2. Structural materials of agrivoltaics and main environmental implications

Material	Main Environmental Implications
Structural steel	High embodied carbon, climate change, resource use
Aluminum	High manufacturing energy demand, resource depletion
Concrete foundations	Cement-related GHG emissions, land disturbance
BOS components	Ecotoxicity, resource depletion, replacement impacts

Elevated systems require more structural steel. Vertical systems generally require less structural material.

STRUCTURAL STEEL PRODUCTION IS THE DOMINANT MATERIAL-RELATED CONTRIBUTOR TO LIFE-CYCLE ENVIRONMENTAL IMPACTS IN ELEVATED AGRIVOLTAIC SYSTEMS.

Busch & Wydra (2022); Krexner et al. (2024); Wagner et al. (2023)

FOUNDATION SELECTION AND BOS COMPONENTS SIGNIFICANTLY INFLUENCE EMBODIED CARBON, RESOURCE USE, AND LONG-TERM LIFE-CYCLE IMPACTS.

Foundations and BOS components

Foundations

- Concrete
- Screw anchors
- Piled foundations

**Low-impact foundations reduce embodied carbon and improve land reversibility.

Foundation type	Climate impact
Screw anchors	166 kg CO_2-eq
Driven-profile foundations	32 kg CO_2-eq

BOS Components

- Inverters
- Cables
- Electrical infrastructure
- Monitoring system

**30–50% of total PV infrastructure impacts (resource depletion, ecotoxicity etc)

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Neumüller et al. (2023); Agostini et al. (2021); Ravilla et al. (2024)

