Journal of Modern Computing and Engineering Research
JMCER
Volume 2025, p. 28-41
https://jmcer.org

A Review on Advanced Rectenna System for Wearable Applications

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Received: 08/ March /2025 Revised: 7 / May / 2025 Accepted: 21/May/2025

Abstract:
This article presents a review of different types of miniaturized rectenna integrated circuits (IC) used for energy harvesting applications such as wearable applications. Two fundamental parts make up the rectenna design: a receive antenna that gathers radio-frequency (RF) energy from the ambient and a rectifier circuit that converts RF energy into DC voltage for use in low-power electronics devices like wearable medical devices (WMDs). In order to increase conversion efficiency and output power at a specific input power and suitable load resistance, microwave Schottky diodes from the HSMS-28xx and SMS-76xx series are utilized as a voltage doubler rectifier (VDR) integrated with a wearable antenna. The miniaturization, patient safety, biocompatibility, operating frequency, insensitivity to detuning, and conversion efficiency are some of the many challenges in the design of wearable rectenna IC. This review paper provides an overview of the entire body of research on rectennas conducted for novel design approaches in wearable devices operating at industrial, scientific, and medical (ISM) bands like 2.4GHz, 915MHz, and 415MHz.

Keywords: *Energy Harvesting System, Wearable Sensors, Rectifier Circuits, and Wearable Antenna*

1 Introduction

With significant economic and social ramifications for the future of our planet, the growing need for clean renewable energy on a global scale in recent years has become a critical issue. Consequently, energy harvesting the process of gathering energy from the environment has grown in importance (Saifi et al., 2024). Therefore, the energy harvesting has become very important to harvest RF energy from the ambient (Rao et al., 2022). Ambient energy is the process by which energy is derived from external sources, such as solar energy harvesting (Xiao et al., 2023), piezoelectric vibration energy harvesting (Sun et al., 2024), thermal energy harvesting (Nakamura and Yamashita, 2024), and RF energy harvesting (RFEH) as shown in Fig. 1 (Singh and Chaturvedi, 2023) .

This review paper's primary focus is on energy harvesting applications that use rectenna circuits to gather environmental radio frequency signals and transform them into DC voltage for low-power electronic devices. As seen in Fig. 2, the fundamental components of the rectenna system are the wearable antenna, rectifier circuit, harmonic regression filter, and load resistance. This system combines different research fields that have a bright future for powering to turn low-power biomedical electronic devices such as WMDs and wireless sensor networks WSNs (Dilruba Geyikoglu, 2023).

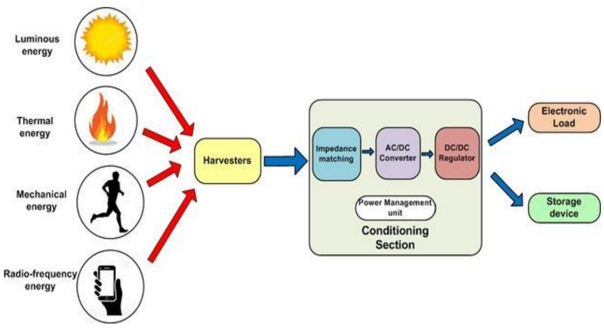


Figure 1: Typical wearable energy harvesting systems (Singh and Chaturvedi, 2023)

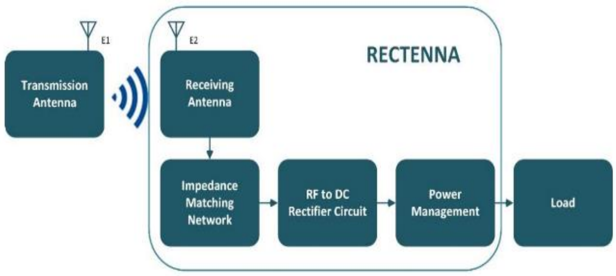


Figure 2: Schematic diagram of RF energy harvesting system (Dilruba Geyikoglu, 2023)

The Wearable Medical Devices (WMDs) have recently attracted the attention of scientists due to people are increasingly using these devices such as smartwatches (Atan et al., 2024), fitness trackers such as the Fitbit Charge (Yan, 2024), VR headsets (Chen, 2024) , smart jewelry (Yang et al., 2024), web-enabled glasses and Bluetooth headsets, as a result of recent advancements in the health-care system and specially after COVID 19 occurrence. Wireless charging is required for WMD in the human body.

