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Research Article

WEARABLE ELECTRONICS FOR PLANT-BASED ENERGY HARVESTING IN SMART FARM

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Abstract

This paper explores the development and potential applications of plant-based wearable energy harvesters, focusing on their role in smart farming. While plant wearables have historically been rigid, recent studies suggest the importance of ultrathin, flexible, and stretchable designs in plant wearables. New designs of the devices take into account the dynamic nature of plants, making wearables durable while decreasing the risk of causing physical damage to the plant. Energy harvested through these plant wearables provide energy to power self-sustaining agricultural sensors that can continuously monitor plant microclimate data. The paper emphasizes the importance of using materials and designs that conform to the dynamic and delicate structure of plants, ensuring both mechanical compatibility and long-term functionality. Stretchable designs like serpentine, wrinkled, kirigami, and island-bridge structures are discussed for enhancing device flexibility. Various energy sources are explored, out of which solar power is highlighted as the most promising by the study. Additionally, mechanical energy from plant movement and chemical energy from biofuel cells are also explored as supplementary options. Despite current challenges, such as efficiency and durability in outdoor environments, plant-based wearables present a promising direction for sustainable agriculture and renewable energy integration.

Keywords: Stretchable energy harvester, Plant-based wearable electronics, Smart farming, Renewable energy, Biofuel cells, Photovoltaic cells, Triboelectric Nanogenerators.

INTRODUCTION

As agricultural systems advance, energy consumption becomes a critical factor. Global economic growth over the centuries has been fueled by non-renewable energy sources such as petroleum, coal, and natural gas (Hao *et al.,* 2013). These fossil fuels, while driving economic expansion, are finite and contribute significantly to environmental degradation through the release of greenhouse gases, leading to climate change and global warming. The depletion of these resources, coupled with rising energy costs, has underscored the urgent need to transition to renewable energy sources. Renewable energy offers a viable alternative, providing both economic and environmental benefits (Güney, 2019). By harnessing clean energy from solar, wind, and plant-based sources, countries can mitigate the harmful effects of fossil fuels while addressing the growing energy demands (Majeed *et al.,* 2023). Among the renewable energy sources being explored, plant-based energy harvesting presents a unique and promising avenue, particularly within the context of smart farming.(Teng *et al.,* 2018) Recent studies have demonstrated that plants can generate electrical signals through their excitable membranes, and this bioelectricity can be harnessed for energy production (Babu *et al.,* 2022). In addition, plants contribute to carbon sequestration by absorbing carbon dioxide, making them a dual-purpose tool for both energy generation and environmental protection. Furthermore, the application of flexible electronics, which can conform to the dynamic and curvilinear surfaces of plants, has opened new possibilities for continuous monitoring of plant health as well as simultaneously harvesting mechanical and chemical energy from the plants (Pechsiri & Puengsungwan, 2023). One of the most innovative approaches within smart farming is the development of plant wearable devices flexible, biocompatible sensors that can be seamlessly integrated with plant surfaces to monitor key physiological and environmental parameters (Qu *et al.,* 2021). These devices provide real-time data on plant health, growth, and environmental conditions, aiding in more informed and precise decision-making. However, the widespread deployment of plant wearables is hampered by challenges related to energy supply, as traditional energy sources are not always practical in remote or large-scale agricultural fields. Energy harvesting technologies offer a promising solution by enabling plant wearables to generate power autonomously from renewable sources. Solar energy, mechanical energy from plant movement (such as leaf oscillation due to wind or rain), and chemical energy generated through bioelectrochemical processes in plants are all viable options for powering these devices (Greenman *et al.,* 2024; Hao *et al.,* 2013; Jadhav & Shreelavaniya, 2023). Flexible electronic materials, such as lightweight photovoltaics, piezoelectric and triboelectric nanogenerators, and biofuel cells, allow plant wearables to capture and convert these various energy forms into usable electrical power. This approach not only overcomes the energy supply issue but also aligns with the goal of sustainable agriculture by reducing reliance on external power sources.

This review will explore the role of plant wearable devices in smart farming, focusing on energy harvesting systems that utilize solar, mechanical, and chemical energy. By integrating these renewable energy solutions into plant wearables, smart farms can achieve self-sustaining, eco-friendly systems that enhance agricultural efficiency and sustainability. (Figure 1) In the following sections, we will discuss the key technologies and materials involved in plant wearables, the energy harvesting mechanisms, and the potential challenges and opportunities for scaling up these systems in modern agriculture.

