

## REVIEW OF SENSOR TECHNOLOGIES FOR MONITORING AGRIVOLTAIC SYSTEMS

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**ABSTRACT:** Agrivoltaics (AgriPV) co-locates photovoltaic generation with crops, coupling microclimate, plant physiology and power conversion. This paper assembles an empirical baseline of current monitoring practice via a systematic review of 123 experimental studies (2014–2024). It presents what is measured across meteorological, energy-performance and agricultural domains, how measurements are acquired (manual, automated, hybrid), and how research themes co-occur. The literature shows a higher volume of papers addressing agronomic/environmental effects, frequently studied alongside system integration/design and energy performance. Meteorological sensing is most prevalent (102 papers), followed by energy-performance (53) and agricultural variables (41). Acquisition is predominantly hybrid: 65.0% combine automated logging (weather/power) with targeted plant measurements; 21.1% are automated-only; 13.8% manual-only. Documentation gaps cluster in operational metadata, such as maintenance/durability, power supply/autonomy, data transmission and calibration/accuracy. Where PAR/PPFD is explicitly measured or robustly derived and co-reported with module temperature and inverter telemetry on a shared time base, studies can trace causal chains from forcing to conversion and crop response, enabling quantitative, design-relevant comparisons. By consolidating what AgriPV studies actually measure and pinpointing concise, high-impact co-measurements and reporting items (timekeeping, calibration, placement, power/telemetry), this review provides the practical foundation for portable, cross-site synthesis and supports emerging data-driven analysis and control in AgriPV.

Keywords: agrivoltaics, sensors, monitoring, microclimate, soil

### 1 INTRODUCTION

The rapid expansion of photovoltaic (PV) capacity is intensifying pressure on land, particularly where food production and energy security are both strategic priorities. Agrivoltaics (AgriPV), which is the co-location of PV generation and crop cultivation, offers a path to dual productivity per unit area and has been repeatedly proposed as a land-sharing solution with agronomic and energetic co-benefits [1], [2]. By altering the radiation field, wind exposure, and surface energy balance, AgriPV structures can moderate heat and water stress and create distinctive microclimates that influence canopy function and soil–plant water fluxes. Evidence spans greenhouse and open-field contexts: spatial photosynthetic photon flux density (PPFD) mapping under PV roofs quantifies light gradients that guide planting geometry and crop placement [3], while instrumented open-field pilots couple plane-of-array or global irradiance, air temperature/humidity and power telemetry to link microclimate with energy conversion in situ [4]. Crop responses are system and species dependent. Multi-crop field studies document both neutral and beneficial outcomes for shade-tolerant vegetables under moderate coverage and more stringent thresholds for cereals [5].

The measurement challenge is therefore central to AgriPV research and practice. Physiological monitoring in perennial systems has demonstrated how shading alters leaf temperature and gas exchange, reinforcing the need to synchronize plant with meteorological data [6]. Sensor-rich tomato deployments show how coordinated monitoring of atmosphere, soil and canopy enables mechanistic interpretation of yield and quality outcomes [7]. Beyond agronomy, optical and spectral design choices can produce hydrological co-benefits, plot-scale experiments report measurable reductions in surface evaporation under tailored PV/glazing configurations [8]. At the water–energy–food nexus, integrated pilots highlight how harmonized data collection supports operational control and policy-relevant assessment [9].

In this work we assemble and organize the experimental AgriPV literature into an empirical baseline of current monitoring practice, mapping which variables are measured across meteorological, energy-performance and agricultural domains, how they are acquired and documented, and highlighting concise, high-impact reporting items and co-measurements that make studies portable across crops, layouts and climates enabling for researchers and practitioners to move from isolated case studies to reproducible, design-relevant synthesis and, in turn, to more credible evidence for AgriPV deployment and management.

### 2 METHODOLOGY

This study follows a systematic review protocol tailored to experimental AgriPV research. The objective was to map how sensors are used to monitor meteorological conditions, agricultural variables, and energy-performance metrics in AgriPV deployments, and to assess the degree of automation, time synchronization, and reporting completeness.

#### 2.1 Literature selection

Scientific papers were extracted from Scopus, Google Scholar, and IEEE Xplore using keyword combinations such as “agrivoltaics”, “monitoring”, “sensors”, “soil”, “IoT”, “case study” and “pilot” published from 2014 to 2024. Only peer-reviewed conference and journal papers published in English and explicitly describing AgriPV systems with identifiable sensor-based monitoring were considered. Purely simulation-based or review papers, and studies lacking experimental data were excluded. Records were deduplicated, screened by title/abstract, and full texts assessed for eligibility. 123 studies met the criteria and were retained for analysis.