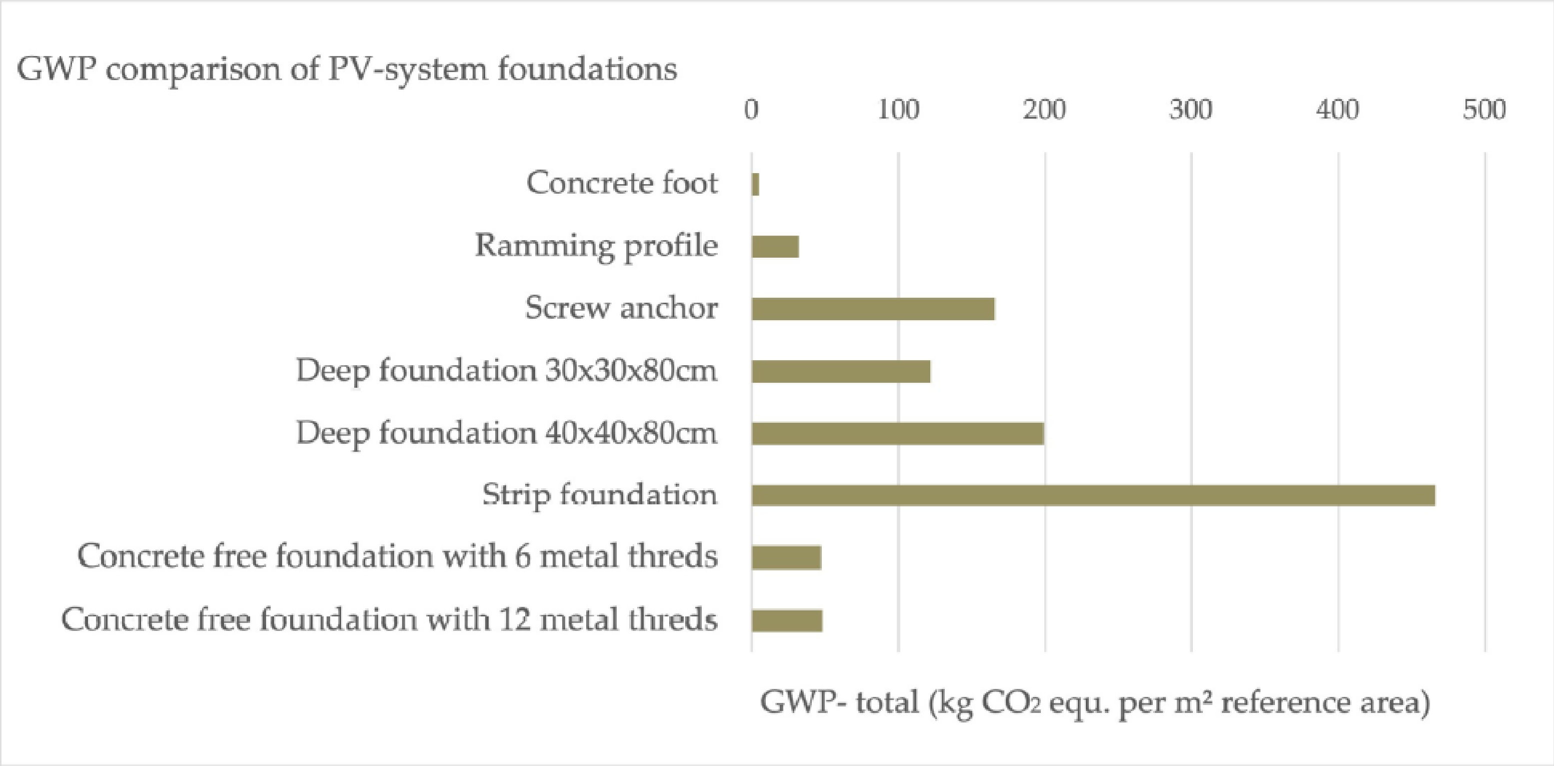


Figure 3. GWP comparison for selected foundations for ground-mounted PV structures. (Neumüller et al., 2023)

Material optimization strategies for sustainable agrivoltaics

Table 3. Possible solutions for material challenges (optimization strategies)

Challenge	**Possible Solution**
High steel demand	Optimized structural design
Primary aluminum	Recycled aluminum
High-impact concrete foundations	Low-impact foundations (screw anchors / driven piles)
BOS replacement	Longer-life components

Higher material demand ⟷ Higher land use efficiency ⟷ Agricultural functionality

MATERIAL OPTIMIZATION IS A KEY STRATEGY FOR REDUCING EMBODIED ENVIRONMENTAL IMPACTS.

ENVIRONMENTAL ASSESSMENT SHOULD CONSIDER MATERIAL EFFICIENCY, LAND-USE EFFICIENCY AND AGRICULTURAL FUNCTIONALITY SIMULTANEOUSLY.

Agostini et al. (2021); Neumüller et al. (2023); Busch & Wydra (2022)

