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Powering the future of farming: RF energy harvesting for environmental sustainability

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Abstract. Modern agriculture faces several challenges, including meeting the needs of an expanding population, mitigating the consequences of climate change, depleting natural resources, and reducing the industry's environmental impact. This paper explores the possibilities of microwave and radio frequency (RF) energy harvesting technologies as alternative and innovative means of advancing sustainable agriculture towards providing solutions for battery replacement. RF energy harvesting has the potential to power precision agriculture equipment, reduce power outages in distant areas, and facilitate the transition to more resource-efficient practices, according to a review of the industry's current and future issues. RF energy harvesting involves capturing ambient radio frequency signals and converting them into usable electrical energy. This technology harnesses energy from RF sources like cellular towers, Wi-Fi signals, and broadcast transmitters. The process includes capturing RF energy using antennas, converting it to DC power using rectifiers, and storing or using it to power devices. Despite the promise, RF energy harvesting faces challenges such as low energy density, limited efficiency of conversion, and fluctuations in signal strength. However, ongoing advancements in rectifiers, antennas, and integration with IoT devices could significantly enhance its viability. Moreover, as smart farming increasingly relies on IoT devices, RF energy harvesting could become a crucial power source for these low-power sensors and devices, promoting more sustainable farming practices by reducing reliance on conventional batteries. The future of RF energy harvesting looks promising with potential advancements in technology, new materials, and supportive policy and regulatory frameworks.

1. Introduction

The increasing global population, projected to reach 10 billion by 2050, poses a significant challenge in terms of food security, leading to heightened uncertainty. Effectively managing the increasing global population to ensure sustainable food production and ecosystem preservation is a multifaceted task. This is due to the depletion of resources, the degradation of the ecosystem, and the imminent threat of climate change.

One of the most important challenges is how to feed the world's growing population while maintaining the health of the earth. It is undeniable that achieving both environmental sustainability and food security at the same time is essential. In addition to being essential to maintaining human existence, the agricultural industry is a major driver of environmental deterioration. Over the past century, the adoption of intensive farming techniques has led to significant greenhouse gas emissions, soil erosion, water scarcity, and loss of biodiversity [1]. By increasing the frequency of extreme weather events, changing the locations of agricultural regions, and disrupting crop production, climate change worsens these problems and puts the most vulnerable populations at risk of experiencing the greatest degree of food insecurity [2]-[5].

The combination of these elements demands a paradigm change in favor of sustainable agricultural methods. There exists an urgent need for novel methodologies that can simultaneously mitigate the environmental harm inflicted by agriculture and enhance food security. Sustainable agriculture refers to methods that satisfy current demands without endangering the capacity of future generations to satisfy the requirements. It seeks to achieve a careful balance between resource conservation, environmental preservation, and enhanced productivity. The field of energy harvesting, more especially the extraction and application of microwave and radio frequency (RF) energy, presents a bright spot for innovation. In today's surroundings, radiofrequency (RF) and microwave energy are present everywhere. These sources include Wi-Fi routers, cellular networks, and broadcast stations. By utilizing even, a tiny amount of this ambient energy, agricultural technologies may be powered less frequently by conventional, frequently non-sustainable power sources. This study investigates the potential of microwave and radio frequency (RF) energy harvesting as a viable strategy to support this crucial transition to sustainable agriculture.

2. Current and Future Issues in Agriculture

One of the primary concerns that confronts agriculture in the present and future are the implications of climate change. The effects of climate change on agricultural cycles include diminished harvests and challenging transitions for cultivators. Flammable occurrences such as wildfires, floods, droughts, and floods caused extensive damage to agricultural infrastructure, livestock, and crops. Particularly for irrigation-dependent agriculture, climate-induced droughts and precipitation changes worsen water scarcity, endangering the future viability of farming in arid and semi-arid regions [6]-[7]. In order to ensure the sustainability of agriculture, these changes necessitate meticulous planning and adaptation.

