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Advances in Electrical Engineering for Sustainable Smart Agriculture: A Comprehensive Review

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Abstract. The global agricultural sector faces mounting pressure to increase productivity while reducing its environmental footprint, water consumption, and dependence on fossil fuels. Electrical engineering has emerged as a central enabler of this transition, providing the power-generation, sensing, communication, control, and automation technologies that underpin modern smart agriculture. This review situates the convergence of electrical engineering and agriculture within the broader context of climate change, freshwater scarcity, and the need to feed a growing global population sustainably. A structured narrative review of 30 peer-reviewed journal articles, conference papers, and technical reports published between 2008 and 2026 was conducted, drawn from IEEE Xplore, ScienceDirect, MDPI, Springer, and related databases, and organized around five thematic clusters: renewable power supply, sensing and communication infrastructure, machinery electrification, aerial robotics, and artificial intelligence integration. The reviewed literature shows that photovoltaic water pumping and agrivoltaic systems can reduce irrigation energy costs and diversify farm income while maintaining acceptable crop yields; energy-harvesting wireless sensor networks and low-power wide-area communication protocols extend the operational lifetime of field monitoring systems; battery-electric tractors and implements lower operating emissions but remain constrained by battery energy density and charging infrastructure; and unmanned aerial vehicles combined with machine learning substantially improve the precision of input application and crop monitoring. Electrical engineering innovations are collectively reshaping agriculture into a data-driven, energy-efficient, and more resilient sector, though widespread adoption still depends on cost reduction, interoperability standards, rural electrification, and farmer training.

Keywords: *Smart Agriculture; Renewable Energy; Photovoltaic Irrigation; Agrivoltaics; Wireless Sensor Networks*

1. Introduction

Agriculture stands at the intersection of two of the twenty-first century's most pressing challenges: ensuring food security for a global population projected to approach nine billion by mid-century, and doing so within the constraints of a changing climate and finite energy and water resources (Food and Agriculture Organization, 2017). Conventional farming practices, which rely heavily on diesel-powered pumps and machinery, manual field scouting, and generalized rather than site-specific input application, are increasingly recognized as inefficient and environmentally costly. Electrical engineering, spanning power systems, power electronics, control theory, sensors, and communications, offers a coherent toolkit for addressing these inefficiencies through what has become known as smart agriculture or agriculture 4.0.

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The transformation of agriculture through electrical and electronic technology is not a single innovation but a convergence of several parallel developments. On the power-supply side, falling costs of photovoltaic modules have made solar-powered irrigation pumps and agrivoltaic installations, structures that generate electricity and grow crops on the same land, increasingly attractive alternatives to grid or diesel power (Chandel et al., 2015; Zahrawi & Aly, 2024). On the sensing and communication side, wireless sensor networks equipped with energy-harvesting circuits and low-power wide-area communication protocols now allow continuous, low-maintenance monitoring of soil moisture, microclimate, and crop status across large field areas (Jawad et al., 2017; Raza et al., 2017). On the machinery side, the electrification of tractors and implements is beginning to displace internal combustion drivetrains, promising quieter, lower-emission, and more precisely controllable field operations (Varani et al., 2025). Finally, unmanned aerial vehicles (UAVs) and artificial intelligence (AI) are enabling a level of spatial and temporal resolution in crop management that was previously unattainable (Del Cerro et al., 2021; Sharma et al., 2021).

Despite the breadth of this literature, syntheses that draw these strands together specifically from an electrical engineering perspective, treating power supply, sensing, machinery, and intelligence as interacting subsystems of a single sustainable agricultural infrastructure, remain relatively scarce. This review therefore aims to (i) summarize the state of the art in electrical engineering technologies applied to sustainable smart agriculture, (ii) identify the technical and economic barriers that continue to limit adoption, and (iii) outline promising directions for future research and development. The remainder of the paper is organized as follows: Section 2 describes the review methodology; Section 3 presents and discusses the findings across five thematic areas; and Section 4 offers concluding remarks.

This research relates relevant abouy electrical engineering technologies to SDG 2 (Zero Hunger) by supporting agricultural productivity, resource efficiency, and sustainable food production. The review also connects these technologies to SDG 7 (Affordable and Clean Energy) through renewable energy, photovoltaic irrigation, energy-efficient systems, and agricultural electrification. Furthermore, their potential to reduce energy consumption, greenhouse-gas emissions, and dependence on fossil fuels is linked to SDG 13 (Climate Action), highlighting their contribution to climate-resilient and sustainable agriculture.