The wearable antenna operates as a receiver to harvest ambient RF signals, as shown in Fig. 2. Different structures of its antenna designs have been used for wearable applications such as micro-strip patch (MSPA) (Khattak et al., 2024), Folded dipole antenna (FDA) (Bakogianni et al., 2024), circular polarized antennas (CP) (Ishihara et al., 2024), and PIFA. The rectifying circuit design based on microwave Schottky tunnel diodes is a role in the wireless power transfer systems through evaluation of both the conversion efficiency and output power. Several topologies of the rectifier circuits such as series/shunt diode (Soleimani and Karabulut Kurt, 2024), half-wave rectifier (Pradeep Dhanawade et al., 2024), full-wave bridge (Abidin et al., 2023), and voltage doubler rectifier (Yeo and Kim, 2024). The optimum load resistance of the rectenna systems is selected in order to achieve high conversion efficiency and DC output power with voltage.

As previously stated, compact size and outstanding efficiency are among the main design problems for wearable rectenna systems. A lot of research has been done on these in an effort to improve that. Firstly, in 2021 Muhammad Shahzad For wristwatch bands, a dual-band AMC-backed tiny antenna with dimensions of 28.81 × 19.22 × 1.58 mm^3 was created. It operates at 2.45 GHz and 5.8 GHz. It maintained SAR values of 0.19 and 1.18 W/kg, well below FCC and ICNIRP limitations, and obtained gains of 2.44 dB and 6.17 dB with efficiencies of 50% and 72%. Bending little affected the antenna's performance, which made it ideal for wearable Internet of Things application (Shahzad et al., 2021a).

Another resarcher in (Khokher et al., 2024), focuses on 45×40 mm^2 patch size microstrip wearable antenna was created for ISM band 2.4GHz applications using jeans fabric. The antenna met IEEE C95.1:1999 requirements by displaying low SAR values and maintaining steady performance under bending situations. SAR is a dependable choice for body-worn health monitoring applications because it reduced as the distance between the antenna and the three-layer tissue rose.

2 Wearable Antenna Design

There are various obstacles in the development of WMD devices, which have been thoroughly investigated in recent years using RF energy harvesting. As a result, this analysis explores antenna design and definition while the human body is present, as well as unique designs that address a number of existing difficulties, including integration, efficiency, miniaturization, and frequency detuning. To optimize the performance of wearable antennas inside human tissue, it is important to study the interaction between embedded antennas and biological tissues, which represents electrical permittivity (ε) and electrical conductivity (σ) (Modak et al., 2024a). The following are the criteria and obstacles associated with designing wearable micro-strip or dipole antennas in the human body.

2.1. Frequency of Operation

WMD devices employ a variety of WPT system approaches. Initially, inductive coupling operates at 13.56 MHz, followed by RF bands like MICS and ISM bands. High frequency can be employed with minimal power loss to create tiny antenna sizes. The most important element that is altered by the operating frequency is the field areas of the implant antennas. The main obstacle in implant antenna design is that when an antenna is placed in bio-tissues that use many frequency bands and transition zones, its effectiveness is decreased. The antenna's reactive, radiation near-field, transition zone, and far-field zones are displayed in Table 1 for medical bands like 403 MHz, 915 MHz, 2.45GHz. Ultimately, we deduce that the antenna's operating frequency is inversely related to the area size and separation between the implant receive antenna (Rx) and transmitter antenna (Tx) (Saha et al., 2024).

Table 1. Field regions for wearable & implant antenna based on the ISM medical bands (Saha et al., 2024)

Radiative Region	***Distance between Tx &Rx [mm]***	***403 [MHz]***	***915 [MHz]***	***2.45 [GHz]***
Reactive near-field	00.159λ	17.30	8.5	3.20
Radiative far-field	λ	108.9	52.7	19.9
Transition zone	2 λ	217.80	107.4	39.7

2.2. Safety and phantom tissues

The rate of energy deposited per unit mass of tissues is known as the specific absorption rate, or SAR. According to IEEE C95.1-2005 Europe and IEEE C95.1-1999 USA, the two standard limits of SAR averaged are 1g and 10g tissue in the form of a cube, respectively. Therefore, 1.6W/kg and 2W/kg are the patient safety levels for human tissues (Abdul-Al et al., 2022) . The needs and difficulties of designing wearable microstrip or dipole antennas in the presence of a human body are described below, as Table 2 illustrates. Skin, fat, and muscle are examples of living tissues whose dielectric characteristics change with frequency.