## 2.2 Data extraction and classification

Studies were systematically examined using a structured data extraction protocol. For each publication, metadata and descriptive information when available were compiled into a database, including research questions addressed, system characteristics, deployment scale, sensor categories, automation and control mechanisms, sensor accuracy and calibration methods, IoT and machine learning use, sensor power supply details, data collection and transmission details, frequency and duration of data collection, as well as maintenance and durability aspects of the monitoring system.

Monitoring variables were systematically classified into three key categories: meteorological, energy performance, and agricultural monitoring. Particular care was taken to distinguish between fully automated sensor-based monitoring and manual field data collection, with the latter categorized separately to maintain consistency. Information was only included when explicitly mentioned in the source document.

Each paper was tagged against six research questions: RQ1—meteorological impacts on PV shading; RQ2—energy generation performance; RQ3—AgriPV impacts on environment or agriculture; RQ4—the roles of digital and automated technologies (IoT/control/ML); RQ5—economic and policy considerations; RQ6—system integration and design strategies. Papers could map to multiple RQs.

Given the heterogeneity of systems and metrics, this classification methodology was designed to allow for cross-study comparison and to highlight both the technological heterogeneity and reporting gaps in AgriPV monitoring research.

## 3 RESULTS AND DISCUSSION

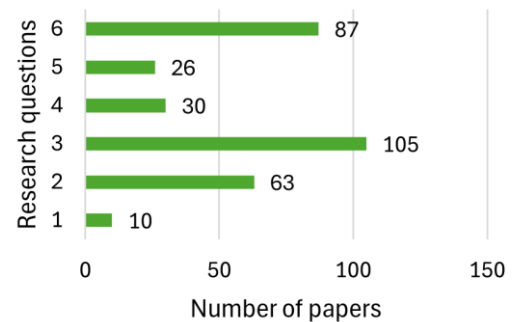
The systematic literature review analyzed 123 peer-reviewed studies on AgriPV, with a specific focus on monitoring systems.

### 3.1 Thematic focus of AgriPV Studies

The reviewed AgriPV studies span a broad range of research objectives. As shown in Fig. 1, RQ3 (the impacts of AgriPV on the environment and agriculture) appears in 105 papers, followed by 87 for RQ6 (system integration/design) and 63 for RQ2 (energy performance), while RQ1 (impacts of meteorological factors on PV), RQ4 (digital/automation) and RQ5 (economics/policy) are comparatively less represented. Studies frequently straddle multiple RQs (Fig. 2): the most common pairing is RQ3 + RQ6 (31 papers), reflecting the tight coupling between crop outcomes and design/layout choices, and a substantial number of RQ2 + RQ3 + RQ6 (17 papers) mirrors the need to evaluate energy yield, agronomy and geometry together.

The emphasis on RQ3 is evident in field and greenhouse experiments that quantify how partial shading modulates microclimate and plant function, often linking soil moisture dynamics, gas exchange and biomass or quality metrics. Rice studies explore yield responses across coverage regimes and altered light fields,

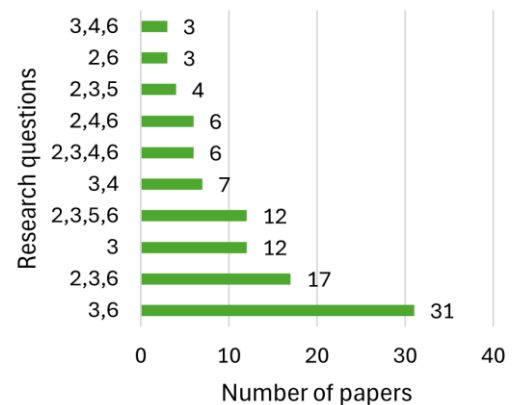
highlighting threshold behavior and the need for crop-specific photosynthetically active radiation (PAR) targets [10]. In greenhouses, tomato experiments track microclimate and plant performance under PV roofing, demonstrating how localized radiation and humidity patterns translate into physiology and quality traits [11]. These investigations place measurement at the center of interpretation: without time-synchronized meteorological and plant data, it is difficult to distinguish beneficial microclimate control from unintended stress.



**Figure 1:** Number of papers addressing each research question.

Under RQ6, researchers increasingly treat layout as a control knob. Algorithmic approaches for semi-transparent or patterned PV optimize shading geometry and spectral transmission to stabilize plant light regimes through the season, connecting optical design with agronomic targets [12]. This design lens extends into open fields, where geometry (row spacing, tilt, vertical vs tilted) is treated as part of an agronomic–energetic trade-off, with instrumentation used to capture wind shelter, shade dynamics and their implications for both plants and power (the latter often appearing under RQ2) [13].

