Photovoltaic energy harvesting for the power supply of medical devices

Hamza Abu Owida[1], Basem Abu Izneid[2], Nidal Turab[3]
[1]Department of Medical Engineering, Faculty of Engineering, Al-Ahliyya Amman University, Amman, Jordan
[2]Department of Robotics and Artificial Intelligence Engineering, Faculty of Engineering, Al-Ahliyya Amman University, Amman, Jordan
[3]Department of Networks and Cyber Security, Faculty of Information Technology, Al-Ahliyya Amman University, Amman, Jordan

Article Info

Article history:

Received Nov 1, 2024
Revised May 1, 2025
Accepted May 25, 2025

Keywords:

Energy harvesting
Healthcare
Medical devices
Photovoltaic
Power supply

ABSTRACT

The increasing demand for sustainable and reliable power sources in portable and implantable medical devices has led to growing interest in photovoltaic (PV) energy harvesting. Traditional power sources, such as batteries, are limited by finite energy capacity and frequent replacement or recharging needs, particularly in implantable devices where surgical intervention is required for battery replacement. Photovoltaic energy harvesting, which converts light into electrical energy, offers a promising alternative, especially in environments with consistent light exposure. This review provides an in-depth analysis of the advancements in PV technologies for powering medical devices. It covers various types of PV materials, design innovations, and the integration of energy storage systems. Additionally, the review highlights the application of PV systems in both external and implantable medical devices, while addressing critical challenges such as ensuring biocompatibility, optimizing performance in low-light conditions, and miniaturizing PV systems for implantation. The potential of PV energy harvesting to improve device longevity and reduce the need for invasive procedures is emphasized. This review concludes by outlining the current challenges and future directions needed to achieve widespread clinical adoption, aiming to contribute to the development of sustainable power solutions in healthcare.

This is an open access article under the CC BY-SA license.

Corresponding Author:

Nidal Turab
Department of Networks and Cyber Security, Faculty of Information Technology
Al-Ahliyya Amman University
Amman, Jordan
Email: n.turab@ammanu.edu.jo

1. INTRODUCTION

The increasing reliance on electronic medical devices, such as pacemakers, insulin pumps, and biosensors, necessitates innovative energy solutions to overcome the limitations posed by conventional batteries. Current battery technology suffers from finite energy capacity and the need for replacement, which can be particularly problematic for implantable medical devices that require invasive surgical procedures for battery changes. As a result, alternative energy solutions that offer continuous, long-term power are being explored [1]-[4].

Photovoltaic energy harvesting represents one of the most promising alternatives for powering medical devices. By converting ambient light—either from natural or artificial sources—into electrical energy, photovoltaic (PV) systems can provide a continuous power source for a wide range of medical applications. The integration of photovoltaic systems into medical devices could extend the operational life of devices, reduce the need for battery replacements, and potentially enable self-sustaining medical technologies [5]-[7].

Photovoltaic cells operate based on the principle of converting light energy into electrical energy through the photovoltaic effect. When light photons strike a photovoltaic material, they excite electrons, creating electron-hole pairs. This process generates an electric current that can be harnessed to power devices [8], [9]. The energy conversion efficiency of photovoltaic cells depends on several factors, including the type of material used, the wavelength of incident light, and the design of the cell [10].

For medical devices, photovoltaic energy harvesting can be achieved using various light sources, including ambient indoor lighting, direct sunlight, or even body-implanted light-emitting diodes (LEDs). The effectiveness of photovoltaic energy conversion in medical settings largely depends on optimizing the materials and designs to operate efficiently under low-intensity and diffuse light conditions commonly found in clinical environments [5], [11], [12]. Figure 1 shows the photovoltaic energy harvesting via the human body.