Table 2: Shows the dielectric properties of human tissue at different frequencies (Abdul-Al et al., 2022)

	ε_r			σ [S/m]		
Freq. [MHz]	**403**	**915**	**2450**	**403**	**915**	**2450**
Skin	46.7	41	38	0.69	0.8	1.47
Fat	5.58	5.5	5.28	0.041	0.04	0.11
Muscle	57.1	52	52.73	0.797	1.73	1.739
Bone	13.14	12.5	11.38	0.092	0.14	0.394

The following tables provide a survey of the literature on the various difficulties in designing wireless wearable rectennae for biomedical purposes. One of the most significant concerns that arises when the environment of the antenna system comes into contact with layers of the human body is biocompatibility. The small antenna can be worn on layers of the human body, including skin, muscle, fat, and bone as shown in Fig. 3. Consequently, it is important to investigate how wearable antennas and bio-tissues interact (Aldhaibani et al., 2024).

2.3. Characterization of the antenna

One of the primary obstacles in the design and manufacturing of wearable antennas for the human body is experimental validation prior to integration with the whole rectifier device. Reflection coefficient, gain, efficiency, radiation pattern, and bending are the far-field characteristics there for Several techniques, including Electromagnetic Band Gap (EBG), Artificial Magnetic Conductor (AMC) (Shahzad et al., 2021b), and Circular Split-Ring Resonators (CSRR) (Sabban, 2022), were employed to optimize these characteristics as in Table 3.

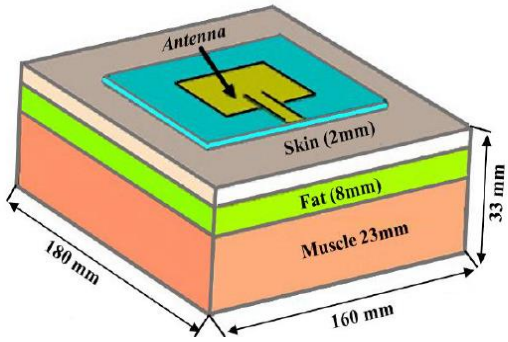


Figure 3: The phantom flat of the human body tissues with a different thickness (Aldhaibani et al., 2024)

2.4 Radiation pattern, gain and efficiency

The framing environment, particularly in the near -field region, has a significant impact on the antenna's efficiency and radiation pattern. the ratio of the antenna's radiated power to the delivered value is known as the radiation efficiency. The SAR value of biological tissue and the radiation effectiveness for on-body antennas are decreased when the radiation pattern's directionality tends to deviate from the body direction. (Abd Rahman et al., 2019).

Table 3: Different methods for improvement antenna's characteristics

Ref	*Size [mm²]*	*Substrate Materials*	*Reflector/ Unit cell*	*Gain [dBi]*
(Rajendran, 2022)	42×30	Felt	EBG/ 4×3	6
(Singh and Verma, 2020)	40×20	Textile	EBG 2×1	4.5
(Pei et al., 2020)	120×120	Leather & Textile	EBG 3×3	7.3
(Ashyap et al., 2020)	60×60	Fabric	EBG 2×2	6.45
(Saeed et al., 2017)	30×20	Denim	AMC	2.05
(Ashyap et al., 2021)	45×45	Fabric	HIS/ 3×3	7.4
(Bait-Suwailam et al., 2020)	145×112	Denim	HIS/ 4×3	6.2
(Joshi et al., 2020)	81×81	Felt	AMC/ 3×3	7.3
(Ejaz et al., 2023)	35.4×82.4	Denim	EBG/ 2×1	7.4

Wearable antennas are crucial to advanced wireless devices, including biomonitoring, medical communications, and the Internet of things, therefore they have developed significantly. The ISM (Industrial, Scientific, and Medical) band is one of the most popular bands for these antennas due to its ability to deliver consistent communications while using little power, making it perfect for wearable devices. Many studies have been conducted to build and optimize these antennas for maximum flexibility, radiation efficiency, and responsiveness to body movements. Modern study has concentrated on the development of bendable antennas, improved components, and novel ways for reducing electromagnetic noise and ensuring consistent performance in a variety of environments. This part summarizes the most significant prior study on portable device antennas in the ISM band.

AdelY. provided. Ashia and Akram Al-Omani conducted research at 2.4GHz frequency to reduce background radiation and enhance wave reaction ratio by 15.5dB using a mobile antenna with a tiny EBG construction. The antenna has a gain of 7.8dB, a low specific absorption rate (SAR) of more than 95%, and a bandwidth of 27% (2.17-2.83 GHz), all of which meet the FCC and CNIRP criteria for portable applications in medicine (Ashyap et al., 2017a).

Amirkhanian Shadia propose an investigation in the 1.38-1.8GHz and 2.25-4.88GHz frequency bands, covering WMTS and ISM, utilizing a tiny and highly efficient mobile antenna. This antenna is based on the fractal Moor design and rectangular loop geometry. The antenna is suitable for biomedical and remote diagnostic applications since it has a very low SAR of approximately 0.025 W/Kg at 24 dBm power, a gain of 2.2dBi , with radiation effectiveness of 95%.(Khan et al., 2022a).