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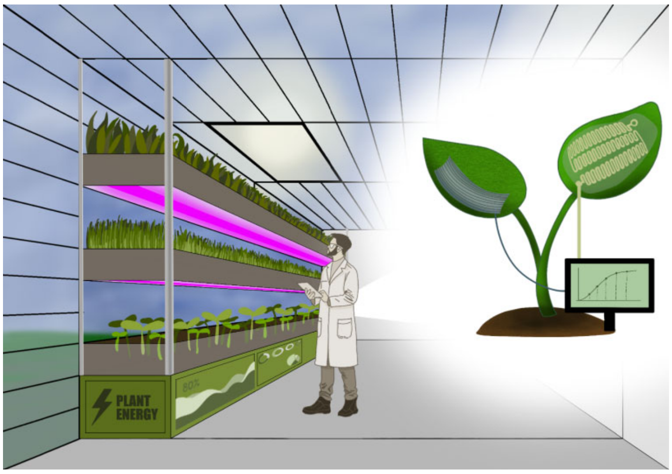

Figure 1. Schematic illustration of smart farm operated by energy supply from plant-based energy harvester

Plant-based wearable device

Plant wearable electronics represent a groundbreaking advancement in smart farming, offering innovative solutions for monitoring plant health and harnessing energy from natural sources. These devices are designed to conform to the dynamic and delicate structures of plants, requiring materials with mechanical properties that closely match those of plant tissues. The development of ultrathin, flexible electronics, along with advanced stretchable designs, enables seamless integration with plant surfaces, ensuring continuous monitoring and energy harvesting without disrupting plant growth or function (Chen *et al.,* 2023). This chapter explores the key factors that contribute to the effectiveness of plant-based wearables, focusing on mechanical compatibility, ultrathin construction, and stretchable design approaches.

Mechanical property

Mechanical compatibility between electronic devices and plants is critical to the success of plant-based wearable electronics. Plants are living organisms that experience continuous growth, expansion, and movement due to environmental factors such as wind, water absorption, and sunlight exposure. Traditional rigid electronics, which are typically constructed from materials such as silicon, metal, and glass, are ill-suited for application on plants because of their high elastic modulus, which leads to mechanical mismatches (Wu *et al.,* 2016). These rigid devices are not designed to accommodate the dynamic and ever-changing shapes of plant tissues, leading to difficulties in maintaining conformal contact with the plant surfaces. The mismatch not only compromises the functionality of the devices but also increases the risk of physical damage to the delicate tissues of leaves and stems.(Dufil *et al.,* 2022) To overcome these issues, the materials used for wearable electronics must possess mechanical properties similar to those of plants, allowing for seamless integration and minimizing stress on plant tissues (Blahovec, 1988). Flexible and stretchable electronics, constructed using materials like elastomers, conductive polymers, and thin-film metals, offer a viable solution to this problem. Elastomers, in particular, have mechanical properties that closely mimic the softness and flexibility of plant tissues. These materials can stretch, bend, and conform to the natural topology of plants without losing their structural integrity or affecting the device's electrical performance. Stretchable materials with low elastic moduli (typically below 100 kPa) align well with the mechanical behavior of plants, which exhibit soft, pliable characteristics. (Figure 2) This ensures that the device maintains intimate contact with the plant surface, facilitating accurate and continuous monitoring of physiological and environmental parameters. The viscoelastic behavior of elastomers further enhances the mechanical compatibility by enabling stress relaxation, reducing strain on the plant tissue, and preventing damage over extended periods of use.

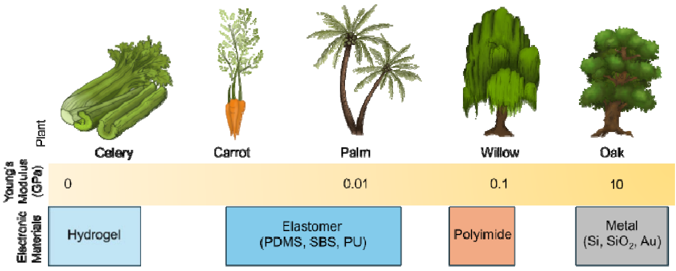

Figure 2. Mechanical property of plant materials and electronic materials

In addition to material selection, the overall design and fabrication process must take into account the dynamic nature of plant growth and movement. By utilizing advanced materials and fabrication techniques, researchers have developed plant wearables that can adapt to changes in plant size and shape while maintaining reliable functionality.(Hickey & Pelling, 2019) These advancements enable the creation of devices that can not only stretch and bend with plant tissues but also resist environmental stressors such as wind, rain, and temperature fluctuations, making them suitable for long-term deployment in agricultural settings.

