

## Chapter 9: Sustainable Power Solutions for Healthcare: Energy Harvesting and Wireless Power Transfer

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**Abstract:** Driven by the demand for continuous health monitoring, personalized medicine, and sustainable medical technologies, biomedical device development has accelerated to evolve self-powered ones. However, traditional batteries used in both wearable and implantable systems pose a number of great concerns, including the need to frequently recharge, with a limited lifespan, and necessitating surgical replacement in implanted applications. Energy harvesting and wireless power transmission technologies have recently emerged as promising alternatives for maintaining energy independence and environmental sustainability without the need for maintenance. This chapter provides an overview of energy harvesting technologies, with a focus on radio frequency energy harvesting and wireless energy transmission. Fundamentals of mechanical, thermal, solar and radio frequency-based energy harvesting, and state-of-art applications in wearable devices, implantable systems, radio-frequency identification-based health care, and the Internet of Medical Things are presented. Within this context, radio frequency energy harvesting and wireless power transmission provide key enablers for the next generation of biomedical devices. The clinical, technical and regulatory challenges related to introducing energy harvesting in healthcare are energy efficiency, biocompatibility, safety and scalability. Lastly, future progresses in systems of hybrid energy harvesting, advanced nanotechnology, and extended operating over new generations in communications technologies, are predictable to cover the way for energy harvesting based on RF systems. Energy harvesting and wireless power diffusion will share a main role in delivering justifiable and suitable energy solutions for patients. This fact offers new transformative elements in wearable, implantable, and connected healthcare technologies.

**Keywords:** Energy Harvesting, Biomedical, Wearable and Implantable Devices, Radio Frequency (RF), Internet of Medical Things (IoMT), Wireless Power Transfer.

## 1 Introduction

Nowadays, over the world, and by the increasing request continuous patient monitoring in real-time and personalized medicine, the healthcare systems are intensively transformed. Chronic diseases, such as cardiovascular diseases, diabetes, and neurodegenerative disorders, are applying a severe load on healthcare infrastructure. Therefore, a call for wearable and implantable medical dispositive has been tested controlling by the way physiological parameters outside clinics and hospitals. Referring to the World Health Organization (WHO), each year, cardiovascular maladies alone account for almost one-third of global deaths that highlights the necessity to develop new technologies for early detection and long-term management of such maladies. Chronic diseases such as cardiovascular disease, diabetes, and neurodegenerative diseases pose huge loads on healthcare infrastructure and thus make new need for wearable and implantable medical devices that can observing patient's vital signs outside the clinic and hospital.

Old-style batteries present also a challenge to various modern biomedical machines. The majority of wearable devices and biosensors, (e.g. fitness trackers and medical patches), need regular restoring. In the other hand, their implanted counterparts (mechanical devices: e.g. pacemakers and nerve stimulators) face to the necessity to preplace and surgical battery, which increase risks and healthcare costs. In addition, growing requests for sustainability expose many disadvantages of systems based on battery. It shows high costs related to the recycling of components from batteries and waste management and environment.

Energy harvesting technologies, transforming energy, present in the neighbouring environment into useful electrical energy, have being developed as a promising alternative (Sudivalayam et al., 2010; Ko et al., 2015). Among these technologies, radio frequency energy harvesting has raised owing to the high density of radio frequency spectrums in the air (Al-Sharif et al., 2019; Ibrahim et al., 2022). Signals from communication antennas, Wi-Fi routers, and towers used for diffusion can be captured through reception antennas and converted into DC power. When implemented into biomedical devices, energy harvesting based on RF allows auto-function, avoid repetitive maintenance, and increases patient comfort by excluding the necessity for regular recharging.

Energy harvesting technologies also show an important role in IoMT, a specialized field in the Internet of Things (IoT) including, implantable, wearables, and sensors devices. These later collect and transmit health information in a continuous manner (Saraereh et al., 2020; Sangoleye et al. 2021). Certainly, energy harvesting becomes a basic component to ensure scalability, durability, and dependability. Since battery-powered systems cannot boost such closely distributed and energy-intensive networks.

This chapter offers an in-depth review of energy harvesting for healthcare with a special emphasis on RF energy harvesting and WPT. It covers the motivations of the healthcare approach, the basic principles of EH, and the design of RF-based systems used in biomedical applications. Particular focus is paid to WPT for wearable and implantable devices with special interest in cardiovascular care. Finally, the chapter concludes with an overview of current challenges and limitations toward the development of future sustainable healthcare ecosystems.