Unlike previous reviews focusing on individual technologies or agricultural applications, this review synthesizes five interconnected electrical engineering domains: renewable power, sensing and communication, machinery electrification, aerial robotics, and artificial intelligence. The review further identifies the cross-cutting technical and practical barriers to integration, including cost, interoperability, energy autonomy, rural infrastructure, and farmer literacy, within a unified framework for sustainable smart agriculture.

2. Methods

This review follows a structured narrative approach rather than a formal systematic review protocol, given the breadth of subtopics involved. Candidate literature was identified through searches of IEEE Xplore, ScienceDirect, SpringerLink, MDPI journals, and Google Scholar, using combinations of the keywords 'smart agriculture,' 'precision agriculture,' 'solar irrigation,' 'agrivoltaics,' 'wireless sensor network,' 'electric tractor,' 'unmanned aerial vehicle,' and 'machine learning agriculture,' each paired with terms such as 'electrical engineering,' 'power electronics,' 'renewable energy,' or 'IoT.' Sources published between 2008 and 2026 were considered, with emphasis placed on peer-reviewed journal articles and recognized conference proceedings; grey literature was limited to a single authoritative institutional report used for global context (Food and Agriculture Organization, 2017).

Thirty sources met the inclusion criteria of (a) direct relevance to an electrical, electronic, or power-related aspect of agricultural technology, (b) publication in a peer-reviewed or otherwise editorially controlled outlet, and (c) availability of sufficient methodological or review detail to support synthesis. The selected works were grouped into five thematic clusters, renewable power supply, sensing and communication infrastructure, machinery electrification, aerial robotics, and artificial intelligence integration, which form the subsections of Section 3. Within each cluster, findings were compared qualitatively to identify converging conclusions, points of disagreement, and open technical gaps. As this is a narrative rather than a meta-analytic review, no quantitative pooling of results (e.g., meta-analysis of yield or efficiency statistics) was attempted; instead, representative quantitative findings from individual studies are reported to illustrate the magnitude of reported benefits.

Inclusion/exclusion criteria

Literature published between 2008 and 2026 was identified through IEEE Xplore, ScienceDirect, SpringerLink, MDPI, and Google Scholar, with emphasis on English-language peer-reviewed journal articles and recognized conference proceedings.

Studies were included when they were directly relevant to electrical, electronic, power, sensing, communication, automation, or AI applications in sustainable agriculture and provided sufficient methodological or technical information.

Duplicate, irrelevant, non-English, out-of-period, and insufficiently documented publications were excluded; one authoritative FAO report was retained as contextual grey literature.