Conformal contact

One of the key requirements for plant-based wearable electronics is the ability to conform closely to the surface of plant leaves and stems. Given the delicate and highly irregular topology of plant surfaces, devices must be ultrathin to maintain good contact, reduce mechanical mismatch, and ensure accurate sensing capabilities. (Figure 3) In traditional electronics, bulk and thickness often lead to increased stiffness, making it difficult for the device to adhere to non-flat surfaces like the intricate shapes of plant leaves. In contrast, ultrathin designs on the order of micrometers or nanometers in thickness Nallow the device to adapt to the curvilinear surfaces of plants without imposing significant mechanical stress.(Rogers *et al.,* 2010)

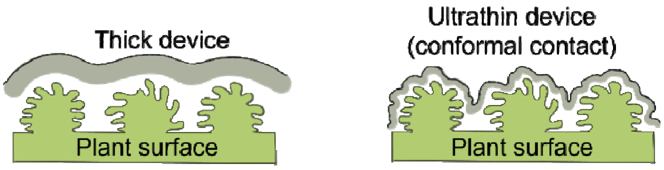

Figure 3. Conformal contact of ultrathin device on irregularly-shaped topology of plant leaf

Ultrathin electronic films, made from materials such as polyimide, polydimethylsiloxane (PDMS), or graphene, are engineered to be lightweight and highly flexible, allowing them to conform naturally to the three-dimensional structure of plant tissues (Meder *et al.,* 2018). These materials can be fabricated by photolithography or soft lithography techniques in layers that are less than 100 micrometers thick, reducing the weight and rigidity of the device. The thinner the device, the more closely it can adhere to the plant surface, ensuring that it follows the plant's natural movement without detaching or causing damage. The ultrathin nature of these devices also reduces their interference with the plant's biological functions, allowing for seamless integration over long periods.

Stretchability

To achieve the desired stretchability in plant-based wearable electronics, specific design architectures must be employed. These designs enable the electronic devices to stretch, bend, and twist along with the dynamic movements of plants while maintaining their electrical functionality. There are four primary stretchable design strategies that have been developed: serpentine, wrinkled, kirigami, and island-bridge structures. (Figure 4).