Jaafar A. Aldhaibaini in 2024 study for medical purposes, a wearable microstrip antenna (WPA) operating at 2.43 GHz was developed and put into use. It demonstrated consistent performance in spite of human body effect and achieved a radiation gain of 7.8224dB. A thin copper layer was added to solve the SMA connector breakage issue, improving the design's robustness and confirming strong agreement between simulation and real measurements (Aldhaibani et al., 2024).

In 2024, Albert Sabban will introduce a new meta-fractal antennas and sensors with dual polarization, small design, and wideband performance for 5G, 6G, IoT, and medical applications with a bandwidth of 9% to 20%. The metamaterial antennas are effective for wearable and smart grid applications since they have a noise figure of 1 dB with the TAV541 LNA and a gain of up to 13.5 dB at 2.83 GHz, which drops to 8 dB at 3.2 GHz (Sabban, 2024a)

A number of the wearable antenna design's structures were released, as indicated in the Table 4.

Table 4: Different antenna structures for wearable applications

Ref.	*Freq. [GHz]*	*Antenna structures*	*Dielectric/ Gain [dBi]*	*Size [mm^3]*
(Ashyap et al., 2017b)	2.4	MSPA based EBG	Denim/ 7.8	46×46×2.4
(Khan et al., 2022b)	2.25 - 4.88	Rectangular patch-based AMC	Rogers 5880/ 2.2	0.13×0.09 ×0.004
(Aldhaibani et al., 2024)	2.43	MSPA based FIT	Copper/ 7.82	41.2×59.9 ×1.6
(Shahzad et al., 2021c)	2.45 - 5.8	MSPA based AMC	Roger/ 5.9	28.81×19.2 ×1.6
(Sabban, 2024b)	2.4	MSPA CSSRS	FR-4/ 8.5	33×20×3.2
(Huang et al., 2022)	0.402-0.405	PIFA antenna	FR-4/ 18.8	10×10× 1.905
(Modak et al., 2024b)	3.5 - 10.5	Monopole antenna	Polymer/ 4-2	16×10 ×0.05
(Dam et al., 2023)	2.4 - 5.2	T-shaped antenna based EBG	RT 5880/ 1.4-6.25	56×56

3 Rectifier Circuit Design

In order to charge the batteries of WMD devices, the rectifying circuit assists in converting the radio frequency signals that antennas receive into an electrical DC current. Selecting the appropriate diode is essential since the rectifier circuit's diode is crucial. The performance of the rectifier affects the performance of the entire rectenna (Muhammad et al., 2020). The harmonic rectifier circuit was examined using a VDR setup. In order to make efficient Rectenna systems for wearable applications, the rectifier circuit topologies based on different key metrics such as compact design, high efficiency and low power.

In this section, a general overview of efficient rectifiers based on diodes have been presented. This section can be divided by two parts: the rectifier circuits based on Schottky barrier diodes have lower forward voltage and faster switching, which is good for efficiency. Secondly, active rectifiers based on MOSFETs are highlighted for lower losses. But this is more general, not specific to wearables.

The primary performance indicator in the rectifier study is the RF to DC conversion efficiency. Due to their large breakdown voltage (V_{br}), low series resistance (R_s), low junction capacitance (C_{jo}), and low threshold voltage (V_{th}) or low turn-on voltage, Schottky diodes are utilized to build rectifier circuits at radio frequency ranges (Pandey et al., 2021). The literature has examined various Schottky-diode family for rectenna application, as shown in Table 5.

Table 5: Several types of Schottky barrier diodes with characteristics parameters (Pandey et al., 2021)

Ref.	*Diode Model*	V_{th} *[V]*	R_s *[Ω]*	C_{jo} *[pF]*	V_{br} *[V]*	I_s *[µA]*
(Zhu et al., 2019)	SMS 7630	0.09	20	0.14	2.0	5.0
(Liu et al., 2022)	HSMS 2852	0.15	25	---	3.8	3.0
(Razak and Hamid, 2021)	HSMS 2860	0.25	6.0	---	6.5	0.05
(Salleh et al., 2021)	HSMS 2850	0.15	25	0.18	3.8	3.0
(Zhou and Chang, 2021)	HSMS 286B	0.69	6.0	0.18	7.1	0.05
(Oh et al., 2022)	HSMS 2820	0.15	6.0	7.0	15	0.02

Numerous studies on the design of rectifier circuits used in medical rectenna systems have been published. Estrada, José Antonio, et al. in 2020 proposed a new wideband tightly coupled rectenna array T-shirt for RF harvest energy from 2 to 5 GHz at power densities of 4-130 µW/cm². The proposed rectifier circuit is based on the SMS7630-079 LF Schottky barrier diode that is coupled by silver paint. The simulated and measured results from real-body testing were consistent with measurements made with a phantom body, which demonstrated up to 32% efficiency at 100 µW/cm². The suitability of conductive ink printing for wearable energy harvesters was confirmed by an analysis of the impacts of curvature, air gap, and washing (Antonio Estrada et al., 2020).