The second concern most farmers are facing in the agricultural sector is resource depletion. Depletion of water resources is the result of excessive groundwater utilization for irrigation, posing a threat to agriculture's sustainability. Rising sea levels and excessive consumption further compromise the water's quality. Erosion and a reduction in soil fertility ensue because of the depletion of soil nutrients caused by intensive agricultural practices [8]-[10]. It is indisputable that excessive tillage and monocropping have adverse impacts on both soil health and biodiversity. The introduction of synthetic fertilizers into ecosystems contributes to the formation of 'dead zones', greenhouse gas emissions, and polluting water sources. The excessive application of pesticides disrupts the ecological balance and promotes the development of parasites that have acquired resistance to these substances [11]-[12].

Additionally, energy demands are a concern in the agricultural sector. The agricultural sector's energy requirements include input production, processing, transportation, and irrigation. Irrigation pumps utilize a considerable quantity of energy when operating in deep aquifer systems. Transportation and postharvest processing impact the industry's carbon emissions [13]-[15]. Furthermore, the use of synthetic fertilizers and pesticides is a source of indirect energy expenses.

Small farmers face challenges in using sophisticated technology due to their limited infrastructure, financial resources, and resources. A viable alternative is radiofrequency energy harvesting, which offers a cheap, sustainable power source for a range of agricultural applications. Soil moisture sensors are essential in this case because they track the amount of water in the soil, allowing for more efficient watering schedules. In agriculture, growth and production depend on efficient water use, particularly in areas with limited water supplies. Radiofrequency energy harvesting could fuel these sensors, lowering maintenance costs and enhancing operational efficiency through continuous monitoring and fewer battery changes. For instance, information sent to a central station from a network of soil moisture

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sensors positioned throughout a field can enable accurate irrigation management. Another essential piece of equipment is a weather station, which gathers meteorological data like temperature, humidity, wind speed, and precipitation. Accurate meteorological data is essential for crop planting, harvesting, and weather protection. These stations can function in remote locations without a grid connection by using RF energy harvesting, allowing for dependable data collection and reducing the need for battery replacements. For example, a solar-powered weather station with an RF energy-gathering device could provide real-time information to improve farming techniques. Systems for tracking livestock are another use case for radiofrequency energy collection. These devices track the movements, health, and activity of cattle to give farmers access to real-time data. A constant watch on cattle health and conduct is essential for early disease detection, effective grazing regulation, and animal welfare. A central system can receive data from animals equipped with radiofrequency (RF) sensors, reducing total maintenance and obviating the need for regular battery changes. Radiofrequency radiation powers RFID tags, which track animal movements and other health indicators, alerting farmers when remedial action is necessary. The monitoring of illnesses and pests is another use for which radiofrequency energy harvesting can be especially useful. Farmers are able to take preventative action since sensors identify early indicators of plant illnesses and pest presence. This results in a reduced requirement for chemical treatments and a decrease in agricultural losses. Radio-frequency energy-based sensors can deliver data in real time and require fewer batteries overall. For instance, an RF-powered pest monitoring system can notify farmers when dangerous insects are present and enable prompt crop protection measures [16].

RF energy harvesting presents a significant opportunity for cost reduction in agriculture, primarily by replacing traditional batteries. This eliminates the need for frequent battery replacements, a labour-intensive and time-consuming task, leading to substantial long-term savings for farmers. Additionally, RF energy harvesting promotes environmental sustainability by reducing battery waste, which can leach harmful toxins if not disposed of properly [17]. Moreover, RF-powered agricultural devices experience improved reliability due to the uninterrupted power supply, minimizing data loss and ensuring the effectiveness of precision agriculture techniques.

In the end, technological limitations take precedence. Inadequacies in digital infrastructure, economic barriers, and technological limitations, such as those pertaining to precision agriculture, impede the efficient distribution of resources in underdeveloped areas. The implementation of these technologies is greatly hindered by obstacles, including inadequate electrical infrastructure, high initial costs, and unreliable internet connectivity. These challenges are particularly severe for small-scale producers located in poor or remote regions.