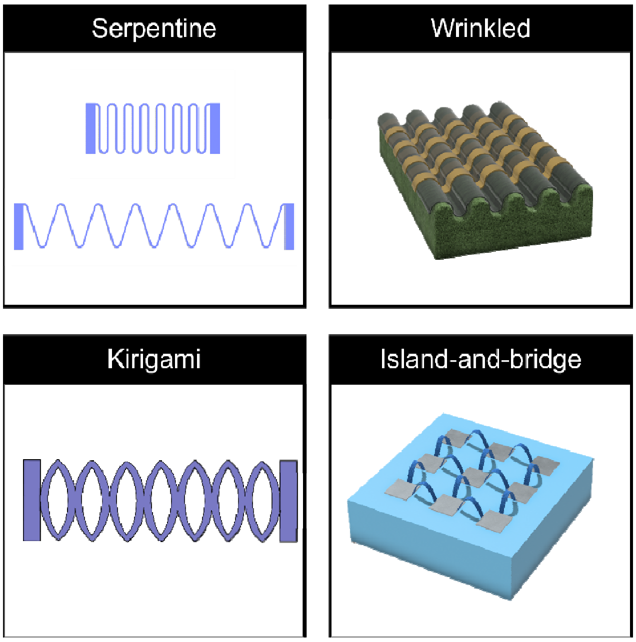

Figure 4. Device design strategy for stretchability

The serpentine design is one of the most widely used approaches for creating stretchable electronics. It involves shaping conductive traces into wavy, serpentine patterns, which allow the material to elongate when stretched (Zhang *et al.,* 2013). This design can accommodate large deformations without causing significant stress to the conductive pathways, ensuring continuous electrical performance even when subjected to high strains. Serpentine structures are ideal for applications that require extensive flexibility and are often used in wearable sensors for both plants and humans. The wrinkled design leverages the concept of pre-straining an elastic substrate and then depositing a thin conductive film on top of it (Jiang *et al.,* 2007). When the strain is released, the conductive layer forms a wrinkled structure, which can accommodate stretching and compression without breaking. This design offers a high degree of flexibility and can adapt to the dynamic movement of plant tissues, making it suitable for long-term deployment in agricultural environments. The kirigami design is inspired by the traditional Japanese art of paper cutting. In this approach, cuts or slits are made in the material to introduce stretchability (Qi *et al.,* 2022). When stretched, the material forms intricate patterns that can expand and contract without losing structural integrity. Kirigami designs provide a unique advantage in that they allow for extreme stretching while minimizing stress on the material. This design is particularly useful for applications where large deformations are expected, such as monitoring the growth of rapidly expanding plant tissues. The island-bridge design involves creating small, rigid "islands" of functional electronic components that are connected by flexible "bridges." The islands contain the active electronic elements, such as sensors or circuits, while the bridges are made of stretchable materials that allow the overall device to deform.(Joo *et al.,* 2020) This design isolates the rigid components from mechanical strain, ensuring that the electronic functionality is maintained even under significant deformation. The island-bridge design is particularly effective for maintaining high-performance electronics in stretchable applications, as it balances the need for rigidity in certain components with the overall flexibility of the device. These stretchable design strategies, combined with advanced materials, enable the development of high-performance plant-based wearables that can conform to the natural movement and growth of plants. By incorporating such designs, wearable electronics can maintain long-term functionality, ensuring accurate data collection and monitoring of plant health and environmental conditions. These innovations represent a significant step forward in the integration of electronics with biological systems, offering new opportunities for intelligent agricultural management and sustainable farming practices.

Plant-based Wearable Energy Harvester

With the growing need for renewable energy sources, plant wearable energy harvesters have gained attention as innovative solutions for tapping into the natural energy surrounding plants. These devices are designed to capture various forms of energy, such as solar, mechanical, and chemical energy, directly from plants and their environment (Meder *et al.,* 2022). By integrating energy harvesting technologies with plant biology, they offer a sustainable means of generating power that can be used for a wide range of applications, from environmental monitoring to powering small devices. This chapter explores three main energy harvesting methods solar, mechanical, and chemical and how they can be effectively applied to plants to enhance energy sustainability and contribute to various technological advancements in smart farming and beyond.

Solar energy

Solar energy is a promising renewable energy source due to its abundance and potential for sustainable power generation, especially in agricultural applications. Photovoltaic (PV) cells, which convert sunlight into electricity, are widely used in solar energy harvesting. These devices work by absorbing photons, generating electron-hole pairs, and transporting the charges to create a current. Flexible PV cells, such as those made from amorphous silicon, are particularly useful in plant-based wearable devices because they can be applied to curvilinear plant surfaces, allowing continuous energy capture. Although less efficient than monocrystalline or polycrystalline silicon cells (which achieve 15–20% efficiency), amorphous silicon cells (10% efficiency) are ideal for flexible, wearable applications that need to adapt to plant movements and topology (Chong *et al.,* 2019).

Research has demonstrated various ways to integrate solar energy harvesting into plant-based systems. One example involves organic solar cells using plant-based sensitizers like orange and purple eggplant extracts, which have been shown to generate electricity with a solar conversion power of 0.66 mW/cm² (Calogero & Marco, 2008). Another significant advancement is the use of flexible PV cells embedded directly onto plant leaves, allowing them to harness solar energy efficiently without the need for external solar tracking systems. This setup is particularly useful since plants naturally orient themselves toward sunlight, optimizing light exposure and, therefore, energy harvesting. In addition to outdoor applications, plant-based solar energy harvesting systems can also function in controlled indoor environments (Yerva *et al.,* 2012). Flexible solar cells applied to plant leaves in greenhouses or indoor farms can capture ambient light and power sensors or monitoring devices. The advantage of this method is that it supports continuous monitoring of plant health, even in low-light conditions. The integration of PV cells into plant systems allows for a steady energy source that can power smart farm technologies without relying on external power supplies (Teng *et al.,* 2018).

