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# Energy-Harvesting Materials for Autonomous Smart Farming Sensors: A Literature Review

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## ABSTRACT

The integration of the Internet of Things (IoT) in smart farming is hindered by limited battery life and the environmental impact of electronic waste. This review evaluates the development of energy-harvesting materials as a solution to power autonomous agricultural sensors. Through a systematic review, this paper analyzes three main mechanisms: Organic Photovoltaic (OPV), triboelectric nanogenerator/piezoelectric nanogenerator (TENG/PENG), and thermoelectric generator (TEG). Flexible polymers for TENGs and perovskite-based solar cells have the highest potential in addressing canopy shading and outdoor weather challenges. However, material toxicity and degradation due to UV and humidity remain major obstacles. Future research must prioritize biocompatible materials and hybrid systems to ensure the sustainability of precision agriculture.

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## 1. INTRODUCTION

Modern agriculture relies heavily on the concept of smart farming or precision agriculture to optimize crop yields and resource efficiency [1]. The backbone of this system is Wireless Sensor Networks (WSN) and IoT devices widely distributed across agricultural fields to monitor soil conditions, temperature, and crop growth in real-time [2]. However, the large-scale implementation of WSNs faces a significant operational hurdle: reliance on conventional batteries. The limited operational lifespan of batteries necessitates periodic replacements that incur high labor costs, while toxic battery waste ultimately threatens agricultural soil ecology [3]. As a viable solution, autonomous sensor technologies (self-powered sensors) driven by energy-harvesting materials have attracted immense attention from the materials science and electronics research communities [4]. This concept utilizes passive energy from the surrounding agricultural environment, such as sunlight, wind gusts, raindrops, and soil temperature gradients, converting it into microwatt to milliwatt-scale electrical energy [5]. The performance of these energy-harvesting systems is entirely dictated by the characteristics of the utilized materials [6]. Harsh agricultural environments demand materials that not only possess high energy conversion efficiency but are also flexible, resilient against extreme weather fluctuations, and ideally biocompatible to prevent local environmental contamination in case of damage [7]. This review comprehensively evaluated the recent advancements in energy-harvesting materials for smart farming applications. Unlike previous reviews that focus more on network architecture, this paper centers on material-level innovations. Specifically, this paper examined the sustainability aspects of the materials, identify the gap between laboratory-scale testing and field deployment, and formulate strategic recommendations to address environmental degradation issues that are often overlooked.

## 2. METHODS

This literature review was structured using a Systematic Literature Review (SLR) approach, adapting the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The secondary data collection process was conducted comprehensively across academic databases. The literature search was restricted to articles published within the last five years to ensure the relevance of the latest technological trends. The search queries were formulated using a combination of keywords: ("energy harvesting materials" OR "self-powered materials") AND ("smart farming" OR "precision agriculture") AND "autonomous sensors". Strict inclusion criteria were then applied: (i) articles must be peer-reviewed journals, (ii) possess an explicit focus on the synthesis or characterization of energy-harvesting materials, and (iii) include testing relevant to outdoor or agricultural conditions. Review articles, proceedings lacking empirical data, and research solely discussing circuit topologies were excluded. The data extraction was specifically focused on power density metrics, durability, and material conversion mechanisms.

## 3. RESULTS AND DISCUSSION

Energy-harvesting materials for smart farming sensors are classified into three dominant mechanisms: photovoltaic, mechanical, and thermal [8]. To overcome the intermittent nature of individual outdoor energy sources, such as the lack of sunlight at night or windless days, recent advancements strongly advocate for a hybrid, multi-modal architecture [9]. It demonstrates how various state-of-the-art energy-harvesting materials (semi-transparent Organic Photovoltaic (OPV), flexible triboelectric nanogenerator/piezoelectric nanogenerator (TENG/PENG), and soil-embedded thermoelectric generator (TEG) can be simultaneously deployed. Furthermore, it details how the harvested energy is consolidated through a centralized Power Management IC (PMIC) to sustainably power agricultural sensor nodes [10]. **Figure 1** illustrates a comprehensive conceptual model of such an integrated system.