In 2020, Chi, Yu-Jin, and Chiu (Chi et al., 2020), presented a novel wearable textile orthogonal antenna array using Cordura fabric and requiring no batteries. The proposed rectifier antenna combines a wearable linearly polarized patch rectifier with a single-stage Grinach rectifier to power handheld devices. A foam layer with an insulating floor reduces the effect of body proximity, and an RF choke is added to prevent impedance mismatch. According to experimental results, the 2x2 rectifier antenna array can produce a maximum output voltage of 1.05 V at a distance of 150 cm from an indoor Wi-Fi access point, qualifying it for use in battery-free applications.

In 2019 , Vital , Dave , and John L. Volakis created a textile-based radio frequency (RF) energy harvesting technology for use in wearable devices. (Vital et al., 2020). To power low-power wearable technology, a lightweight, flexible, and integrated textile orthotic antenna system is proposed. Based on the Skyworks SM-7630 Schottky barrier diode, the single-diode rectifier circuit used in this work achieves an RF-to-DC conversion efficiency of over 70% with an RF input power of approximately 8 dBm. Low-power wearable sensors and body-mounted electronics could benefit from the efficiency of the proposed technology, which harvests 600 microwatts of power at 10 cm and 80 microwatts at 60 cm from a Wi-Fi source.

Trikolikar, Anand, and Swapnil Lahodkar (2021) suggested and investigated a dual-band rectifier circuit design for ambient radio frequency energy harvesting applications (Trikolikar and Lahudkar, 2021). An SMS-7630 Schottky diode and an inexpensive FR-4 substrate were used to create two single-frequency (2.35 GHz and 2.24 GHz) and two dual-band (1.84 and 2.42 GHz, 883 MHz and 2.35 GHz) rectifiers. With a conversion efficiency of 86.32%, the circuit produced an output voltage of 1.67 V at 0 dBm.

The active rectifiers are widely used in the energy harvesting systems for powering of wearable medical devices (WMDs) due to their balance of conversion efficiency and simplicity, especially when paired with impedance matching networks. These rectifiers include Bridge rectifiers, Cross-coupled differential drive rectifiers (CCDDR), and synchronous rectifiers for IoT, RFID, and wearable applications. Table 6 presents a performance comparison of different rectifier circuit topologies for wearable applications based on the provided research results.

Table 6: Different topology of the rectifying circuit design based on diodes and their performances

Ref.	*Rectifier Topology*	*Freq. [GHz]*	*PCE/ Pin*	*Application*
(Vital et al., 2020)	Rectifier based single SM-7630	2.4	70/8	WMDs
(Trikolikar and Lahudkar, 2021)	Rectifier based SM-7630	2.45	86.3/0	IoT, and RFID
(Alkhalaf et al., 2022)	Bridge/Four Schottky diodes	2.45	85/10	WMDs
(Dai et al., 2015)	CCDDR based 65nm CMOS	UHF	65/4	WMD, IoT, RFID
(Rabah et al., 2025)	CCDDR based TSMC 65nm	5.8	83/5	RFID, IoT
(Ihlou et al., 2023)	Shunt rectifier	5.8	74/10	Wireless power transfer
(Li and Jiang, 2024)	Synchronous rectifier	2.4	30/10	RFEH

5 Wearable Rectenna System

This part of the article focuses on the rapid emergence of mobile devices and their profound impact on communication, entertainment, exercise, and healthcare. These gadgets, including smartwatch and fitness monitors, have become indispensable in daily life due to functions such as tracking movements, health tracking, and wireless communication. However, because traditional batteries are often bulky, stiff, and require regular charging their use causes wearability, comfort, and continuous operating issues.