Energy performance (RQ2) in AgriPV is typically assessed through inverter telemetry coupled with module temperature and irradiance proxies, either in situ or inferred for the plane-of-array. Studies that co-report agricultural outputs and AC generation are particularly informative because they expose the simultaneity of benefits and trade-offs—e.g., rice–PV configurations that quantify electricity production alongside yield stability under different layouts [14].



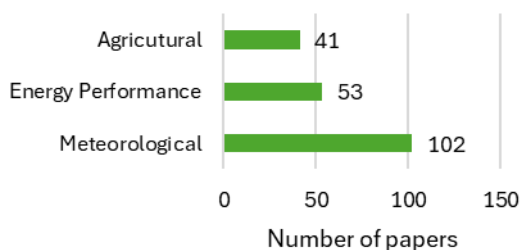
**Figure 2:** Most frequent combinations of research questions addressed in individual papers.

Digital and automated technologies (RQ4) are emerging. IoT-based fertigation platforms demonstrate how soil-moisture-driven control loops and low-power telemetry can stabilize water status while creating reproducible data streams for agronomic analysis, but such implementations remain the exception rather than the rule [15]. Finally, RQ5 (economics/policy) appears in techno-economic assessments that relate module transparency/coverage and crop response to leveled metrics and payback, providing a first link between sensor-evidenced agronomy and investment logic [16].

Taken together, the pattern in Fig. 1–2 suggests a maturing field that already recognizes the need to co-measure energy, environment and crop physiology.

### 3.2 Categories of sensors

Across literature, meteorological monitoring dominates (Fig. 3) with 102 studies reporting meteorological variables, typically global or plane-of-array irradiance and PAR/PPFD, air temperature and humidity, wind and precipitation. Open-field pilots that log plane-of-array irradiance alongside air temperature and humidity provide the basic scaffold for linking microclimate to agronomy and power, typically with dataloggers appropriate for long-term deployments [4]. Where geometry itself is the treatment, multi-station layouts capture gradients in wind, radiation components and PAR across vertical versus tilted arrays, enabling design-level inference [13].



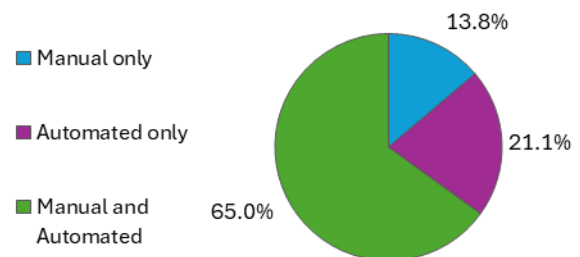
**Figure 3:** Number of papers with automated sensors by monitoring category.

Energy-performance sensing appears in 53 papers and most often comprises inverter telemetry coupled with back-of-module temperature, with occasional string-level current/voltage or I–V traces for detailed diagnostics. Greenhouse-integrated studies often access AC output through manufacturer platforms, which are helpful for continuity even when internal climate is sparsely documented [17]. Studies that time-align the electrical stream with radiation and temperature offer clearer attribution of transient behavior (e.g., cloud-edge events), a practice increasingly visible in geometry-comparison pilots that record power at short intervals [13] and in field trials where PV–crop co-location is evaluated with concurrent weather logging [4].

Papers using automated agricultural sensors are the fewest in number (41 papers) yet they ultimately validate AgriPV’s agronomic value. The most common variables are soil moisture and temperature at depth, soil pH/EC/NPK, and leaf or canopy indicators such as chlorophyll indices or NDVI. Where physiological mechanisms matter, campaigns with portable gas-exchange (e.g., LI-6400) are used to connect microclimate to photosynthesis and stomatal control, generally layered

onto the automated weather baseline [7]. Chlorophyll-a fluorescence is also applied to track photo-physiological status in crop-specific contexts (e.g., tomatoes or cereals), tying light regime and plant performance to yield and quality outcomes [11], [14]. Greenhouse and semi-transparent configurations, in particular, show how spectral control reshapes plant light budgets and physiology, underscoring the need to report sensor placement and heights relative to canopy [11], [18].

Acquisition modes mirror field reality (Fig. 4): 65.0% of studies combine manual and automated measurements, 21.1% are automated-only, and 13.8% remain manual-only. This hybrid pattern works provided two basics are met: time-synchronization across streams and explicit metadata on sensor siting (heights, within vs inter-row, above/below canopy). Where calibration or accuracy is reported (particularly for PAR/PPFD or soil moisture) comparability improves substantially. Recent IoT-enabled systems document calibration steps, telemetry, and low-power autonomy, illustrating a reproducible template for field deployments [15].