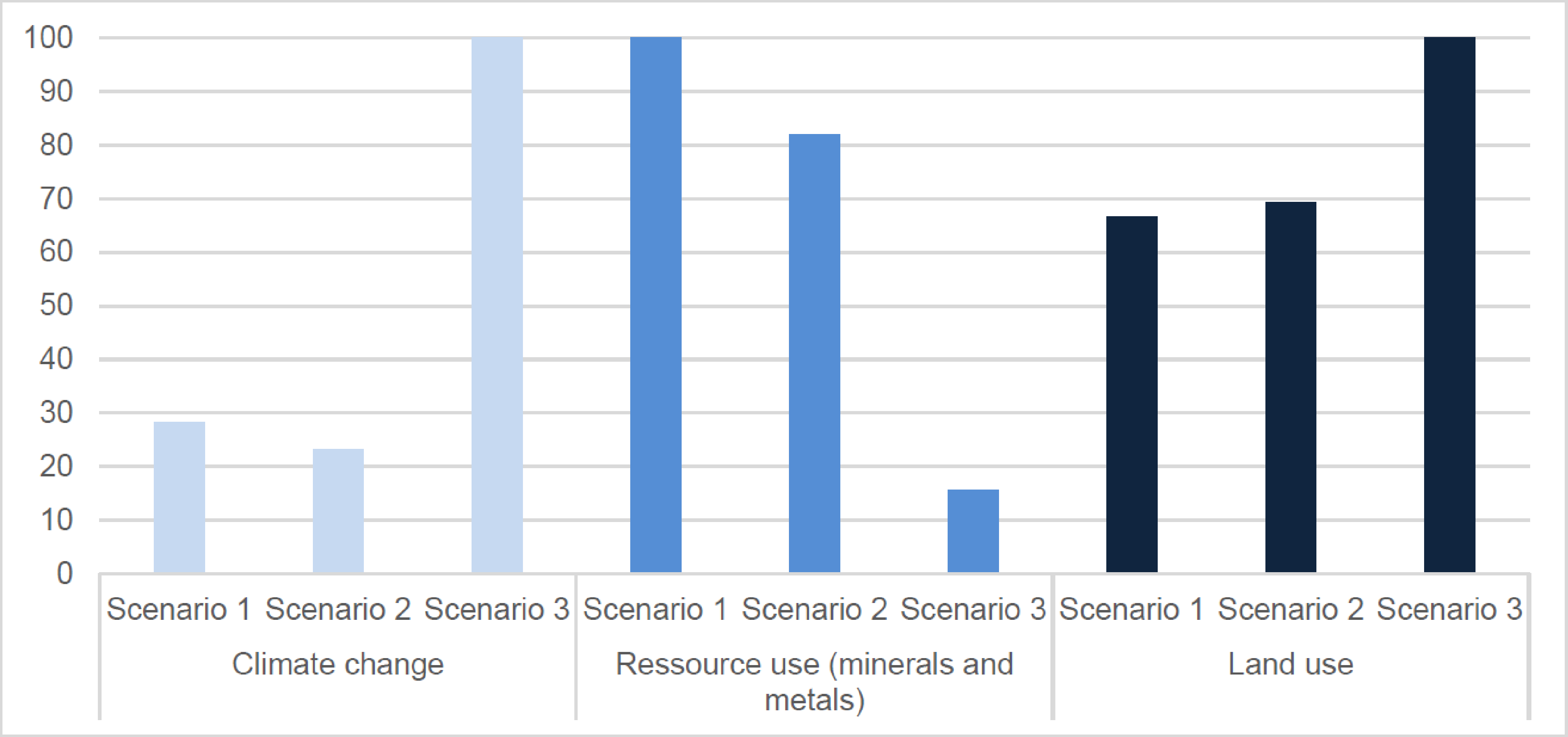
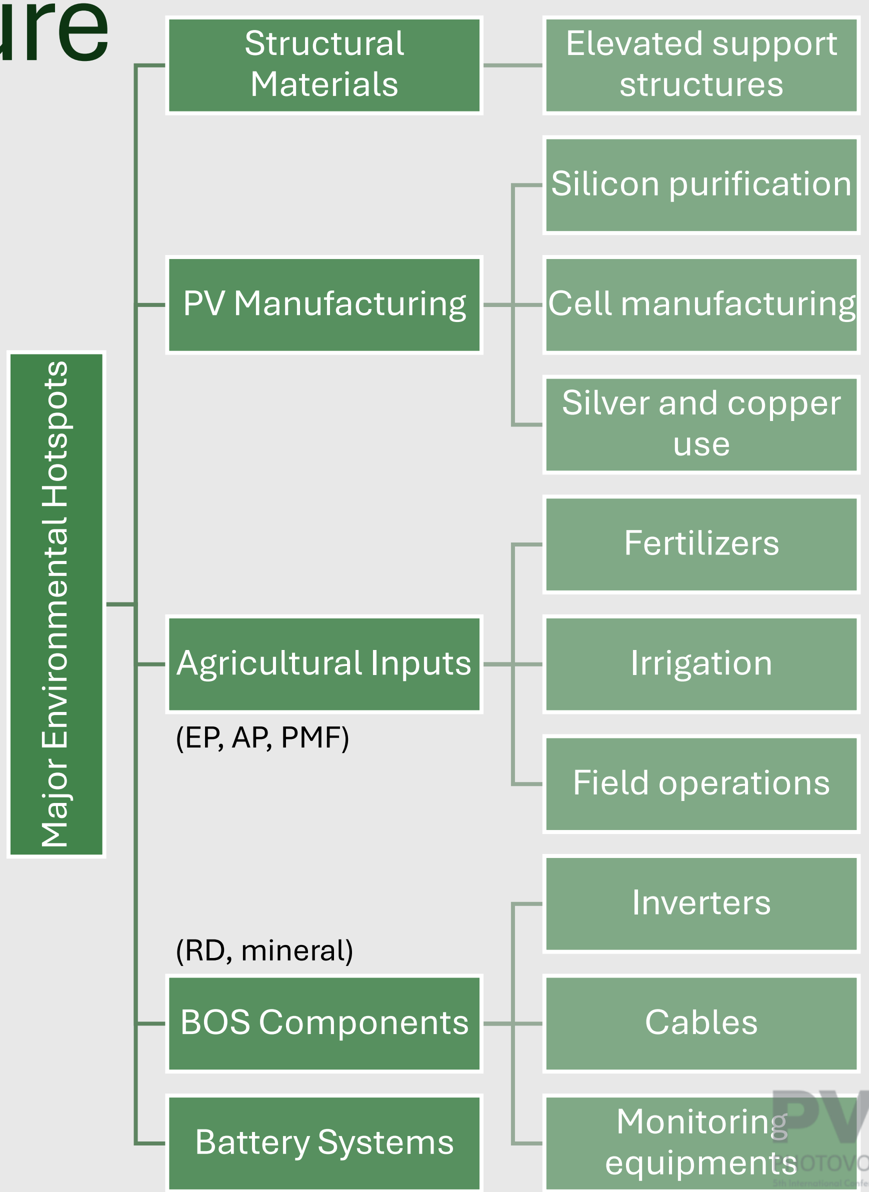