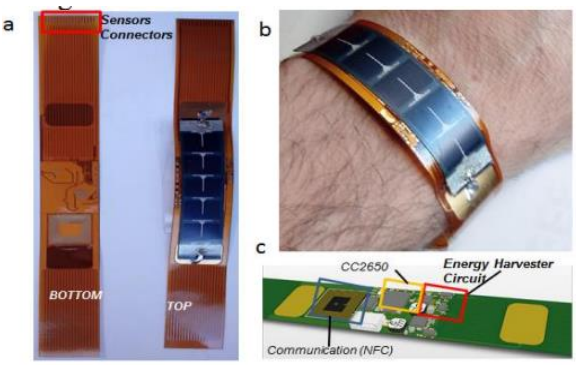
Energy harvesting systems are one potential solution for these limits. These advancements may minimize, or possibly eliminate, the requirement for conventional batteries by transforming ambient energy from the environment or our bodies into electrical energy. Despite their potential, current research often focuses on certain units under specific circumstances, which limits their implementation in different real-world contexts. With the aim of informing the creation of future wearable electronic devices that optimize the quality lifestyles and encourage increased use.

This review aims to offer a comprehensive overview of recent advances in energy harvesting, energy management, and energy storage systems for devices that are wearable. Recently, that have occurred significant developments in movable energy harvesting technology, due to the increasing need for reliable and sustainable energy sources. These resources consist of triboelectric nanotechnology (TENGs) (Walden et al., 2023), thermoelectric generators (TEGs), piezoelectric generators (PEGs) (Wang et al., 2024) , photovoltaics (PVs) (Chakraborty et al., 2024) , and biofuel cells (BFCs) (Zhu et al., 2024) , Among these energy harvesting methods: All of those devices utilize ambient energy sources, such as heat, light, biological fluids, and mechanical movement.

5.1 Photovoltaic Energy Harvesting

Many studies have been undertaken on photovoltaic cells' capacity to change light to electricity. Recent developments have mostly focused on the flexibility and effectiveness of photovoltaic power in portable applications. Lv, Dan, et al. have demonstrated that. In 2022, they demonstrated the potential use of an organic fiber-based solar cell for wearable textiles, reporting a power conversion efficiency (PCE) of up to 9.4% (Lv et al., 2022).

In 2017, Jokic, Petar, and Michele Magno introduced a flexible smart bracelet that uses a flexible solar energy harvesting device to monitor health over an extended period of time (Jokic and Magno, 2017). This gadget combines a flexible photovoltaic panel with low power components including a microprocessor and Bluetooth module. Achieving an energy conversion efficiency of 85-90%, the bracelet may capture up to 16mW of electricity outdoors and 0.21mW indoors, according to experimental results. The wristband demonstrated self-sustainability with an average illumination of 1000 lux in a test environment, effectively performing blood oxygenation tests every minute and transmitting data over Bluetooth.



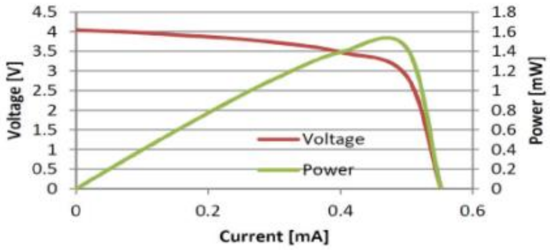


Figure 4: The solar rectenna system for powering of flexible smart bracelet: (a, b, c) complete bracelet device, and output characteristic of the solar cell (Jokic and Magno, 2017).

5.2 Biofuel Cells

In 2021 (Sun et al., 2021), Sun, Mimi, et al. created a new flexible and wearable epidermal biofuel cell (BFCs) that harvests energy in real time from ethanol in sweat, demonstrating its potential for on-body energy harvesting. They suggest a wearable, flexible epidermal microfluidic human exogenous substance called ethanol/oxygen BFC for the simultaneous collection of sweat samples and the production of sweat bioelectricity on the skin of alcohol users as shown in Figure 5. A number of real-world scenarios related to the body's absorption and excretion of alcohol were taken into account and studied for skin-on, continuous in situ sweat ethanol bioenergy synthesis in controlled settings.

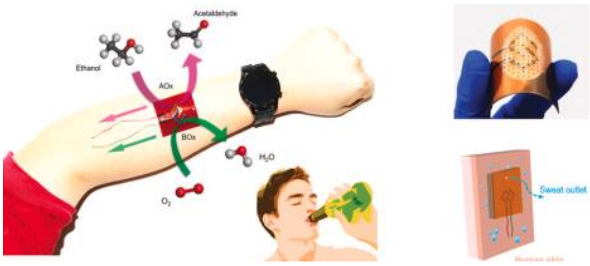


Figure 5: Wearable epidermal biofuel cell (BFCs) real-time harvests bioenergy from human sweat (Sun et al., 2021)

5.3 Triboelectric and Piezoelectric Energy Harvesting

The capacity of piezoelectric nanogenerators (PENGs) and triboelectric nanogenerators (TENGs) to transform mechanical energy into electrical power has been the subject of much research. Song, Yu, et al. in 2020 (Song et al., 2020), introduced a Wireless battery-free wearable sweat sensor powered by human motion using freestanding triboelectric nanogenerator (TENG) technique. The well-designed FTENG has a high-power output of around 416 mW.m^{-2}. They demonstrate a battery-free tribo electrically powered system that can power multiplexed sweat biosensors and wirelessly transmit data to the user interfaces via Bluetooth during human on-body trials through seamless system integration and efficient power management as shown in Fig. 6.