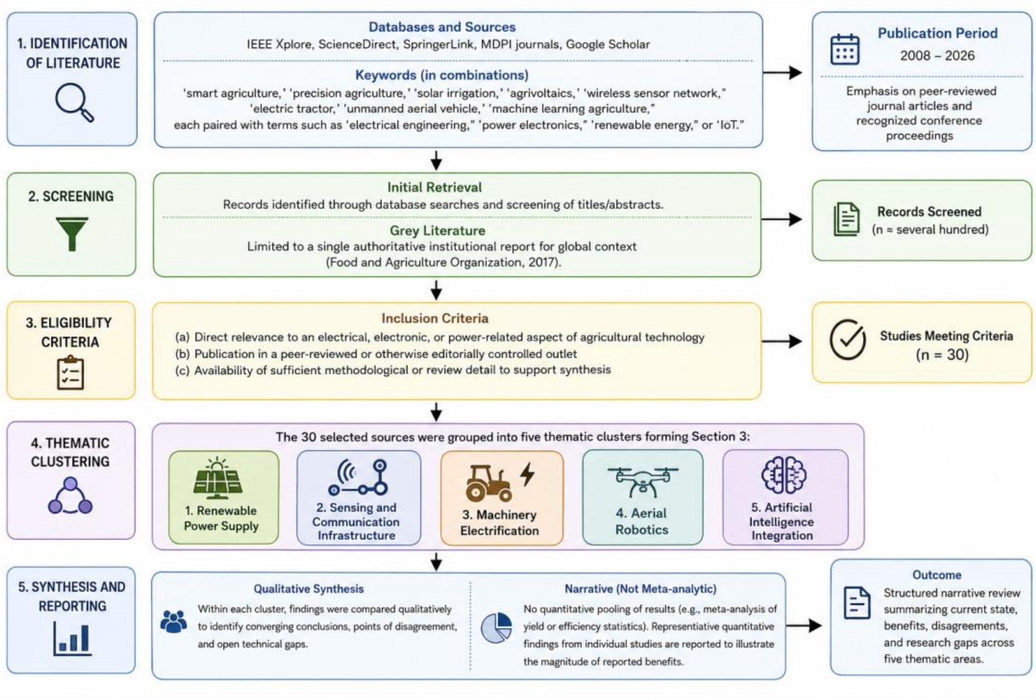

Figure 1. Genral SLR Flow diaagram

3. Results and Discussion

The reviewed literature clusters naturally around five interacting subsystems of the smart-agriculture ecosystem, each of which is discussed in turn below and summarized comparatively in Table 1.

3.1. Renewable Power Supply for Agricultural Operations

3.1.1. Solar Photovoltaic Water Pumping and Irrigation

Table 1. Summary of Research on Solar Photovoltaic Water Pumping and Irrigation Systems

Author(s) & Year	Research Focus	Methodology / Approach	Key Findings	Main Contribution / Implication
Muhsen et al. (2017)	PV water pumping system design and control strategies	Review of PV pumping design methods, system sizing, and control techniques	Maximum power point tracking (MPPT) and proper matching of motor-pump combinations are essential for improving water output under fluctuating solar radiation conditions	Provided guidelines for improving the efficiency and reliability of PV irrigation pumping systems
Chandel et al. (2015)	Technical assessment of solar photovoltaic pumping systems	Comprehensive review of PV pumping applications for irrigation and drinking-water supply	PV pumping systems are technically mature and suitable for rural applications; however, high initial investment remains a major limitation compared with diesel pumps	Highlighted the feasibility of replacing diesel-based pumping with renewable energy solutions
Al-Ali et al. (2019)	IoT-enabled solar irrigation pumping	Integration of IoT monitoring and remote control technologies with solar-powered pumps	IoT connectivity enables remote monitoring, adjustment of irrigation schedules, and improved operational management	Demonstrated the role of smart technologies in enhancing PV irrigation efficiency
Cervera-Gasco et al. (2023)	Intelligent management of solar-powered irrigation	Development of an irrigation scheduling model coupled with PV	Direct coordination between irrigation demand and solar energy generation reduces dependence	Introduced a cost-effective approach for battery-free solar

Author(s) & Year	Research Focus	Methodology / Approach	Key Findings	Main Contribution / Implication
		pumping availability	on battery storage and minimizes energy losses	irrigation management
Mercedes Garcia et al. (2022)	Hybrid renewable energy systems for irrigation	Modeling and simulation of hybrid renewable energy configurations	Hybrid renewable systems can achieve near-zero net energy consumption for agricultural irrigation applications	Showed the potential of integrating multiple renewable sources for sustainable farming
Kumar et al. (2022)	Solar-tree-based pumping systems for smallholder agriculture	Design and performance evaluation of solar-tree pumping configuration	Solar-tree systems improve land-use efficiency while providing renewable energy for irrigation in small farms	Proposed an innovative PV installation approach suitable for land-constrained agricultural regions
Mekhilef et al. (2013)	Renewable energy challenges in agricultural applications	Review of renewable energy technologies and implementation barriers	Battery durability, lack of standardized components, and limited financing remain major challenges for renewable irrigation adoption	Identified key barriers affecting large-scale deployment of renewable-powered irrigation systems