3. RF and Microwave Energy Harvesting for Sustainable Agriculture

RF and microwave energy harvesting holds great potential for promoting sustainable agriculture. However, it is crucial to maintain a balanced viewpoint that recognizes both the significant benefits this technology offers and the practical obstacles that must be overcome for its widespread adoption. RF/microwave energy harvesting has the potential to greatly decrease dependence on fossil fuel-based energy sources for powering low-consumption agricultural devices, especially in distant areas. This can result in a reduction in greenhouse gas emissions linked to conventional grid-powered systems. In addition, the decreased necessity for regular battery replacement and disposal can help reduce the environmental impact of agricultural sensor networks [18]-[24]. However, researchers and engineers are faced with the present constraints of energy conversion efficiencies. Power densities in the environment are often at a low level, which means that careful antenna design and efficient power conversion circuits are necessary in order to provide usable energy [25]. Ongoing progress in these fields is essential for optimizing the potential of RF/microwave energy harvesting in agriculture.

Figure 1. RF energy harvesting as an alternative power source for sustainable agriculture.

3.1. Concept and fundamental of radio frequency energy harvesting

RF and microwave energy propagates through the environment from sources such as radio and television broadcast stations, cellular base stations, Wi-Fi routers, and satellite transmissions. While the power density of these signals is relatively low, specialized harvesting technologies can capture this energy. Conversion methods encompass the use of a specialized antenna, commonly referred to as a rectenna [26], which is employed to resonate at the exact frequencies of the RF and microwave sources in its vicinity. Rectification is the process of transforming the accumulated AC signal into practical DC power by means of a rectifier circuit. Power management involves the utilization of voltage regulators and energy storage components to maintain a consistent power supply to devices in situations where power harvesting is limited or sporadic.

An antenna is a device that receives and transmits radio frequency signals from many sources, such as broadcast transmitters, cellular towers, and Wi-Fi routers. Yagi-Uda, dipole, and patch antennas are among the types of antennas whose selection is based on the frequency range and specific needs of the application. A matching network oversees lining up the antenna's impedance with the rectifier to attain maximum power transfer. Typically, designs arrange capacitors and inductors precisely to improve impedance matching. The rectifier converts the received RF signals (AC) into a constant direct current (DC) electrical flow. Typically, components consist of capacitors, diodes, and occasionally transistors. The diodes change the alternating current (AC) input into a direct current (DC) signal, and the capacitors get rid of any noise in the rectified signal to make the DC output stable and constant. The rectifier's efficiency directly influences the effective conversion of RF energy into usable electrical power, making it an essential component. The rectified DC voltage undergoes transformation to the appropriate level for the intended usage. Typical components are switching devices, capacitors, and inductors. Furthermore, this phase could apply Maximum Power Point Tracking (MPPT) strategies to improve the energy conversion process's efficiency. Lastly, is the energy storage goal, which is used to store the energy gathered for later use or to provide a consistent power source in situations where RF signals are inaccessible or weak. Rechargeable batteries and supercapacitors are common storage components in electronic systems. The duty cycle and power requirements of the application will determine whether supercapacitors or batteries are best. The electricity management unit (PMU) is one part of a system that is responsible for controlling and managing electricity. The aim is to oversee the allocation of collected energy to the load, which comprises wireless transmitters, microcontrollers, and sensors. Microcontrollers, switches, and voltage regulators are among the parts that guarantee efficient power distribution and shield the system from overvoltage or undervoltage conditions [27].