## 2. Healthcare Needs and Technological Trends

These are the two major driving forces for healthcare delivery worldwide: the ever-increasing prevalence of chronic diseases and the growing demand for inexpensive, accessible, continuous medical monitoring. Due to the increased aging of the population and changes in the pattern of life, cardiovascular, diabetic, and respiratory disorders continue to escalate. Cardiovascular diseases alone are responsible for approximately 17.9 million deaths annually and are the leading cause of death worldwide (Abdul Ghani et al., 2023). Conditions like these need long-term monitoring in real time, which is beyond the scope of hospital-based care.

Healthcare these days is embracing the shift towards preventive, personalized, and decentralized care models in order to meet these demands. Instead of symptomatic treatment in a reactive way, the concentration now is on continuous monitoring for early detection and proactive intervention. Reference (Heikenfeld et al. 2018) has studied wearable sensors, implantable medical devices. As discussed by (Jung et al. 2015), and (Navas et al. 2021), connected health systems can collect and transmit in real-time, physiological data.

There are various disadvantages limiting its possible manufacturing:

- **Network and data demands:** M-IoT platforms, which collect and transmit data continuously and operate across thousands of devices. It requires removed energy power source.
- **Limitations of energy:** (i) Replacing batteries for implantable devices implicates invasive surgical procedures which will be risky and expensive for the patient. (ii) Frequent charging of wearables weakens user compliance.
- **Sustainability:** Electronic production and environmental pollution were impacted by batteries fabrication. To exacerbate these difficulties, we need eco-friendly environment.
- **Availability in the world:** Battery replacements are not available in poor and income countries (in low- and middle-world).

By collecting ambient energy, (e.g. body heat, movement, and RF signals), this knowledge extends device lifecycle. To offer ecological, maintenance-free power for biomedical devices, latest developments utilize energy harvesting and wireless power transfer technologies as allowing tools. Integration with biocompatible materials, microelectronics, and wireless communication systems is speed up this shift towards a novel generation of auto-powered healthcare. The following sections detail how RF energy harvesting is positioned to lead innovation in biomedical applications and enable development of smarter, more sustainable healthcare.

### 3. Principles of Energy Harvesting

Energy harvesting is one of the means of collecting small portions of energy from the environment and converting them into electrical power, usable in practice. Contrary to conventional power systems operating either on replaceable batteries or external power supplies, energy harvesting technologies enable self-sustained and autonomous operation of electronic devices. This property makes them especially attractive to healthcare, where medical devices need to be extremely reliable, lightweight, and able to operate continuously with a minimum of patient intervention.

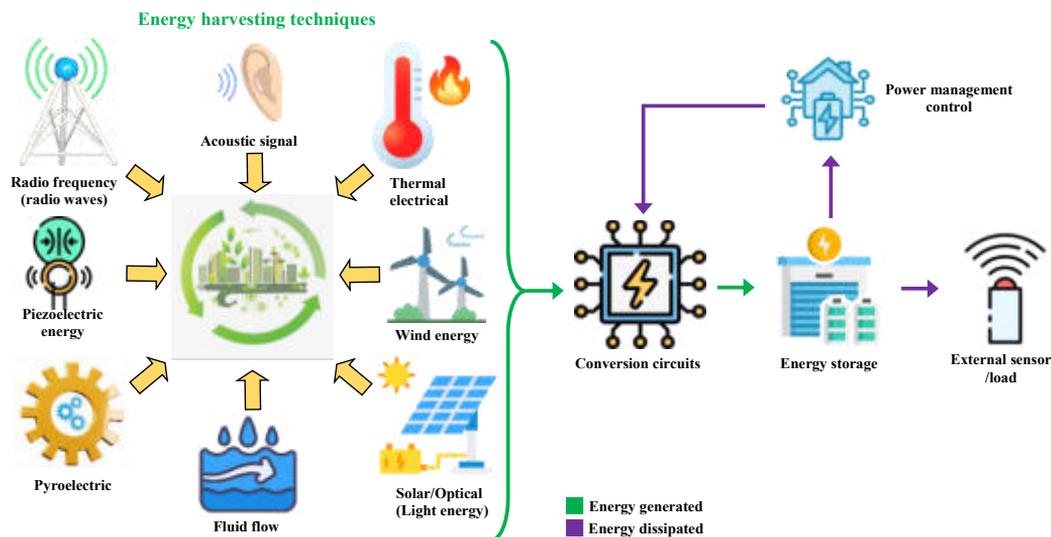
Fig. 9.1 illustrates several types of ambient energy sources, which can be leveraged for this purpose. Mechanical energy emanating from motion, vibration, or pressure can be scavenged through the implementation of piezoelectric, triboelectric, or electromagnetic transducers (Zhu et al., 2018). In healthcare, for instance, biomechanical energy emanating from walking, breathing, or even a heartbeat may be converted to electrical energy with the ability to power sensors. Thermal energy provides yet another opportunity in that temperature gradients between the human body and its surrounding environment may be converted to electrical energy by thermoelectric generators (Kishore et al., 2018). This has already been practiced in some wearable devices, wherein these operate partially from body heat. Equally important is solar and optical energy since photovoltaic cells have the ability to harness energy from sunlight or even from indoor lighting (Vasiliev et al., 2019), making them suitable for wearable patches and smart textiles in outdoor health monitoring (Khane et al., 2022).