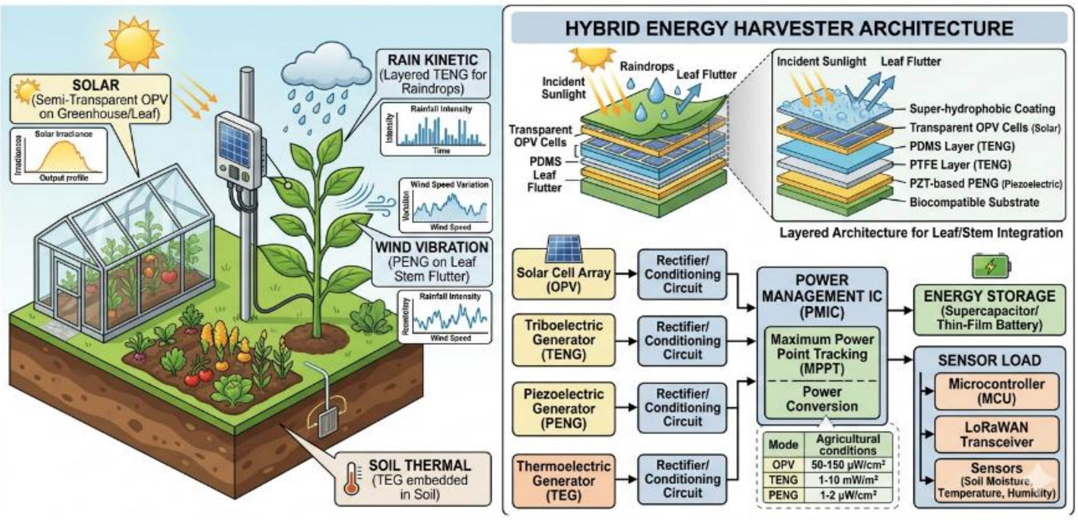

**Figure 1.** Hybrid multi-modal energy-harvesting system for autonomous smart farming sensors.

## 3.1. Energy Requirements of Smart Farming Sensors

Before selecting the appropriate harvesting material, it is crucial to match the material's power output with the sensor's power consumption. **Table 1** outlines the power profiles of various agricultural sensors to provide a baseline for material performance evaluation.

**Table 1.** Power requirements of common smart farming sensors.

| SENSOR TYPE | ACTIVE POWER | SLEEP POWER | TRANSMISSION MODULE | TOTAL DAILY REQUIREMENT |
|---|---|---|---|---|
| Soil Moisture | 15 mW | 5 μW | LoRaWAN | ~2-5 mWh |
| Temperature/Humidity | 5 mW | 1 μW | Zigbee | ~1-3 mWh |
| Plant Growth (Strain) | 2 mW | <1 μW | BLE | <1 mWh |

## 3.2. Photovoltaic Materials Evaluation

Solar energy offers the highest power density. However, conventional silicon panels are too heavy and rigid to be mounted on leaves or greenhouse structures [11]. Current research focuses heavily on OPV and Perovskite Solar Cells (PSC). Polymer-based OPVs offer extreme flexibility and semi-transparent properties, allowing direct installation on crop canopies without blocking Photosynthetically Active Radiation (PAR) [12]. **Figure 2** illustrates the integrated application of a flexible semi-transparent OPV cell within a smart farming context. It demonstrates how the engineered material strategically manages the incoming solar spectrum: specific wavelengths are efficiently absorbed by the semi-transparent OPV layers to generate clean energy, while the critical PAR spectrum is transmitted seamlessly to the crop canopy below, supporting uninterrupted plant growth [13].