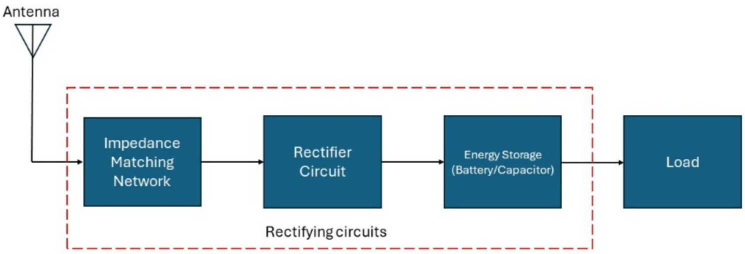

Figure 2. Block Diagram of RF Energy Harvesting

Many researchers have reported that wireless Internet of Things (IoT) sensors are starting to be powered by radio frequency (RF) energy harvesting, which does away with the requirement for batteries and the related storage and lifespan restrictions. Telemetry systems, passive radio frequency identification (RFID) systems, and biomedical implanted equipment are further potential uses. The components of an RF energy harvester are an RF-to-DC converter and an existing wireless source (such as Wi-Fi or cellular) that scavenges electromagnetic energy sent by a specialized transmitter to create a DC supply source. [28]-[31].

3.2. *Smart farming applications*

The utilization of RF/microwave energy harvesting technology enables the continuous operation of various sensors, resulting in cost and maintenance reductions within the field of precision agriculture. For example, soil moisture sensor. Optimizing irrigation to prevent water waste using RF/microwave energy harvesting technology was reported in [32].

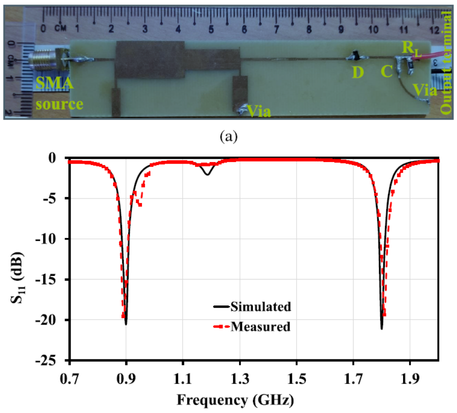

Figure 3. (a) Fabricated of RF-rectifier circuit (b) Simulated and measured reflection coefficient S_{11} [32]

The paper presents a dual band rectenna with a large range for extracting ambient radio frequency (RF) energy from GSM/900 and GSM/1800. The rectenna circuit is simplified using a dual-band impedance matching network (IMN), incorporating a dual-band inverted-F monopole antenna with the RF rectifier. This reduces the complexity of the circuit, enhancing the efficiency of RF-to-dc power conversion. The design achieved a maximum power conversion efficiency of 12.93% and 8.0% for an input power of -30 dBm at frequencies of 0.9 GHz and 1.8 GHz. The ambiance measurement achieved a direct current voltage output of 0.374 V, and the low-powered bq25504-674 evaluation module (EVM) provided a voltage of 0.747 V. Other examples include nutrient level sensors and crop health sensors.

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Remote Monitoring is also another example of application for RF/microwave harvesting, which can provide power in regions with unreliable or non-existent electrical grids. Climate data, such as temperature and rainfall, is gathered by environmental monitoring systems to generate localized forecasts and conduct risk assessments. Livestock tracking devices are used to monitor the whereabouts of animals and assess their health indicators [33]-[38].

Lastly, irrigation and automation system. Where RF/microwave harvesting offers the potential to power smart irrigation controllers and IoT development [39], for example the system receives input from soil moisture sensors to tailor water application indirectly preventing overuse. Localized actuators by control valves or other components of precision irrigation systems, enabling precise control of water distribution.

4. Advantages and Challenges

4.1. Advantages

RF and microwave energy harvesting provides numerous advantages from an environmental sustainability perspective. By harnessing ambient RF and microwave radiation from multiple sources, agricultural enterprises can reduce their reliance on fossil fuels to power low-energy devices such as sensors and monitoring systems. These results can help to reduce greenhouse gas emissions linked to conventional grid-based electricity generation and transmission [40]-[42].

Furthermore, RF and microwave energy harvesting reduces the need for regular battery replacement and disposal, thereby mitigating the environmental consequences of discarded batteries, some of which may contain hazardous substances [43]-[44]. This technology has the potential to enhance the sustainability of the agricultural sector by encouraging the adoption of greener energy sources and decreasing dependence on finite resources.