Mechanical energy

Mechanical energy harvesting involves capturing kinetic energy from motion, vibration, or other mechanical forces and converting it into electrical energy. This approach is highly relevant to plant wearables, as plant structures like leaves and branches constantly move due to wind, rain, and other environmental forces (Guigon *et al.,* 2008). Among the techniques used for mechanical energy harvesting, piezoelectric, electromagnetic, and triboelectric mechanisms are particularly prominent. Piezoelectric systems, for instance, utilize materials that generate electric charges when subjected to mechanical stress, making them ideal for capturing energy from the bending and swaying of plants. Piezoelectric energy harvesting systems have been demonstrated to generate varying levels of recoverable energy depending on environmental conditions. For example, researchers have found that energy harvests from rainfall can range from 0.8 μJ/s during light rain to 1.2 mJ/s during heavy downpours.(Guigon *et al.,* 2008; Ong *et al.,* 2016; Wong *et al.,* 2015) To optimize energy output, researchers like F. Viola et al. have explored different piezoelectric structures, concluding that cantilever designs are more effective in capturing vertical movements, such as the impact of raindrops on plant leaves.(Viola, 2018) However, despite the promise of piezoelectric systems, their energy output is often inconsistent and requires additional storage systems to stabilize the harvested power for continuous use in agricultural sensors.

Triboelectric nanogenerators (TENGs) offer an alternative approach to mechanical energy harvesting. TENGs work by harnessing the triboelectric effect, in which two materials with different electron affinities generate electrical charges upon contact and separation. When integrated into plant-based systems, TENGs can convert the motion of leaves or the impact of rain into electrical energy. For instance, the first leaf-assembled TENG (Leaf-TENG) developed by Jie et al. successfully captured mechanical energy from plant leaves under manual vibration, generating a maximum power output of 45 mW/m².(Jie *et al.,* 2018) This power was sufficient to charge a capacitor and power small devices, such as LEDs and temperature sensors, demonstrating the feasibility of TENG-based energy harvesting in plant wearables. Several studies have further explored the potential of TENGs for plant-based energy harvesting in natural outdoor environments. Meder et al. demonstrated the first triboelectric energy harvesting system using living plants, such as Rhododendron yakushimanum and Nerium oleander, which captured wind energy through leaf movement (Meder *et al.,* 2018). By optimizing the dielectric materials and increasing the contact area, the system achieved power outputs of up to 15 μW/cm². The group also designed systems that could scale energy harvesting by connecting multiple leaves, resulting in a maximum power output of 300 Nw (Meder *et al.,* 2020). Such systems are ideal for powering small-scale electronic sensors that monitor plant health and environmental conditions.

In more recent advancements, researchers have focused on enhancing TENG designs to better withstand outdoor conditions, such as wind, rain, and humidity. For example, Lan *et al.* developed a waterproof and breathable TENG (WB-TENG) that adhered to plant leaves and efficiently converted wind and raindrop impact into electrical energy (Lan *et al.,* 2021). The film-based design, embedded with fluorinated carbon nanotubes, improved output performance while ensuring excellent water repellency and breathability. Such systems hold the potential to serve as wireless power stations for plant-based wearable sensors, transmitting data about plant health to mobile devices.