Of these sources, the energy produced by radio frequency has gained much attention. Modern environments are indeed filled with electromagnetic signals, which come from cellular base stations, Wi-Fi routers, television transmitters, and other wireless devices. A rectenna is able to capture and convert such signals into DC power, thus enabling operation of medical devices without any battery dependence (Surender et al., 2022). Unlike solar or mechanical sources, RF energy is generally available in indoor as well as outdoor environments, providing a more consistent and reliable supply of power.

**Table 9.1** Techniques of energy harvesting for healthcare applications.

<b>Technique</b>	<b>Energy Source</b>	<b>Power Density</b>	<b>Key Advantages</b>	<b>Limitations</b>	<b>Healthcare App.</b>
<b>RF</b>	Ambient or dedicated RF signals	$\mu\text{W} - \text{mW}/\text{cm}^2$	Widely available in urban environments	Efficiency drops with distance	Wearables, implantable sensors, RFID tags, IoMT nodes
<b>Piezoelectric /Trieboelectric</b>	Mechanical motion	$\mu\text{W} - \text{mW}/\text{cm}^2$	Harvests natural	Device fatigue over time	Cardiac implants, motion sensors, prosthetic monitoring
<b>Thermoelectric</b>	Temperature gradient	$\mu\text{W} - \text{mW}/\text{cm}^2$	Continuous energy source- Silent	Requires sufficient gradient	Wearables, smart patches, implant monitoring
<b>Photovoltaic</b>	Sunlight or indoor artificial light	$\text{mW} - 10\text{s mW}/\text{cm}^2$ (outdoors) $\mu\text{W} - \text{mW}/\text{cm}^2$ (indoors)	Can recharge rapidly	Limited by lighting availability	Smart patches, hospital asset tracking, wearables
<b>Acoustic</b>	External ultrasound beams	$\mu\text{W} - \text{mW}$	Can penetrate tissues	Efficiency drops with depth	Deep-tissue implants, wireless biosensors, targeted medical implants
<b>Inductive</b>	Magnetic fields from external transmitter	$\text{mW} - \text{W}/\text{cm}^2$	Safe and well-studied	External charger needed	Implantables (pacemakers, cochlear implants), wearables
<b>Radiative WPT</b>	Directed RF/microwave	$\text{mW} - \text{W}$	Works through tissue and barriers	Safety and regulatory constraints	Distributed implant networks, remote powering of biosensors

The application determines the energy source, but in reality, one source is never enough for all conditions. This has oriented development into hybrid systems, integrating different approaches of energy harvesting: from generation of the thermal power to RF frequency energy harvesting. These hybrid techniques ensure operation continuity, which is reasonably important in medical domains since any defaults could lead to a dangerous situation that kill patients.