4.1.1. Reduced environmental impact

With the rise of extreme weather and changes in the climate, the chances of power grid interruptions are increasing. In such situations, RF and microwave energy harvesting can serve as a vital backup power supply for key agricultural monitoring equipment. Data continuity is crucial for making well-informed decisions both during and after disruptions. Moreover, the collection of energy might potentially facilitate fundamental irrigation operations in the event of power failures, protecting crops from drying out and reducing potential decreases in agricultural production. This increased ability to recover quickly and effectively is especially important for farms or regions that are physically isolated or frequently experience severe weather events [45]-[46].

4.1.2. Accessibility

RF and microwave energy harvesting provides a transformative option for powering precision agriculture sensors in areas with unreliable electrical infrastructure or where expanding the power grid is excessively costly. This technology has the potential to enable farmers in underserved areas to utilize a variety of sensors and monitoring tools that would otherwise be inaccessible. RF/microwave energy harvesting has the potential to transform agricultural practices in these areas by facilitating the adoption of precision irrigation systems, soil moisture sensors, and automated data collection tools. These advancements can result in substantial enhancements in the management of water, the application of fertilizers, and the overall production of crops, even for small-scale farmers with limited resources. Moreover, the capacity to energize environmental monitoring systems and animal tracking devices might improve agricultural decision-making and encourage the adoption of more sustainable farming techniques [47]-[48].

4.1.3. Resilience
With the rise of extreme weather and climate change, the chances of power grid interruptions are increasing. In such situations, RF/microwave energy harvesting can serve as a vital backup power supply for key agricultural monitoring equipment. Data continuity is essential for making well-informed decisions both during and after disruptions. Moreover, the collection of energy might potentially facilitate fundamental irrigation operations in the event of power failures, protecting crops from drying out and reducing potential decreases in agricultural production. This increased ability to recover and adapt is particularly crucial for farms or regions that are geographically isolated or susceptible to severe weather occurrences [49]-[51]

4.2. Challenges
However, to fully realize the potential of microwave and radiofrequency energy harvesting in agriculture, scientists and engineers will need to overcome several obstacles. An important obstacle exists in the present constraints on energy conversion efficiencies. Due to the often-low power densities of ambient RF and microwave signals, it is necessary to employ meticulous antenna design and sophisticated energy conversion circuitry in order to efficiently capture and convert sufficient energy to operate agricultural devices [18-[19]. Continued research is being conducted to create rectenna systems that are more efficient, capable of functioning well across a broader spectrum of frequencies, and adaptable to different environmental circumstances.

Another obstacle involves the establishment of suitable regulatory frameworks for this emergent technology. To avoid interference with current communication systems and the development of safety risks related to electromagnetic radiation, clear restrictions will be required as RF/microwave energy harvesting becomes more common. In order to create these frameworks and promote innovation while preserving the environment and public health, cooperation between regulatory agencies, technological developers, and the agriculture industry will be essential.

4.3 Innovative technologies and materials
Advancements in RF energy harvesting technologies and materials are crucial to improve the efficiency, affordability, and scalability of these systems. Key areas of innovation include rectenna design, energy storage, power management, and integration with other technologies. Rectennas, specialized antennas that convert RF radiation into DC power, are being researched to improve efficiency, broaden frequency range, and reduce costs, with new materials like graphene and metamaterials being explored. Efficient energy storage is essential, especially with intermittent RF sources, and research focuses on new battery technologies, supercapacitors, and hybrid solutions. Intelligent power management circuits are needed to optimize energy flow, using techniques like maximum power point tracking, voltage regulation, and load matching. Integrating RF energy harvesting with other technologies, such as solar and thermoelectric energy harvesting, can create hybrid systems that harvest energy from multiple sources, increasing reliability and versatility [52].