**Figure 4:** Percentage of papers by acquisition method.

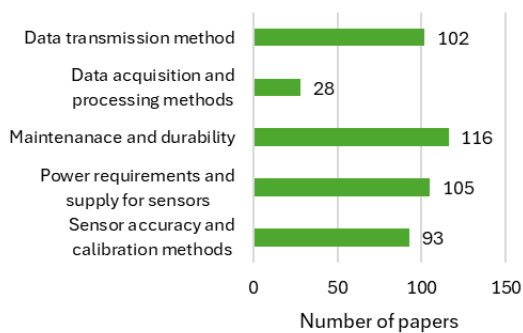
Taken together, Fig. 3–4 indicate a field that already measures the dominant forcing (meteorology) and the electrical conversion stream, but still under-instruments continuous plant-side responses and under-reports the metadata that make results transferable.

### 3.3 Data acquisition practices

Fig. 5 reports gaps (number of papers lacking each item) across the 123 studies. The largest omissions are maintenance/durability (missing in 116 papers) and power supply/autonomy (105), followed by data-transmission method (102) and sensor accuracy/calibration (93). By contrast, only 28 papers fail to describe data-acquisition/processing, indicating that most studies now state sampling and basic processing, whereas operational metadata remain under-reported.

These omissions matter for reproducibility: without maintenance logs or power/telemetry descriptions, drift, dropouts and soiling effects are hard to interpret. Positive exemplars show what helps: explicit soiling/cleaning records alongside short-interval power and microclimate logging in geometry trials [13]; clear PAR to PPFD conversion and calibration notes where the photosynthetic light environment is central [19]; and concise statements of logger cadence and channels in pilot deployments [4]. Where telemetry is used, a one-line “how data leave the field” (e.g., LoRaWAN to cloud or inverter portal) plus time-synchronization notes makes datasets portable and auditable [15]. In short, most studies already state how they sampled, what is still missing, and most useful to add, are the operational details (power, transmission,

calibration, maintenance), that make AgriPV monitoring comparable across sites and seasons.



**Figure 5:** Number of papers missing information on key aspects of data acquisition.

#### 4 CONCLUSIONS

This review of 123 experimental AgriPV studies shows a field converging on an integrated treatment of crops, climate and power. Most studies prioritize agronomic effects while layout and energy performance are co-determinants, and the prevailing hybrid acquisition model (continuous logging of weather and electrical variables complemented by targeted plant measurements) now enables causal chains from forcing to conversion and crop response to be traced with increasing confidence. Where photosynthetic light is explicitly resolved through PAR/PPFD sensing or robust irradiance-to-PPFD conversions, crop outcomes are interpretable in terms of the light budget rather than generic “shade,” and geometry can be evaluated as a control parameter in its own right, from vertical/tilted rows in open fields to spectral tailoring in protected cultivation [3], [13], [19]. The literature also reveals that operational details such as timekeeping, calibration/uncertainty, placement relative to canopy and rows, and simple notes on power/telemetry and maintenance, remain the information most likely to be omitted, yet they are precisely the details that make results portable across sites and seasons.

Consolidating the evidence across studies, three elements of current practice consistently underpin credible AgriPV inference. First, co-reporting PAR/PPFD, inverter telemetry and module temperature on a shared time base provides a direct bridge from light environment to electrical conversion and plant response. When this triad is present, attribution improves, and design comparisons become quantitatively defensible. Second, pairing microclimate with soil-water information (at minimum, soil moisture at two or more depths and simple irrigation volumes) connects radiation and wind to water status and yield, enabling the interpretation of crop outcomes beyond instantaneous weather. Third, when layouts are the experimental treatment, multi-station measurements that resolve spatial gradients in wind and illumination across rows or panel orientations capture the heterogeneity that drives both physiology and power.

To make results truly portable, the most effective step is not more instrumentation but concise, high-impact documentation that standardizes what studies already do. At minimum, papers should specify logger clocks and time zones, sampling and aggregation intervals for each stream,

sensor models and stated accuracies, exact placement relative to canopy height, row position and panel geometry, and one-line statements on power supply, telemetry and cleaning/maintenance. Providing these items in a machine-readable appendix with consistent variable names and SI units allows cross-site synthesis without reinterpretation. With such documentation and the co-measurement choices outlined above, the community can progress from coverage counts to transferable response functions that inform positioning, geometry and optical choices by crop and climate, and assess when simple automation (e.g., moisture-triggered fertigation) delivers operational benefit.

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