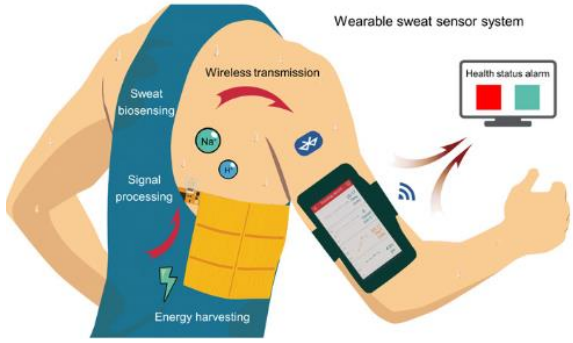


Figure 6: Schematic illustration of a wearable sweat sensor that runs on TENG in freestanding mode (Song et al., 2020)

5.4 Thermo-electric Energy Harvesting

The potential of thermoelectric generators (TEGs) to produce electrical energy from body heat has been explored. In 2020 (Yuan and Zhu, 2020), Yuan et al. demonstrated a new structure of a flexible thermoelectric generator (TEGs) energy harvesting system for wearable applications. The proposed system is used for powering of multimodal bracelets with a high output current density of above 3.5 $\mu W \cdot cm^{-2}$. Ren et al. in 2021 (Ren et al., 2020), showed the potential of wearable TEGs for ongoing health monitoring by creating a high-performance device with programmable and self-healing features. A wearable wristband for continuous glucose monitoring was developed by Kim et al. 2021 to solve the low voltage output problem. It is powered by a TEG and Li-S battery.

6 Challenges and Design Requirements

To meet the requirements of photovoltaic devices, portable energy harvesting systems must maximize power output, ensure portability and durability under repeated mechanical stress, and reduce component size without compromising efficiency. Because gathered energy is irregular and intermittent, proper energy management is required. Energy must be dispersed and stabilized via sophisticated procedures. Another critical difficulty is integrating energy harvesters with other electrical components, like sensors and batteries, without losing performance. To address these concerns, requirements for design include high power efficiency of conversion, adaptive and long-lasting materials, scalable and multifunctional integrating, and improved power management units (PMUs) for effective power storage and delivery. By addressing these characteristics, dependable, pleasant, and sustainable wearable technology may be built and integrated into every life. (Sun et al., 2023).

Tables 3 through 6 show the antenna and rectifier after each part analysis. This antenna is an important component of handheld devices because it quickly transforms electromagnetic waves into useable electrical energy. This part will go over contemporary antenna designs, important system concerns, and novel ways to improve their performance in portable device applications.

6.1 Output Power of Rectenna

Optimizing power output is a major concern in portable energy collecting equipment. Optimizing the efficiency of energy transformation is critical since it has a direct impact on how much useful energy can be generated from the source. To maximize energy recovery and decrease losses, device design must be improved. Solar power plants can be used with piezoelectric or thermoelectric generators to improve overall efficiency by employing various energy sources at the same time (Morsy Ismail and Saleh, 2024) . the next study should focus on creating new designs and innovative materials to boost energy output and conversion rates.

6.2 Miniaturization

Wearable technology downsizing provides a number of hurdles, notably in terms of mechanical integrity and energy conversion efficiency. Because of the restricted surface area available for energy collecting and the variety of ambient variables, small-scale devices frequently provide extremely varied results. It is vital to create materials that are resilient but malleable enough to bear mechanical stress while maintaining functioning. Further more controlling power generation and increasing efficiency in compact devices need novel design strategies (Hussein and Mohammed, 2023).

6.3 Power Management and Self Powered Sensors

To enhance the effectiveness of portable energy harvesters, proper power control is essential. Controlling electricity from many sources involves complex algorithms and technology in order to achieve a suitable equilibrium between power input and output. Portable gadgets may dramatically increase their lifespan while using less power by monitoring energy access and initiating sleep and wake cycles the capacity of a power management unit (PMU) to control a wide range of power supplies and improve their ability to store will be crucial in future improvements.