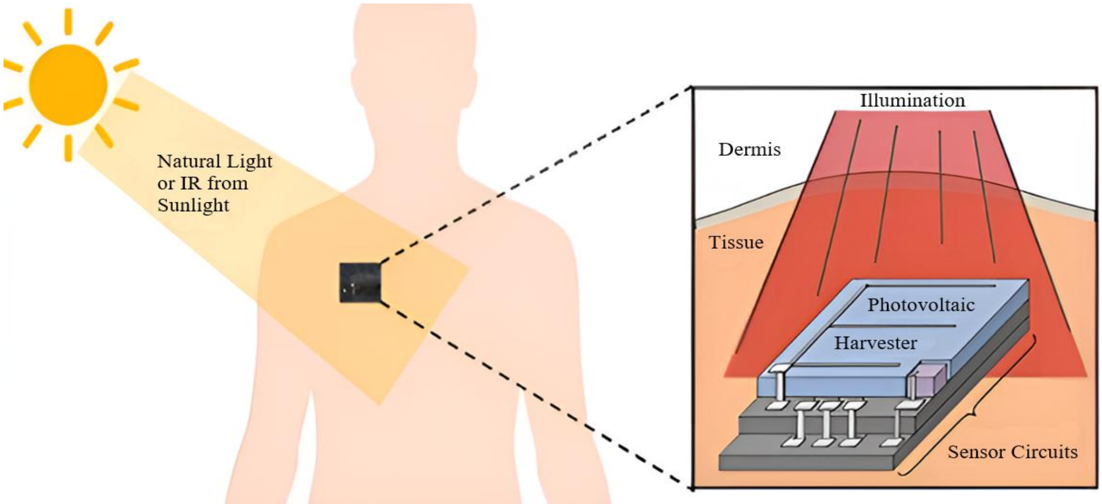

Figure 1. The photovoltaic energy harvesting via human body

This review aims to provide a comprehensive overview of photovoltaic energy harvesting in the context of medical devices. We discuss the different types of photovoltaic materials, their energy conversion efficiency, and how these systems are being integrated into healthcare technologies. Furthermore, we examine the challenges associated with the use of photovoltaic energy in medical applications and propose future directions for research and development.

2. SOLAR PHOTOVOLTAIC MATERIALS

The selection of PV materials is crucial for maximizing energy harvesting efficiency, particularly in the low-light environments commonly found in medical settings. Medical devices often operate in controlled indoor environments or within the human body, where light exposure is limited. Therefore, PV materials must be highly sensitive and capable of converting low-intensity light into usable electrical energy. Commonly used materials in PV systems for medical applications include silicon-based materials, organic photovoltaics, dye-sensitized solar cells, and perovskite-based materials. Each material offers distinct advantages, such as flexibility, biocompatibility, and efficiency, making them suitable for specific medical device applications [13]-[15].

Silicon is the most widely used material in PV cells due to its high efficiency and technological maturity. Silicon-based PV cells, including monocrystalline and polycrystalline silicon, offer reliable performance and durability. However, their rigid structure and large size limit their use in flexible or implantable medical devices [16], [17].

In line with actual results, Santbergen and Zolingen [18] showed that a conventional encapsulated c-Si photovoltaic cell's AM1.5 absorption factor can reach 90.5% using a two-dimensional (2D) computational model. Achieving a high absorption factor was made possible by the c-Si wafer's surface having an ideal steepness texture. Therefore, c-Si cells can achieve absorption efficiencies of up to 93.0% at AM1.5

circumstances by reducing reflective losses throughout the solar spectrum. The following generation of crystalline silicon solar cells, known as high-efficiency silicon heterojunction solar cells.

The promise of transition metal oxides produced via the atomic layer deposition process was highlighted by Costals *et al.* [19], who explained that vanadium oxide films provide better surface passivation, effective lifespan values of up to 800 s, and solar cell efficiencies surpassing 18%. To solve the difficulty of establishing a high aspect ratio (AR) of the metallic digits in a bifacial (BF) copper-plated silicon crystalline solar cell. With a two-step deposition BF plating process, Han *et al.* [20] created a unique hybrid-shaped Cu finger device. This device demonstrated a front-side efficiency of 22.1% and a BF factor of 0.99. In the end, c-Si solar cells' efficiency can be improved by using a grading process.