Chemical energy

Chemical energy harvesting, particularly through biofuel cells, represents a promising approach for generating electricity from plants by converting chemical energy into electrical energy. One method involves enzymatic biofuel cells, which use oxidoreductase enzymes to catalyze the conversion of chemical compounds like glucose and oxygen into electricity. This technology has been extensively studied in medical applications, such as powering implantable devices. However, its potential application in plant systems has only recently gained attention, with studies demonstrating the feasibility of converting the chemical energy in plants into usable power. A significant breakthrough in plant-based biofuel cells was first demonstrated by Mano *et al.,* who developed a biofuel cell using grapes (Mano *et al.,* 2003). The device was based on carbon fiber electrodes functionalized with redox polymers, glucose oxidase, and bilirubin oxidase enzymes. The grape biofuel cell was able to generate 240 $\mu W/cm^2$ of power and maintain 78% of its initial output after one day of operation. Similarly, biofuel cells have been implanted in cactus plants, where the power output increased by 70% under light conditions compared to dark conditions, suggesting the role of photosynthesis in boosting glucose and oxygen levels.(Flexer & Mano, 2010) However, the overall power output from the cactus biofuel cell was significantly lower (9 $\mu W/cm^2$), indicating that the concentration of glucose in different plant species can impact the performance of these cells. Another advancement in biofuel cell technology came with the development of a needle-shaped biofuel cell, designed for easier insertion into various living systems, including plants. This design separated the anode and cathode to prevent oxygen limitations at the cathode while improving the cell's overall performance. The needle-based biofuel cell implanted in a grape achieved a power output of 111 $\mu W/cm^2$ and was capable of powering a small LED (Miyake *et al.,* 2011). Researchers also explored the use of carbon nanotubepatterned electrodes, which significantly enhanced electron transfer between the enzyme reaction center and the electrode, resulting in a power density of 3.375 mW/cm^2 in grape biofuel cells (Yoshino *et al.,* 2013). Recent research has expanded the application of biofuel cells to larger fruits, such as oranges(Gordiichuk *et al.,* 2021). A biofuel cell implanted in an orange generated 90 μW/cm^2 and powered a transmitter that sent an email when the required voltage of 2.3 V was reached. The device was engineered to harvest energy from two different sugar sources glucose and fructose using pyrroloquinoline-quinone-dependent glucose dehydrogenase and flavin adenine dinucleotide-dependent fructose dehydrogenase, which are oxygen-independent enzymes. Despite being a destructive method for the fruit, this biofuel cell demonstrated that energy could be harvested from living plants to power small electronic devices and transmit data wirelessly.

Microbial fuel cells (MFCs) offer another approach to chemical energy harvesting in plant systems. In this method, electrochemically active bacteria colonize plant roots, where they oxidize organic substrates and transfer electrons to an external circuit, generating electricity. Early experiments with plants like Glyceria maxima and Spartina anglica demonstrated that microbial activity on the root surfaces could generate a small but steady current, making this technique promising for applications such as powering biosensors in wetland environments (Timmers *et al.,* 2010, 2012). Further research has focused on optimizing the performance of plant microbial fuel cells (P-MFCs) by enhancing the electron transfer rate and reducing internal resistance (Deng *et al.,* 2012). Although biofuel cells and microbial fuel cells provide a renewable source of energy from plants, challenges remain. Enzymes used in biofuel cells tend to lose activity over time, limiting the long-term stability of the power output (Dufil *et al.,* 2022). Additionally, the complexity of biological systems can result in electron losses, reducing the overall efficiency of energy conversion. However, ongoing research into electrode materials, enzyme stabilization, and system miniaturization continues to improve the performance and feasibility of plant-based chemical energy harvesting systems. These innovations have the potential to power low-energy devices in agriculture, supporting the development of self-sustaining plant wearable electronics for intelligent farming systems.

Conclusion

The development of plant-based wearable energy harvesters represents a transformative step in the pursuit of sustainable energy solutions, particularly within the context of smart farming and renewable energy integration. This review explored various energy harvesting technologies, including solar, mechanical, and chemical approaches, that can be integrated into plant wearables to provide autonomous power sources for agricultural sensors and other low-power devices. Solar energy, harvested through flexible photovoltaic cells, offers a reliable method for generating power by utilizing plant surfaces to capture sunlight, while mechanical and chemical energy harvesters tap into the natural movements and bioelectrochemical processes of plants, providing diverse energy alternatives that align with the goal of sustainable agriculture. Solar energy harvesting remains the most promising and widely applied technology due to its abundance and efficiency, particularly when integrated into flexible devices that can conform to plant surfaces. Mechanical energy harvesters, such as triboelectric nanogenerators, complement solar energy by capturing energy from wind and rain, further expanding the functionality of plant wearables. Chemical energy harvesters, including biofuel and microbial fuel cells, leverage the natural biochemical processes in plants, offering a unique way to generate power from the plant's own metabolic activities. These systems, when integrated with flexible and stretchable electronics, not only reduce dependence on external power sources but also contribute to the environmental benefits of clean energy production. Despite significant advancements, challenges remain in scaling up these technologies for widespread agricultural use. The efficiency of energy harvesters is often influenced by environmental factors, and the durability of devices in outdoor settings needs to be enhanced to withstand long-term exposure to the elements. Additionally, improving the power output of chemical and mechanical energy harvesters is essential for their practical application. Nonetheless, continued research and innovation in materials, design, and integration strategies hold great potential to overcome these obstacles, paving the way for plant-based wearable energy harvesters to play a pivotal role in the future of sustainable farming and renewable energy systems.

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