Irrigation is among the most energy-intensive operations in agriculture, and diesel-fuelled pumping remains common in regions without reliable grid access. A substantial body of work has examined photovoltaic (PV) water pumping as a lower-emission alternative. Muhsen et al. (2017) reviewed PV pumping system design methods and control strategies, concluding that maximum-power-point tracking and appropriately sized motor-pump combinations are critical to achieving acceptable water yield under variable irradiance. Chandel et al. (2015) similarly found that PV pumping is technically mature for both irrigation and community drinking-water supply, though upfront capital cost remains a barrier relative to diesel systems in the short term. More recent work has focused on system intelligence: Cervera-Gasco et al. (2023) proposed a management model that directly couples irrigation scheduling to solar pumping output, avoiding the cost and losses associated with battery storage, while Al-Ali et al. (2019) integrated Internet of Things (IoT) monitoring with solar-powered pumps to allow remote adjustment of irrigation timing. Hybridization with other renewable sources has also been explored; Mercedes Garcia et al. (2022) modeled hybrid renewable systems designed to approach zero net energy consumption in irrigation, and Kumar et al. (2022) demonstrated a solar-tree pumping configuration intended to improve land-use efficiency for smallholder farms in India. Collectively, these studies indicate that PV pumping is a technically sound and increasingly cost-competitive solution, with the principal remaining challenges being battery lifetime (where storage is used), component standardization, and financing mechanisms for smallholders (Mekhilef et al., 2013).

3.1.2. Agrivoltaics: Dual Land Use for Energy and Food

Agrivoltaic (or agriphotovoltaic) systems co-locate PV arrays with crop or livestock production on the same parcel of land, addressing the land-use competition that can arise between energy and food production. Zahrawi and Aly (2024) provide a broad review of agrivoltaic system configurations, noting that panel height, row spacing, and tracking strategy strongly influence both electricity yield and the microclimate experienced by crops beneath the array. Weselek et al. (2019) similarly emphasize that partial shading from PV modules can, for some shade-tolerant crops, reduce water stress and evapotranspiration, partially offsetting any yield penalty. From a systems perspective, Walston et al. (2022) argue that agrivoltaics should be evaluated against multiple, sometimes competing, objectives, energy generation, food output, water use, and pollinator habitat, rather than optimized for electricity yield alone. Mahim et al. (2026) extend this discussion to policy and standardization, observing that the absence of universal design standards and inconsistent incentive structures across countries remain significant barriers to scaling agrivoltaic deployment despite strong technical feasibility. From an electrical engineering standpoint, the key design questions in agrivoltaics concern inverter sizing, array configuration for partial shading tolerance, and grid or off-grid interconnection strategy, all of which interact with the agronomic layout of the underlying farm.

3.2. Sensing, Communication, and IoT Infrastructure

3.2.1. Wireless Sensor Networks and Energy Harvesting

Distributed sensing is fundamental to precision agriculture, allowing farmers to move from uniform, calendar-based management to management that responds to local field conditions. Kim et al. (2008) demonstrated one of the earlier field deployments of a distributed wireless sensor network for irrigation control, establishing many of the design patterns, including duty-cycled radio operation and soil-moisture-triggered actuation, still used today. Because sensor nodes are typically battery powered and deployed in remote field locations where routine maintenance is costly, energy efficiency has become a central research theme. Jawad et al. (2017) provide a comprehensive taxonomy of energy-efficient and energy-harvesting techniques for agricultural wireless sensor networks (WSNs), comparing solar, piezoelectric, and radio-frequency harvesting approaches and their suitability to different deployment contexts. Their review underscores that no single harvesting technology is universally optimal; solar harvesting performs best in open fields with consistent irradiance, whereas piezoelectric or vibration-based harvesting is better suited to nodes mounted on moving machinery. Complementary work on short-range and body- or equipment-mounted connectivity, such as near-field magnetic induction, offers additional options for low-power sensor communication in constrained agricultural environments (Pal & Kant, 2019).

3.2.2. Communication Protocols and Connectivity

Beyond individual sensor nodes, the choice of wide-area communication protocol strongly affects both energy consumption and coverage. Raza et al. (2017) review low-power wide-area network (LPWAN) technologies such as LoRa and Sigfox, concluding that these protocols offer a favorable balance of range, energy consumption, and infrastructure cost for sparsely instrumented rural farmland compared with cellular or short-range alternatives such as ZigBee. Field validation of long-range links under real agricultural conditions has been reported by Yavasoglu et al. (2023), whose on-site testing of a long-range wireless link achieved reliable communication over several kilometres, supporting the feasibility of LPWAN-based monitoring across large farm holdings. At a systems level, Gatkal et al. (2024) and Khanna and Kaur (2019) both trace the evolution of IoT architectures in agriculture, from simple point sensors toward layered architectures combining edge processing, gateway aggregation, and cloud-based analytics, while Qazi et al. (2022) highlight that data security and interoperability between competing IoT platforms remain unresolved challenges that limit farmer trust and cross-vendor integration.