Figure 4 Ratio of the environmental impacts of scenarios 1, 2 and 3 for the selected impact categories climate change, resource use (minerals and metals) and land use in %. (Busch and Wydra, 2022)

Major environmental hotspots identified in literature



ENVIRONMENTAL HOTSPOTS EXTEND BEYOND PV MODULES AND ARE STRONGLY INFLUENCED BY STRUCTURAL DESIGN CHOICES.

Krexner et al. (2024); Ravilla et al. (2024); Cusenza et al. (2026)

Land use efficiency in agrivoltaics

Land Equivalent Ratio (LER):
****LER > 1 indicates that agrivoltaic systems use land more efficiently than separate food and electricity production.**

LER REFLECTS LAND-USE EFFICIENCY BUT SHOULD BE INTERPRETED TOGETHER WITH LIFE-CYCLE ENVIRONMENTAL IMPACTS.
HIGH LER DOES NOT NECESSARILY IMPLY LOW ENVIRONMENTAL IMPACTS.

Table 4. Reported LER values in literature

Study	Reported LER
Typical AV systems	1.2–1.8
Italy	1.46
Heggelbach (Germany)	1.60–1.86

Agostini et al. (2021); Ravilla et al. (2024); Krexner et al. (2024)

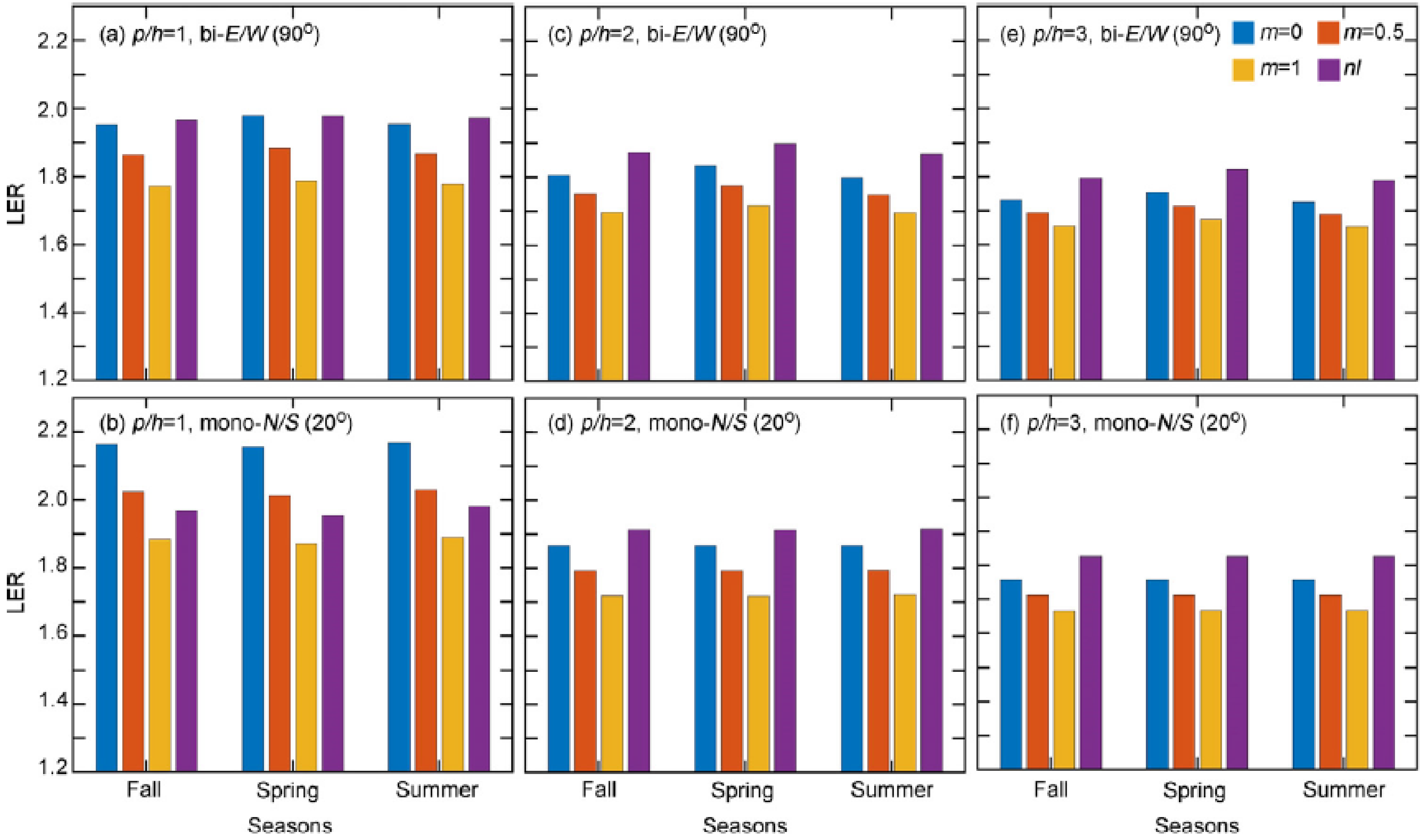
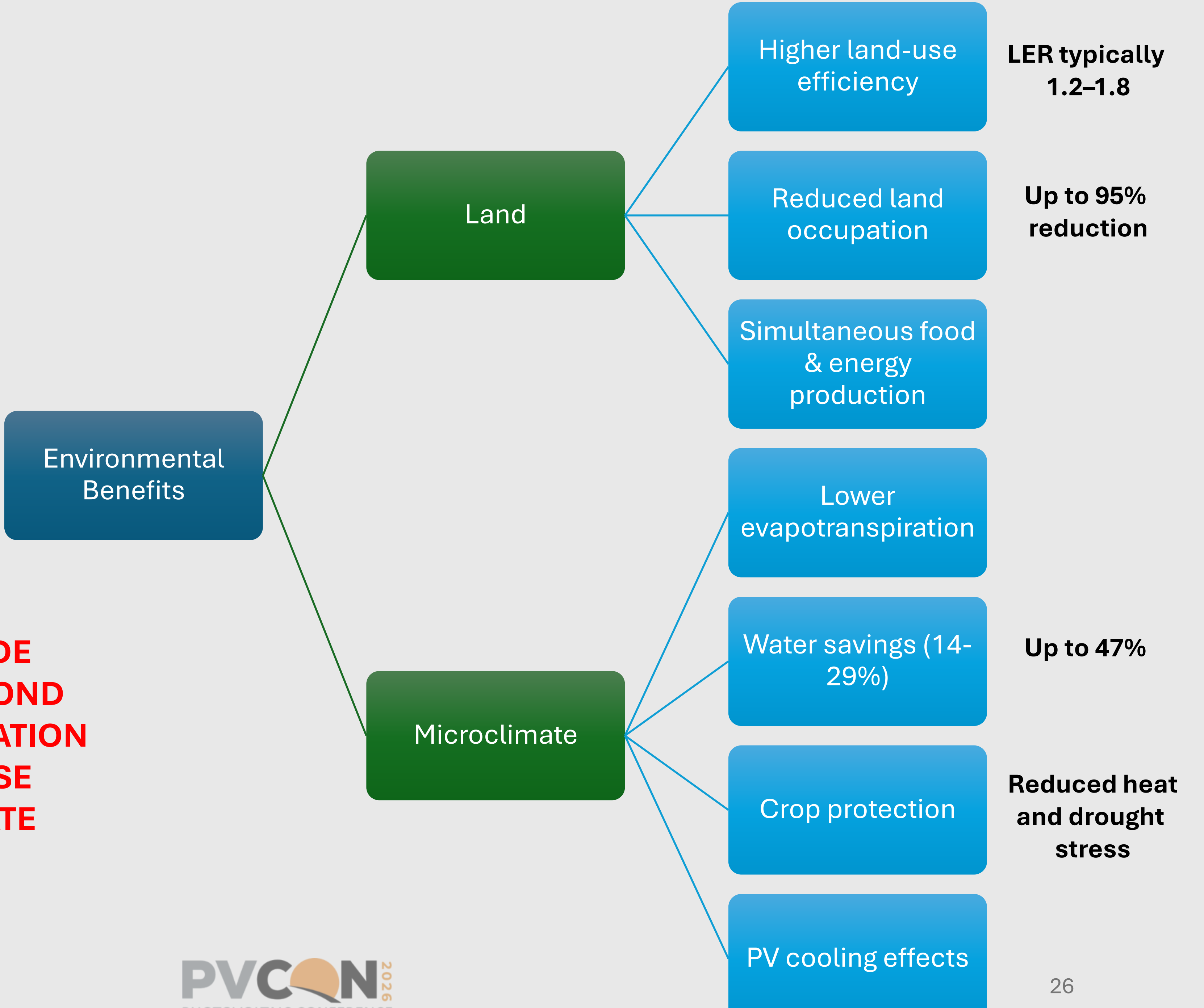