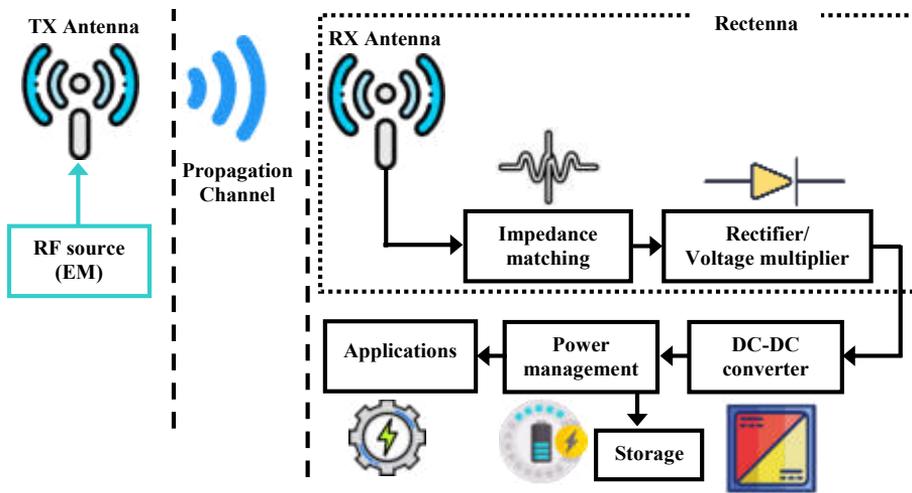


**Fig. 9.1** Overview of energy harvesting techniques and emerging trends in electronic applications.

Table 9.1 compares different energy harvesting technologies and their applications in the health field. They also have to fulfill strict safety standards: they should not overheat and should ensure long-term biocompatibility. The importance of energy harvesting in healthcare is demonstrated by a number of requirements specific to medical devices. Wearable and implantable devices must be small and discreet, with the ability to operate continuously without the need for frequent charging or surgical replacement. Traditional batteries cannot meet these requirements because of their bulk, limited life, and environmental impact. In contrast, energy harvesting technologies come as a substitute for batteries that is sustainable, maintenance-free, and eco-friendly. Amidst them, RF energy harvesting presents the most promising technology due to the reasons that besides providing energy continuously, RF energy harvesting naturally fits into the concept of wireless communication systems that form the backbone of modern healthcare technologies.

#### 4. Radio Frequency (RF) Energy Harvesting

Among various energy harvesting modalities, RF energy harvesting has attracted particular attention due to the prevalent presence of electromagnetic signals around us in modern environments as revealed by (Moloudian et al. 2024). RF energy harvesting refers to the process of collecting electromagnetic field energy from surrounding sources and converting that into usable electrical power. It is enabled by a device called a rectenna, meaning a device that combines a receiving antenna, an impedance matching network, and a rectifying circuit for transforming AC electromagnetic waves to DC electric current as shown by (Surender et al. 2021). A conceptual diagram of a rectenna is given in Fig. 9.2.



**Fig. 9.2** Sensor powered by wireless power transfer and energy harvesting.

There are two basic approaches to the implementation of RF energy harvesting. In ambient RF energy harvesting, devices collect signals that already exist in a given environment, including those from television broadcasting towers, cellular base stations, Wi-Fi routers, and personal communication devices. Since RF signals are practically omnipresent in urban and indoor environments, this method has the advantage of leveraging already existing and continuous energy without requiring further infrastructure. On the other hand, energy becomes weak and irregular, varying with proximity to the source and the interference level.

By contrast, dedicated WPT systems actively transfer power to a receiver using an RF transmitter designed for that purpose. In this radiative WPT method, electromagnetic waves are focused on the receiving device, enabling strong and predictable power supply compared with power harvesting from an ambient environment. Specific qualities of the approach make it of crucial importance for biomedical applications requiring a source of energy with controlled and reliable operation. Therefore, for

instance, a wearable sensor or implantable medical device could be continuously energized by a transmitter placed in a patient's home or clinical environment.

According to Ullah et al. (2022), one important factor for enhancement in the performance of RF energy harvesting systems is the design consideration of the receiving antenna. The design of antennas may be single-band, multi-band, or broadband for capturing energy from one or more frequency bands simultaneously. Multi-band and broadband designs are very promising in healthcare devices owing to the possibility of concurrent harvesting from different sources, which enhances reliability. Besides, the rectifier circuit, often based on Schottky diodes or CMOS technology, has much significance in maximizing efficiency, mostly under low input power typical of ambient harvesting scenarios.