3.3. Electrification of Agricultural Machinery

Mobile agricultural machinery, tractors, sprayers, and harvesters, has historically relied on diesel internal combustion engines, but recent advances in battery technology and power electronics have renewed interest in electrified powertrains. Varani et al. (2025) developed a data-driven electrification index using real-world CANBUS telemetry from a diesel tractor fleet, finding that electrification feasibility depends strongly on farm scale, duty cycle, and access to charging infrastructure, with smaller, lighter-duty operations generally better suited to current battery-electric technology than heavy continuous-duty field operations. This finding is consistent with broader techno-economic assessments showing that well-to-wheel efficiency for battery-electric tractors charged from renewable sources such as rooftop photovoltaics can substantially exceed that of diesel equivalents, even though absolute range and continuous power remain limited by present-day battery energy density. From a power-electronics perspective, the central engineering challenges in agricultural machinery electrification are the design of traction motor drives and converters capable of tolerating the vibration, dust, and thermal extremes typical of field operation, the sizing of onboard battery packs against variable and often unpredictable duty cycles, and the development of charging infrastructure, potentially itself renewably powered, at or near the point of use. Electrified machinery also enables tighter integration with automation and precision-application systems than is practical with hydraulically actuated diesel equipment, since electric drives offer faster and more precise torque control.

3.4. Unmanned Aerial Systems and Robotics

Unmanned aerial vehicles have become one of the most visible applications of electrical and electronic engineering in agriculture, combining flight control, battery-electric propulsion, remote sensing payloads, and wireless data links. Del Cerro et al. (2021) provide a broad survey of UAV applications across the crop production cycle, from soil and field analysis through planting, monitoring, and harvest-related tasks, noting that multirotor platforms dominate small-plot applications because of their vertical take-off capability, while fixed-wing platforms are preferred for large-area mapping because of their longer endurance.

Imaging payload design is itself an active area of electrical engineering research; Honkavaara et al. (2013) describe the development and calibration of a lightweight hyperspectral imaging system for UAV-based crop monitoring, illustrating the trade-offs between sensor weight, spectral resolution, and platform flight time. Beyond imaging, UAVs are increasingly used for direct field intervention: Mogili and Deepak (2018) and Meng et al. (2018) both examine UAV-based pesticide and adjuvant spraying, reporting that precise control of spray droplet size and flight parameters, governed by onboard electronic control systems, significantly affects both application efficacy and off-target drift. Hafeez et al. (2023) review the broader state of drone-based monitoring and spraying, concluding that battery endurance and payload capacity remain the primary constraints limiting the field area that a single UAV can service per flight, motivating research into swappable battery systems, in-field charging stations, and multi-drone coordination.

3.5. Artificial Intelligence and Machine Learning Integration

The value of the sensing and connectivity infrastructure described above depends substantially on the analytical methods used to convert raw data into actionable decisions. Sharma et al. (2021) present a comprehensive review of machine learning (ML) applications in precision agriculture, spanning soil-parameter estimation, crop-yield prediction, and pest and disease detection, and note that while classical ML techniques remain widely used for structured sensor data, deep learning methods, particularly convolutional neural networks, have become dominant for image-based tasks such as UAV-derived disease and weed detection. Cisternas et al. (2020) similarly find, through a systematic review of precision-agriculture implementations, that data-driven decision support is most effective when it is tightly coupled to the underlying sensing and actuation hardware rather than treated as an independent analytics layer. At the intersection of AI and IoT, Kuppusamy et al. (2023) discuss machine-learning-enabled IoT architectures for smart agriculture operations, arguing that edge-based inference, running lightweight models directly on gateway or sensor-node hardware, can reduce both communication energy costs and decision latency compared with cloud-only architectures, an important consideration given the energy constraints discussed in Section 3.2.1. Together, these studies suggest that AI is best understood not as a separate technology but as the coordinating layer that links renewable power supply, distributed sensing, and mobile electrified platforms into a coherent decision-making system.