Figure 5. LER for the AV farm for varying shade-tolerance levels for crops for both bi-E/W and mono-N/S PV farms at different values of p/h. (Riaz et al., 2021)



AGRIVOLTAIC SYSTEMS PROVIDE ENVIRONMENTAL BENEFITS BEYOND RENEWABLE ELECTRICITY GENERATION THROUGH IMPROVED LAND-USE EFFICIENCY AND MICROCLIMATE REGULATION..

Agostini et al. (2021); Krexner et al. (2024); Ravilla et al. (2024)

Design trade-offs in agrivoltaic systems

Table 5. Design parameters and their implications for environmental performance in agrivoltaic systems.

Design Parameter	Climate Change (GWP)	Resource Use (Metal/Mineral Demand)	Water Use & Microclimate	Land-Use Efficiency (LER)
Increased Mounting Height	↑	↑	↓	↑
Dynamic Tracking Systems	↑	↑	↔ / ↓*	↑
Vertical Bifacial Systems (VB-APV)	↓	↓	↔ / ↓**	↑
Wider Row Spacing	↑ / ↓***	↓	↑	↑
Foundation Design (Concrete vs. Screw Anchors/Piles)	↑ (Concrete)	↑ (Concrete)	↔	↓****
Tensile Structures	↓↓	↓↓	↔	↑
Bifacial Modules	↓ (per kWh)	↔	↔	↑
Semi-Transparent OPV Modules	↓	↓	↑	↑
Battery Integration	↑	↑↑	↔	↔

Busch & Wydra (2022); Agostini et al. (2021); Neumüller et al. (2023); Krexner et al. (2024); Wagner et al. (2023)

Methodological challenges: Functional unit selection

Table 6. Possible functional unit selection of agrivoltaics for LCA and main focuses

Functional Unit	Focus
1 kWh electricity	Electricity generation
1 kg crop	Agricultural production
1 ha land	Land-use efficiency
Integrated functional unit	Combined food and electricity production
Economic functional unit	Economic performance

NO UNIVERSALLY ACCEPTED FUNCTIONAL UNIT CURRENTLY EXISTS FOR AGRIVOLTAIC LCA; THE CHOICE SHOULD REFLECT THE MULTIFUNCTIONAL NATURE OF THE SYSTEM.

Leon & Ishihara (2018); Krexner et al. (2024); Sponagel et al. (2024)

Methodological challenges: Allocation and system boundary

Allocation

- System expansion (preferred by ISO 14044 whenever feasible.)
- Economic allocation
- Energy-based allocation

**ISO 14044 recommends avoiding allocation where possible; if it cannot be avoided, system expansion is the preferred approach.

**Different allocation methods produce different environmental results

System Boundary

- Cradle-to-farm-gate
- Cradle-to-grave
- End-of-life modelling (inclusion/exclusion)

**Different boundaries produce different impact estimates

METHODOLOGICAL CONSISTENCY IN ALLOCATION AND SYSTEM BOUNDARY SELECTION IS ESSENTIAL FOR COMPARING AV-LCA STUDIES.

ISO 14044; Krexner et al. (2024); Wagner et al. (2023)

Table 7. Comparison of agrivoltaic LCA studies with respect to system configuration, methodological choices, and environmental hotspots.