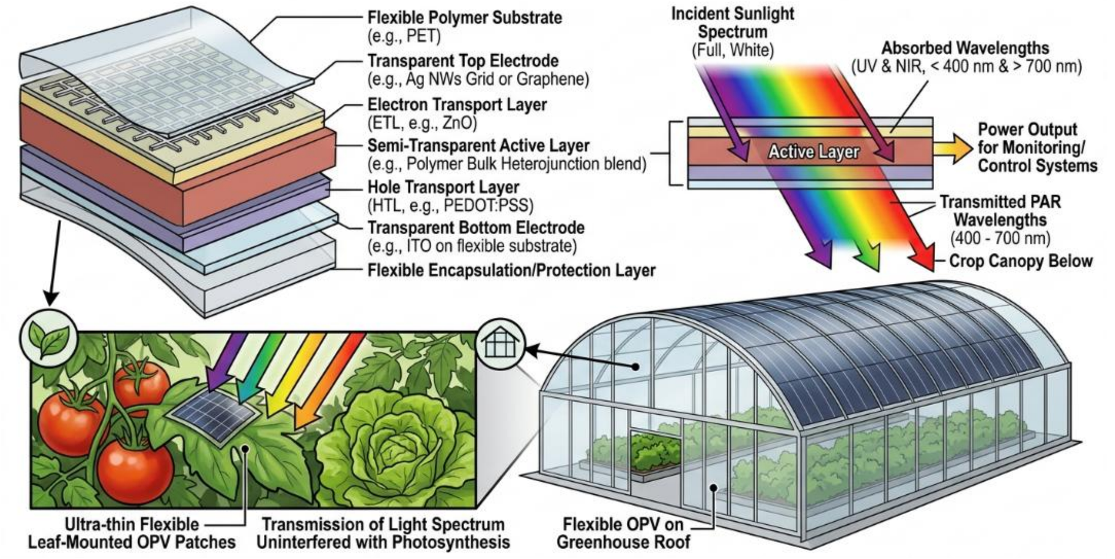

**Figure 2.** Semi-transparent OPV built in OPV in smart farming and material engineering.

### 3.3. Mechanical Energy Harvesting (TENG and PENG)

The limitation of photovoltaics during the night is overcome by harvesting the kinetic energy of wind and raindrops using TENG and PENG [14]. Polymer materials such as PTFE (Polytetrafluoroethylene) and PDMS (Polydimethylsiloxane) heavily dominate TENG designs due to their ability to generate electricity from the mechanical friction of falling raindrops [15]. **Table 2** outlines the performance comparison of mechanical energy harvesting materials.

### 3.4. Thermoelectric Generators (TEG)

TEG materials utilize the temperature gradient between the sun-exposed soil surface and the cooler underground layers. Inorganic alloy $Bi_2Te_3$ remains the standard due to its high figure of merit (ZT) at ambient temperatures [16]. However, recent studies are shifting towards organic thermoelectric materials based on conductive polymers (PEDOT:PSS) to reduce production costs and avoid placing heavy metals in agricultural soil [17].

### 3.5. Critical Discussion: Environmental Degradation and Toxicity

To visualize this advanced material solution, the following schematic illustrates the integrated application of a flexible semi-transparent OPV cell within a smart farming context [18]. It demonstrates how the engineered material strategically manages the incoming solar spectrum: specific wavelengths are efficiently absorbed by the semi-transparent OPV layers to generate clean energy, while the critical PAR spectrum is transmitted seamlessly to the crop canopy below, supporting uninterrupted plant growth [19]. Toxicity is the biggest barrier to mass commercialization. Deploying tens of thousands of PZT-based sensors (containing lead) would create an ecological contamination crisis if the sensors are left in the field [20]. Future research trends must aggressively shift towards biodegradable materials (such as polylactic acid/PLA or coated cellulose) that can safely decompose into the soil at the end of their lifespan, combined with non-toxic micro-super capacitors [21]. Although laboratory energy metrics are satisfactory, the transition to field applications is still hindered by fundamental issues summarized in **Table 3.**

**Table 2.** Performance comparison of mechanical energy harvesting materials.

| MATERIAL TYPE | CORE MECHANISM | AVERAGE OUTPUT | MAIN ADVANTAGES | WEAKNESSES IN AGRICULTURE |
|---|---|---|---|---|
| PVDF-TrFE | PENG (Wind) | 1.5 µW/cm² | Flexible, motion-responsive | Vulnerable to UV radiation degradation |
| PTFE/PDMS | TENG (Rain) | 8.2 mW/m² | Waterproof, high efficiency | Performance drops in high humidity |
| Cellulose | TENG (Leaf Friction) | 2.1 mW/m² | Biocompatible, very cheap | Low long-term mechanical durability |

**Table 3.** Environmental challenges and material mitigation strategies.

| ENVIRONMENTAL CHALLENGE | EFFECT ON ENERGY-HARVESTING MATERIAL | CURRENT MITIGATION STRATEGY |
|---|---|---|
| High Humidity (RH > 85%) | Drastic charge leakage in TENG | Super hydrophobic coating ($SiO_2$ nanoparticles) |
| Constant UV Exposure | Photodegradation of OPV bonds | Thermal encapsulation using fluoropolymers |
| Soil Contamination Risk | Heavy metal toxicity (Pb) from PZT | Material substitution to lead-free piezoelectrics |

## 4. CONCLUSION

The development of energy-harvesting material innovations offers the most promising route to realizing autonomous, battery-maintenance-free smart farming sensor networks. This review concludes that flexible polymer TENG and OPV are currently the most superior candidates due to their outdoor functionality. Nevertheless, actual adoption is still obstructed by material vulnerability to UV degradation, absolute humidity, and soil toxicity risks. Future research focus must absolutely prioritize resilient material encapsulation engineering and the creation of fully biodegradable energy-harvesting materials to prevent a potential new electronic waste crisis in the agricultural sector.

## 5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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