Portable and self-contained monitors are required for real-time monitoring of the surroundings and health. The two primary concerns are limiting the impact of environmental factors and guaranteeing precise performance validation. Improved power and control methods are necessary for these gadgets to run optimally with out the use of an external power source. To offer dependable data in a range of settings, future research should focus on enhancing sensor resilience and accuracy. (Sohail et al., 2024).

Wearable patch antenna structures rely on appropriate energy storage devices to save incoming energy and provide constant and dependable functioning. Several aspects impact energy storage technique selection, including energy density , power density , flexibility , weight , size , textile-integrated energy storage, biocompatibility , and biocompatible energy storage systems. (Sohail et al., 2024), define storage of energy options for wearable straight antenna structures as supercapacitors, thin-film batteries, flexible lithium batteries, solid state chargers, micro supercapacitors, biocompatible energy storage, textile integrated energy storage, and hybrid energy storage systems.

Thin-film supercapacitors and battery packs represent some of the most attractive battery alternatives for portable rectangular shaped antennas due to their versatility, quick charging, and compatibility with low power energy harvesting systems. As technology develops, solid-state charging and textile-integrated storage solutions will be used to power more future -oriented portable electronics. Hybrid technologies that combine batteries and supercapacitors may offer the best equilibrium for portable devices with varying power requirements (Sohail et al., 2024).

Wearable devices may be powered effectively and reliably using hybrid systems that combine rectifier antenna with battery-driven power control circuits. These devices combine the benefits of battery energy harvesting and storage to enable efficient, dependable, and persistent functioning in every day situations. This hybrid technology gives portable devices a dependable and efficient power sourly by combining the benefits of battery energy harvesting and storage. When using rectangular antennas that transform electromagnetic waves into power, sustainable material choice and environmental concerns are important variables. Sustainability design, which aims to minimize environmental impact, depends primarily on the utilization of low impact, reusable , and biodegradable materials, for example polylactic acid (PLA) substrates for electrical components. (Chen et al., 2024).

Wearable rectangular antennas have been created from a range of eco-friendly, reusable, and low-impact materials. They involve biodegradable and nontoxic resources, recycling, energy-efficient production, and raw material sources (Chen et al., 2024) . environmental circumstances have an impact on portable rectilinear antenna systems, potentially lowering their longevity and performance. To ensure their dependability and lifespan, several variables must be considered these factors include humidity, temperature variations, mechanical stress, UV light, oxidation, and chemical exposure. Table 7 outlines many wearable energy collecting methods that can be used to wirelessly power wearing healthcare devices.

7 Conclusions

Wearable devices have transformed contemporary technology and had a tremendous influence on medicine, exercise, entertainment, and communications. These small devices, including smartwatches and advanced medical sensors, have become indispensable in daily life thanks to features such as motion detection and health monitoring. Their comfort, wearability, and continuous functioning are, however, restricted by their dependence on conventional batteries.

This paper presents a comprehensive list of wearable energy harvesting technologies for self-powered portable sensors due to harvesting from sources such as light, body fluids, biomechanical movements, and body heat. Despite challenges in output power optimization, miniaturization, durability, and power management, ongoing advancements in materials, design, and integration are paving the way for next-generation wearable electronics. Future research should focus on overcoming these hurdles to fully realize the potential of energy harvesters, leading to more versatile and autonomous devices that seamlessly integrate into daily life, improving user experience and fostering broader adoption in various applications.

Table 7: Performance comparison of different energy harvesting systems for wearable applications

Ref.	*Freq. [GHz]*	*Antenna/Rectifier Topologies*	*PCE [%]/ Pin[dBm]*	V_{out} @ R_L
(Huang et al., 2024)	5.8	MSPA based om meta-surface/ Voltage multiplier	82.8/ 0	1 @ 3
(Wagih et al., 2020)	23-24.5	5G broadband wearable antenna / VDR	70/ 10	1 @ 10
(Tachrifat et al., 2024)	2.45	Wearable dipole antenna/ Schottky diode rectifier	70 / -15	---
(Cheriyan et al., 2023)	2.45	Meandered MSPA/ HSMS 2862 Schottky diode	72/ -29	2 @ ---
(Alkhalaf et al., 2024)	2.45	Flexible Meta-Patch wearable rectenna array/7 Stages VDR	52/ -1	6.7 @ 50
(Lin et al., 2018)	2.45	Wearable textile/ Greinacher HSMS 2862 rectifier	17/ 0	2.2 @ 10
(Younis and Hussein, 2025)	5.8	MSPA based on AMC technique	74/ 20	3.85 @ 2.2

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