Study	AV Type	Functional Unit (FU)	Allocation Approach	System Boundary	Main Environmental Hotspot
Leon & Ishihara (2018a,b)	PV greenhouse	1 kg tomato; modified land area (m^2); economic value	System expansion, economic allocation, solar allocation	Cradle-to-farm-gate	Yield-loss sensitivity and allocation-dependent environmental outcomes
Hollingsworth et al. (2020)	Greenhouse-integrated AV (SPRING)	1 kg tomato	Not specified	Cradle-to-farm-gate	Greenhouse heating demand and greenhouse construction materials
Agostini et al. (2021)	Overhead tensile agrivoltaic system	1 MJ electricity delivered to the grid	No allocation (PV-focused assessment)	25-year operational lifetime	Support structures (steel/aluminum) and PV modules
Pascaris et al. (2021)	Pasture-based agrivoltaics	Total MWh electricity + total kg meat	System expansion	Cradle-to-farm-gate	Feed production and manure-related burdens in reference systems
Busch & Wydra (2022/2024)	Elevated (stilted) agrivoltaic system	Electricity production and potato yield	System expansion	Cradle-to-farm-gate	Structural steel demand, module production, and fertilizer-related emissions
Wagner et al. (2023)	Fixed overhead agrivoltaic system	Agricultural products/feed + electricity	Consequential LCA with system expansion	Extended system boundary including indirect consequences	PV infrastructure and BOS components
Ravilla et al. (2024)	Static and tracking agrivoltaic systems	Life-cycle income per hectare ($\$ ha^{-1}$)	Functional equivalence approach	Cradle-to-end-of-use	Electricity-generation infrastructure, structural BOS, modules, and inverters
Krexner et al. (2024)	Stilted (S-APV) and vertical bifacial (VB-APV) systems	Integrated FU: 1 kWh electricity + crop basket	System expansion	Cradle-to-farm-gate	China-based module production and steel-intensive elevated structures
Sponagel et al. (2024)	Vertical bifacial and 2P-tracking systems	1 kWh electricity	Not specified	Full life cycle (ISO-based)	PV module production (>85% of total impacts)
Cusenza et al. (2026)	Overhead agrivoltaic system with bi-axial tracking	1 kWh AC electricity	System expansion	Cradle-to-grave	Steel-intensive tracking structures and yield reductions associated with shading

Implications for sustainable agrivoltaic development

Key implications:

- Integrate LCA at the design stage
- Optimize structural material use
- Balance food and energy production
- Consider multiple environmental impact categories

LCA SHOULD SUPPORT DESIGN DECISIONS BEFORE CONSTRUCTION RATHER THAN MERELY EVALUATING COMPLETED SYSTEMS.

Key recommendations for sustainable agrivoltaic development

Table 8. Recommendations for sustainable agrivoltaic development with expected benefits

Recommendation	Expected benefit
Integrate LCA in early design	Better environmental decision making
Optimize structural materials	Lower embodied environmental impacts
Consider circular design	Improved resource efficiency
Balance LER and material demand	More sustainable AV systems
Adopt harmonized LCA methodology	Improved comparability across studies

Recommended methodological framework:
- **ISO 14040/14044**
- **Product Environmental Footprint (PEF)**
- **IEA PVPS Task 12**

SUSTAINABLE AGRIVOLTAIC DEVELOPMENT REQUIRES BALANCING ENVIRONMENTAL PERFORMANCE, LAND-USE EFFICIENCY, AGRICULTURAL FUNCTIONALITY, AND SOUND LCA METHODOLOGY.