5. Discussion
The problems caused by unsustainable agricultural practices, exacerbated by population expansion, climate change, and limited resources, necessitate an urgent shift to more intelligent and resource-efficient farming. RF energy harvesting is a promising technology for advancing Internet of Things (IoT) applications and smart farming systems, particularly in sustainable agriculture operations. This technology allows wireless devices to extract energy from radio frequency (RF) signals for their information processing and transmission needs [53]. RF-based energy harvesting is suitable for low-power applications like sensor networks and can also be extended to scenarios with higher power requirements through dedicated wireless power transmission methods [54]. This approach has the potential to reduce or eliminate the need for batteries, thus lowering system costs, and enables the extraction of RF power from the environment [55]. The development of compact folded dipole rectennas with RF energy harvesting capabilities has been proposed to enable the autonomous operation of IoT

smart sensors [56]. Efficient rectennas have been designed to harvest RF energy, with some incorporating innovative elements like vertical ground-walls to enhance energy harvesting capabilities [57]. In the context of sustainable agriculture, integrating lean principles and optimization methodologies is crucial for minimizing waste in agricultural production systems to ensure sustainability [58]. Furthermore, renewable energy sources, including RF energy harvesting, offer opportunities to enhance agricultural practices' resilience and efficiency [59]. Precision agriculture, enabled by technologies like RF energy harvesting, plays a vital role in improving the efficiency, productivity, and sustainability of agricultural operations [60].

By harvesting of the ambient RF energy present in the environment, even a small portion, this technology offers the potential to overcome power limitations for a variety of low-power IoT devices essential for precision agriculture and environmental monitoring. For example, RF energy harvesting can power sensors that continuously monitor soil moisture, nutrient levels, and crop health in remote areas or underserved regions lacking reliable power infrastructure. Data collected by these sensors allows for targeted and optimized irrigation, minimizing water waste and preserving this critical resource. Additionally, timely data on nutrient levels enables tailored fertilizer application, preventing overuse and its negative environmental consequences, such as eutrophication of waterways.

The ability to power remote environmental monitoring systems through RF energy harvesting further enhances decision-making for sustainable farming. In areas without electricity, this can include sensors for collecting localized climate data (temperature, rainfall, humidity). Access to this real-time information facilitates climate-resilient crop selection, adaptive planting schedules, and proactive risk mitigation strategies in line with changing weather patterns. RF energy harvesting also holds promise for powering livestock tracking in extensive grazing systems, contributing to more sustainable land use, and facilitating animal health assessments in dispersed settings.

While there are challenges in current conversion efficiencies and a developing regulatory landscape, the potential benefits of RF energy harvesting for sustainable agriculture are significant. Its contribution to reduced fossil fuel reliance for small-scale devices, lessened battery waste, and expansion of precision agriculture tools into off-grid areas collectively promote environmental sustainability goals.

Continued innovation in antenna design, circuit efficiency, and energy storage solutions is crucial for maximizing the potential of this technology. Many authors demonstrating the economic viability and positive ecological impacts of RF-powered IoT devices in the field will play a key role in shaping future regulatory frameworks and fostering broader adoption. The integration of RF energy harvesting within a holistic approach to sustainable agriculture practices has the potential to reduce environmental impact, improve yields, and empower farmers worldwide, especially in underserved regions.

6. Conclusion

RF and microwave energy harvesting holds significant promise for transforming agricultural practices, particularly in areas with limited or unreliable access to grid power and where resource constraints are a major challenge. By reducing reliance on fossil fuels and batteries for powering agricultural monitoring and low-power applications, this technology can play a pivotal role in fostering more sustainable practices. This can lead to improved water management through precision irrigation, optimized fertilizer application based on real-time soil nutrient data, and earlier detection of pests and diseases, all contributing to increased yields and reduced environmental impact. Furthermore, RF/microwave energy harvesting can empower smallholder farmers in underserved regions to adopt precision agriculture technologies that would otherwise be out of reach, promoting greater equity and resilience within the agricultural sector. As research progresses and the technology matures, the potential applications of RF/microwave energy harvesting in agriculture are likely to expand, offering exciting possibilities for a more sustainable and food-secure future.

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