3.6. Cross-Cutting Challenges and Future Directions

Several challenges recur across the thematic areas reviewed above. First, cost remains a barrier to adoption in all five clusters: photovoltaic pumping and agrivoltaic installations, energy-harvesting sensor networks, electrified machinery, and UAV platforms all carry higher upfront capital costs than their conventional counterparts, even where lifecycle costs are favorable (Mekhilef et al., 2013; Varani et al., 2025). Second, interoperability and standardization are incomplete; the coexistence of multiple competing IoT platforms and communication protocols complicates integration across vendors and limits data portability (Qazi et al., 2022). Third, energy autonomy at the sensor and node level remains an active research problem, since battery replacement across a large, distributed sensor network is logistically costly, motivating continued work on energy harvesting and ultra-low-power circuit design (Jawad et al., 2017). Fourth, rural electrification and connectivity infrastructure, grid access, mobile network coverage, and broadband availability, vary widely by region and constrain which technologies are practically deployable, particularly in the smallholder farming contexts common in much of the developing world (Food and Agriculture Organization, 2017). Finally, most of the reviewed technologies still require a degree of technical literacy that many farmers do not currently possess, underscoring the importance of training, extension services, and user-centred system design alongside the underlying engineering advances.

Looking forward, the literature points toward tighter integration of the five subsystems discussed above: photovoltaic and agrivoltaic power generation sized and controlled in coordination with electrified machinery charging schedules; sensor networks whose sampling and transmission rates are dynamically adjusted by AI models to conserve harvested energy; and UAV or ground-robot platforms that draw on the same on-farm renewable power infrastructure used for irrigation and machinery. Realizing this integration will require continued advances in power electronics, low-power communication, and edge computing, alongside complementary progress in agricultural economics, policy, and farmer training.

Table 2. Summary of electrical engineering contributions, and their reported benefits and limitations, across the five thematic clusters reviewed in Section 3.

Technology Domain	Key Electrical Engineering Contribution	Principal Reported Benefit / Limitation
PV water pumping	Maximum-power-point tracking, motor-pump drive design	Lower operating cost than diesel; higher upfront capital cost (Chandel et al., 2015)
Agrivoltaics	Array layout, inverter sizing, partial-shading tolerance	Dual land-use income; potential crop microclimate trade-offs (Zahrawi & Aly, 2024)
Wireless sensor networks	Energy harvesting, duty cycling, low-power radios	Continuous field monitoring; battery/maintenance constraints (Jawad et al., 2017)
Electric tractors and implements	Traction motor drives, battery sizing, power converters	Lower emissions and noise; limited range and duty cycle (Varani et al., 2025)
UAV / aerial robotics	Flight control, imaging payload design, spray actuation	High-resolution, timely field data; battery endurance limits (Hafeez et al., 2023)
AI / machine learning	Edge inference, predictive analytics, decision support	Improved input precision; requires quality data and connectivity (Sharma et al., 2021)

3.7. Limitations of existing studies

The reviewed evidence is largely based on technical feasibility studies, laboratory experiments, prototypes, and small-scale field demonstrations, with relatively limited long-term and large-scale agricultural validation.

Several studies also provide limited evidence regarding economic sustainability, interoperability, reliability under diverse environmental conditions, and long-term adoption by farmers.

These limitations highlight the need for large-scale, multi-season field trials and long-term evaluations to validate the technical, economic, environmental, and practical performance of electrical engineering technologies in sustainable smart agriculture.

Conclusions

This review has examined how electrical engineering underpins the transition toward sustainable smart agriculture across five interacting domains: renewable power supply, sensing and communication infrastructure, machinery electrification, aerial robotics, and artificial intelligence. Across the 30 sources reviewed, a consistent picture emerges: photovoltaic pumping and agrivoltaic systems can meaningfully reduce the energy footprint of irrigation and diversify farm revenue; energy-harvesting wireless sensor networks and low-power wide-area communication protocols make continuous, farm-scale monitoring practical; battery-electric machinery offers emissions and control benefits but remains constrained by current battery technology; and UAV platforms combined with machine learning substantially increase the precision and timeliness of field management decisions. At the same time, cost, interoperability, energy autonomy, rural infrastructure, and farmer digital literacy remain significant, recurring barriers across all five domains. Future progress will likely depend less on breakthroughs in any single technology than on the deeper integration of these subsystems into coherent, farm-scale electrical infrastructures, coordinated by intelligent control and supported by appropriate policy, financing, and training mechanisms.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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