RF energy harvesting has three advantages, from the healthcare perspective. Firstly, it can render devices battery-free and reduce the needs for surgical replacements of the used-up batteries in implantables like pacemakers and neurostimulators. Secondly, it enhances patient comfort and compliance because wearables can now be much lighter, thinner, less intrusive, and free of bulky battery compartments. Third, it enables the expansion of the Internet of Medical Things, where networks of wearable and implantable sensors require a sustainable and continuous source of power to keep them running for a very long time.

Although these advantages, energy harvesting based on RF will face to various challenges. Energy conversion efficiency depends strongly on the distance from the transmitter, antenna orientation, and ambient RF signal density. Besides, safety is another critical concern in the biomedical applications—as exposure to RFs must be kept well within established guidelines to avoid tissue heating or interference with sensitive medical equipment. Moreover, regulatory bodies impose rather strict limits on the RF transmission power, thus constraining the amount of energy that could be safely harvested.

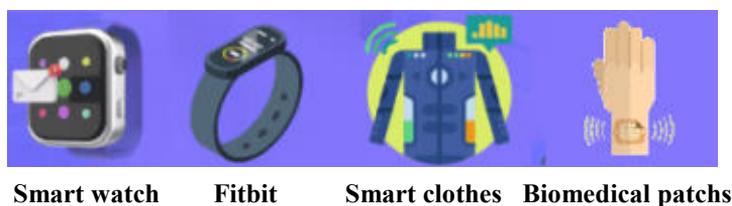
## **5. RF Energy Harvesting Technology Applications.**

To operate reliably without frequent battery replacement or recharging, RF energy harvesting into healthcare needs for new solutions such as self-powered and autonomous devices. The main motivation towards integrating In transforming ambient or dedicated RF signals into usable electrical power, biomedical devices achieve extended usage life, reduced periodic maintenance needs, and greater design freedom. Specific applied domains are most relevant: wearable devices, implantable devices, radio-frequency identification systems, and large-scale Internet of Medical Things networks.

## 5.1 Wearable Healthcare Devices.

Wearable electronics, including fitness trackers, smart textiles, and biomedical patches, have already become part of daily life; see Fig. 9.3 for an example (Iqbal et al. 2021). In the medical context, these devices can provide continuous monitoring of various physiological signals, including heart rate, blood oxygen saturation, glucose levels, and body temperature. The immediate reasons that wearables are not yet as widely used as might be envisioned include that most require periodic recharging. RF energy harvesting enables self-charging wearables, which can capture energy from wireless signals present in the surroundings.

For example, a health-monitoring patch embedded with a rectenna can potentially scavenge energy from a nearby Wi-Fi router or cellular tower without the need for periodic charging. Not only does this enhance patient compliance, but it enables designers to lighten and miniaturize devices by eliminating heavy batteries. The incorporation of RF energy harvesting in smart fabrics or flexible electronics opens up possibilities for unobtrusive, comfortable, and continuous health monitoring. A comprehensive review of recent advances in wearable healthcare devices can be found in Refs. Lu et al., 2020; Luo et al., 2024.



**Fig. 9.3** Overview of wearable technology applications.

## 5.2 Implantable Medical Devices

Implantable devices, like pacemakers, defibrillators, cochlear implants, and drug delivery systems play an important role in the treatment of chronic diseases and long-term patient care. These conventionally require internal batteries that need surgical replacement when depleted, posing substantial risks to patients' health. RF energy harvesting has eliminated this drawback as it has opened up opportunities toward battery-free or wirelessly rechargeable implants. Fig. 9.4 represents selected implantable medical devices that are used in precision healthcare, by showing their anatomic locations and clinical uses in cardiac, neurological, and metabolic systems. Such a scenario would involve an independent RF transmitter, located outside of the body, which can wirelessly impart energy into an implanted rectenna to ensure consistent device operation without invasive surgeries. Other than cardiovascular

applications such as powering up pacemakers or sensors for the monitoring of blood pressure, neuro-stimulators and biosensors detecting specific chemical markers in the body have started to exploit this harvesting from RF. This will largely improve the life quality of patients while reducing healthcare costs due to repeated surgeries.