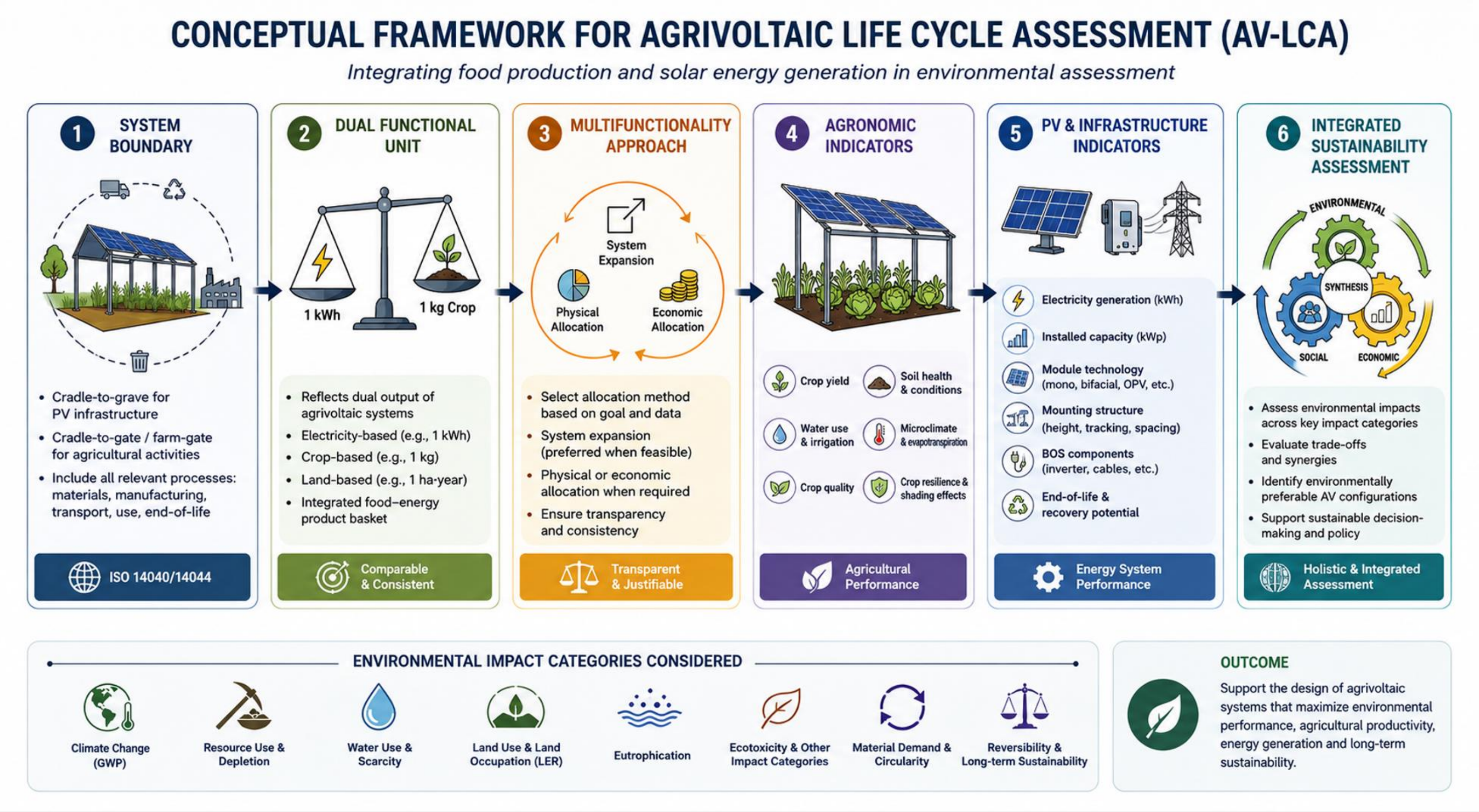
ISO 14040/14044; Product Environmental Footprint (PEF); IEA PVPS Task 12

CONCLUSIONS AND FUTURE OUTLOOK

- Agrivoltaics improves land-use efficiency.
  - Typical LER: 1.2–1.8
- Environmental hotspots are mainly associated with:
  - Structural steel (≈36.23 kg m^{-2})
  - PV module manufacturing
  - Foundation systems (+12% GWP; +14% mineral & metal resource use)
- Design choices strongly influence environmental performance.
  - Elevated vs. vertical bifacial systems
  - Material-efficient support structures
  - Low impact foundations
- Methodological harmonization is needed.
  - Functional unit
  - Allocation
  - System boundary

SUSTAINABLE AGRIVOLTAIC SYSTEMS REQUIRE BALANCING LAND-USE EFFICIENCY, ENVIRONMENTAL PERFORMANCE, AND METHODOLOGICAL CONSISTENCY.

CONCLUSIONS AND FUTURE OUTLOOK



Design matters.
Materials matter.
Methodology matters.
Integrated AV-LCA enables sustainable agrivoltaic development.

Figure 6. Conceptual framework developed in this study to guide the life cycle assessment of agrivoltaic systems.

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