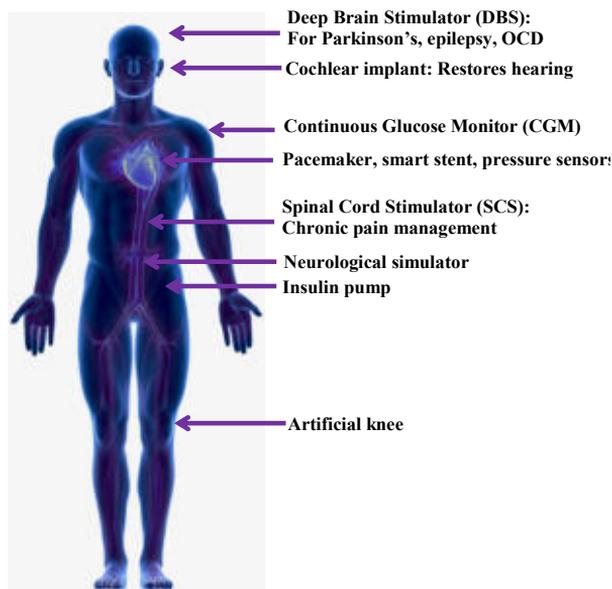


Fig. 9.4 Key implantable medical devices in precision medicine.

### 5.3 RFID-Based Healthcare Systems

Radio-frequency identification is widely used in healthcare for applications such as patient identification, medication tracking, and hospital asset management. Traditional passive RFID tags obtain energy from a reader, while active tags are equipped with internal batteries that need to be replaced. Equipped with RF energy harvesting, the active RFID tags can then be designed to be self-sustainable and require less maintenance, hence reliably operating in a critical healthcare environment.

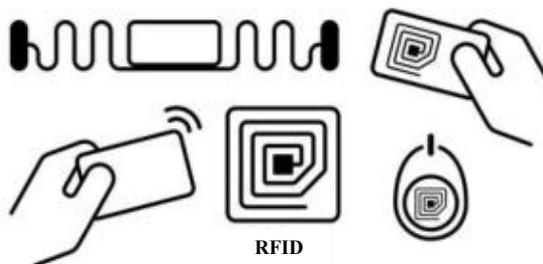


Fig. 9.5 Example of RF-powered RFID tags.

For instance, RF-powered RFID tags, as presented in Fig. 9.5, can be attached to the wristbands of patients to enable continuous monitoring of vital signs or movement without the use of batteries. In hospital logistics, self-powered tags have the potential to enhance the tracing of medical equipment, pharmaceuticals, and supplies by making the processes faster and more cost-effective. Thus, RFID and energy harvesting together support patient care and efficiency within the healthcare system.

#### **5.4 Broader Benefits**

In these various applications, energy harvesting based on RF offers multiple overall benefits:

- It improves patient accessibility by decreasing the need for device recharging.
- It reduces healthcare costs by reducing maintenance/surgical interventions.
- Perhaps most importantly, it will enable a shift towards continuous and immediate health monitoring.

### **6. Wireless Power Transmission and Biomedical Applications**

Although the advantage of harvesting ambient RF energy lies in exploiting pre-existing electromagnetic (EM) signals. Its output power is habitually limited and variable.

Where reliability and safety are mandatory, WPT ensures better predictability and control for medical applications. By avoiding the need for frequent battery replacements also physical connectors, wireless power transmission offers a direct power supply to vital medical devices. Yet, it has obtained significant importance in many fields applications.

#### **6.1 Principles of WPT**

By implementing WPT technologies, there are three major design approaches:

- *Inductive Coupling*: This is the most mature and adopted technique, in which two aligned coils in proximity transfer energy via magnetic fields. Currently, this technology is used in commercial applications, such as cochlear implants and transcutaneous charging units for cardiac pacemakers. Although it is highly efficient at small distances, the transmitter and receiver must be very close to each other and aligned carefully.

- *Resonant Magnetic* Energy can be transferred over a larger distance and with less stringent alignment when both transmitter and receiver coils are tuned to the same resonant frequency. This approach enhances patient comfort since less strict positioning is required; thus, it is quite suitable for implants which need to be deeper inside the body.
- *Radiative WPT* Far-field transmission takes advantage of electromagnetic waves, typically at RF or microwave frequencies, to carry the power over larger distances. While less efficient compared to the methods related to induction, radiative WPT presents several advantages in distributed networks of medical sensors or devices requiring mobility.

Improvement in antenna miniaturization, rectifier efficiency, and development of biocompatible materials enhances the feasibility of this technology within a biomedical context. It can also be part of hybrid energy systems that propose the extraction of energy from the surrounding environment and its controlled transmission for reliable operation under changing environmental conditions.

## **6.2 Applications in Healthcare**

In fact, the most promising applications for WPT are concerned with implantable medical devices, considering that traditional batteries impose particularly strict limitations. Usually, the replacement of batteries in, defibrillators, neuro-stimulators, pacemakers, and drug delivery systems implicates invasive surgery.

Wireless power transfer reduces this problem considerably by allowing periodic wireless recharging. In some cases, even continuous power delivery that greatly extends because of wireless power transfer device lifespan while reducing surgical risks. Wearable devices also have many advantages and are very important for medical electronics. For example, these devices can be completely closed since there are no charging ports that provide better resistance to, water, sweat, and contamination properties.

## **6.3 Cardiovascular Applications Case Study.**

Cardiovascular diseases are a leading cause of death worldwide, necessitating a high demand for implantable diagnostic and therapeutic devices. In this respect, WPT technology has emerged as a very promising technology. In this context, the cardiovascular system itself acts as a source for mechanical energy harvesting.

It is easy to convert the biomechanical movement provided by the heart and arteries into electrical energy using piezoelectric or frictional energy converters. However, these sources alone cannot guarantee continuous operation. On the other hand, WPT technology provides an effective alternative or complementary power source for supplying implanted cardiac devices such as pacemakers, blood pressure sensors, and ventricular assist devices with power.

For instance, implantable sensors of cardiac output or blood pressure can be wirelessly powered by magnetic resonance coupling, thus allowing for continuous monitoring without repeated surgery to replace batteries. Thermoelectric power generators using body heat may also be combined in hybrid systems with WPT technology for reaching the highest efficiency and safety. In this way, cardiovascular devices operate more independently and reliably for the benefit of patients.

## Conclusion

Energy harvesting and wireless power transmission are transformative technologies set to redefine biomedical devices by reducing their dependence on traditional batteries. Their integration with RFID systems and the Internet of Medical Things is accelerating the shift toward real-time health monitoring and personalized care.

However, several challenges remain, such as the limited power density of ambient radio signals, alignment constraints in wireless power transfer, and efficiency loss over long distances. Implantable devices also require strict compliance with safety standards related to electromagnetic exposure, tissue heating, and biocompatibility. Additionally, issues of cost, scalability, and accessibility continue to restrict their widespread adoption.

In essence, these technologies go far beyond engineering innovation. They are key enablers of self-operating, sustainable, and patient-responsive healthcare systems. Continued interdisciplinary research and responsible implementation will revolutionize clinical practice, empower patients, and broaden access to personalized healthcare worldwide.

## References

- Abdul Ghani, M. A., Ugasman, A., Latip, J., & Zainalabidin, S. (2023). Role of terpenophenolics in modulating inflammation and apoptosis in cardiovascular diseases: a review. *International journal of molecular sciences*, 24(6), 5339.
- Alsharif, M. H., Kim, S., & Kuruoğlu, N. (2019). Energy harvesting techniques for wireless sensor networks/radio-frequency identification: A review. *Symmetry*, 11(7), 865.

- Detka, K., & Górecki, K. (2022). Wireless power transfer—a review. *Energies*, 15(19), 7236.
- Endalamaw, A., Khatri, R. B., Mengistu, T. S., Erku, D., Wolka, E., Zewdie, A., & Assefa, Y. (2024). A scoping review of continuous quality improvement in healthcare system: conceptualization, models and tools, barriers and facilitators, and impact. *BMC Health Services Research*, 24(1), 487.
- Heikenfeld, J., Jajack, A., Rogers, J., Gutruf, P., Tian, L., Pan, T., ... & Wang, J. (2018). Wearable sensors: modalities, challenges, and prospects. *Lab on a Chip*, 18(2), 217-248.
- Ibrahim, H. H., Singh, M. J., Al-Bawri, S. S., Ibrahim, S. K., Islam, M. T., Alzamil, A., & Islam, M. S. (2022). Radio frequency energy harvesting technologies: A comprehensive review on designing, methodologies, and potential applications. *Sensors*, 22(11), 4144.
- Iqbal, S. M., Mahgoub, I., Du, E., Leavitt, M. A., & Asghar, W. (2021). Advances in healthcare wearable devices. *NPJ Flexible Electronics*, 5(1), 9.
- Joung, Y. H. (2013). Development of implantable medical devices: from an engineering perspective. *International neurology journal*, 17(3), 98.
- Khan, A. S., & Khan, F. U. (2022). A wearable solar energy harvesting based jacket with maximum power point tracking for vital health monitoring systems. *IEEE Access*, 10, 119475-119495.
- Kishore, R. A., & Priya, S. (2018). A review on low-grade thermal energy harvesting: materials, methods and devices. *Materials*, 11(8), 1433.
- Ku, M. L., Li, W., Chen, Y., & Liu, K. R. (2015). Advances in energy harvesting communications: Past, present, and future challenges. *IEEE Communications Surveys & Tutorials*, 18(2), 1384-1412.
- Lu, L., Zhang, J., Xie, Y., Gao, F., Xu, S., Wu, X., & Ye, Z. (2020). Wearable health devices in health care: narrative systematic review. *JMIR mHealth and uHealth*, 8(11), e18907.
- Luo, X., Tan, H., & Wen, W. (2024). Recent advances in wearable healthcare devices: From material to application. *Bioengineering*, 11(4), 358.
- Moloudian, G., Hosseinifard, M., Kumar, S., Simorangkir, R. B., Buckley, J. L., Song, C., ... & O'Flynn, B. (2024). RF energy harvesting techniques for battery-less wireless sensing, Industry 4.0, and Internet of Things: A review. *IEEE Sensors Journal*, 24(5), 5732-5745.
- Navaz, A. N., Serhani, M. A., El Kassabi, H. T., Al-Qirim, N., & Ismail, H. (2021). Trends, technologies, and key challenges in smart and connected healthcare. *Ieee Access*, 9, 74044-74067.
- Sanislav, T., Mois, G. D., Zeadally, S., & Folea, S. C. (2021). Energy harvesting techniques for internet of things (IoT). *IEEE access*, 9, 39530-39549.
- Saraereh, O. A., Alsaraira, A., Khan, I., & Choi, B. J. (2020). A hybrid energy harvesting design for on-body internet-of-things (IoT) networks. *Sensors*, 20(2), 407.
- Sudevalayam, S., & Kulkarni, P. (2010). Energy harvesting sensor nodes: Survey and implications. *IEEE communications surveys & tutorials*, 13(3), 443-461.
- Surender, D., Khan, T., Talukdar, F. A., & Antar, Y. M. (2021). Rectenna design and development strategies for wireless applications: A review. *IEEE Antennas and Propagation Magazine*, 64(5), 16-29.
- Surender, D., Khan, T., Talukdar, F. A., De, A., Antar, Y. M., & Freundorfer, A. P. (2022). Key components of rectenna system: A comprehensive survey. *IETE Journal of Research*, 68(5), 3379-3405.

- Talpur, M. S. H., Abro, A. A., Ebrahim, M., Kandhro, I. A., Manickam, S., Laghari, S. U. A., ... & Uddin, M. (2024). Illuminating healthcare management: A comprehensive review of iot-enabled chronic disease monitoring. *IEEE Access*, 12, 48189-48209.
- Ugwu, C. N., Ugwu, O. P. C., Alum, E. U., Eze, V. H. U., Basajja, M., Ugwu, J. N., ... & Uti, D. E. (2025). Sustainable development goals (SDGs) and resilient healthcare systems: Addressing medicine and public health challenges in conflict zones. *Medicine*, 104(7), e41535.
- Ullah, M. A., Keshavarz, R., Abolhasan, M., Lipman, J., Esselle, K. P., & Shariati, N. (2022). A review on antenna technologies for ambient RF energy harvesting and wireless power transfer: Designs, challenges and applications. *IEEE Access*, 10, 17231-17267.
- Vasiliev, M., Nur-E.-Alam, M., & Alameh, K. (2019). Recent developments in solar energy-harvesting technologies for building integration and distributed energy generation. *Energies*, 12(6), 1080.
- Zhang, Z., Pang, H., Georgiadis, A., & Cecati, C. (2018). Wireless power transfer—An overview. *IEEE transactions on industrial electronics*, 66(2), 1044-1058.
- Zhou, M., Al-Furjan, M. S. H., Zou, J., & Liu, W. (2018). A review on heat and mechanical energy harvesting from human—Principles, prototypes and perspectives. *Renewable and Sustainable Energy Reviews*, 82, 3582-3609.