Dye-sensitized solar cells (DSSCs) are an emerging class of photovoltaic materials that are well-suited for low-light environments, such as indoor medical settings. They offer relatively high efficiency under diffuse lighting conditions and can be fabricated on flexible substrates, making them promising for medical applications [21], [22]. The N3 dye was shown to be stable as a pure solid in the atmosphere up to 280 °C, at which point decarboxylation takes place. It endures 108 redox cycles under prolonged illumination without any functional degradation [23].

In their study, Yadav *et al.* [24] created a hibiscus dye using TiO2 nanorods and a variety of counter electrodes, such as carbon, graphite, and gold. In each case, the writers noted an efficiency of 0.07%, 0.10%, and 0.23%. An important step forward for DSCs was the use of mesoporous TiO2 electrodes in 1991, which allowed for an increase in surface area and a large internal surface area for a sensitizer monolayer. The sustainability, pliability, and lightweight properties of textile DSCs are being investigated for their recent developments, according to Bandara *et al.* [25].

To reinforce the epoxy Epon 862 matrix, Zhu *et al.* [26] utilized carbon nanotubes (CNTs) having single walls. The Epon 862 matrix, a long CNT-reinforced composite, and a short CNT-reinforced composite are the three periodic systems investigated using the molecular dynamics approach. After treating CNTs in an acid bath and subsequently ball-milling them using high-rate heating (HRH) bonding techniques, Sui *et al.* [27] created CNT/NR composites. Mechanical, vulcanization, and thermal characteristics of CNT/NR composites were investigated. Carbon nanotubes (CNTs) were absorbed into NR more rapidly and with less energy than CB. The over-curing reversion of CNT/NR composites was decreased. Acid treatment and ball milling improved the CNT dispersion in the rubber matrix as well as the CNT-matrix interaction.

3. APPLICATIONS OF PHOTOVOLTAIC ENERGY HARVESTING IN MEDICAL DEVICES

Photovoltaic energy harvesting has promising applications in medical devices, particularly in powering implantable devices, biosensors, and drug delivery systems. Additionally, it is used in wearable health monitors and diagnostic devices, reducing the need for frequent battery replacements. This sustainable power solution enhances device longevity, minimizes surgical interventions, and supports continuous monitoring of patients [5], [28]. Figure 2 shows a photovoltaic energy harvesting system with the flexible battery mounted on the curved surface.

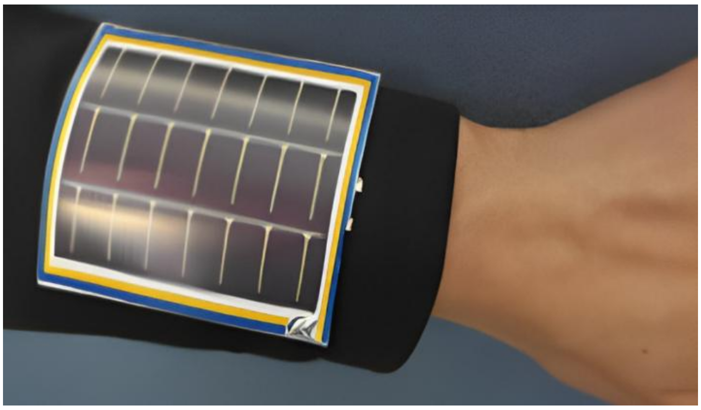

Figure 2. Photovoltaic energy harvesting system with the flexible battery mounted on the curved surface

The use of photovoltaic energy harvesting in implantable medical devices presents a unique set of challenges, primarily due to limited light exposure inside the body. However, innovative approaches are being explored to address this issue. For instance, implantable photovoltaic systems can be combined with optical fibers or miniaturized LEDs implanted under the skin to deliver light to PV cells, enabling them to generate power even in the absence of external light. Research is also ongoing to develop biocompatible PV materials and designs that can operate efficiently in the human body. By integrating PV cells with energy storage systems, such as supercapacitors or micro batteries, implantable devices could achieve long-term, self-sustaining operation, reducing the need for battery replacements and associated surgical procedures.

A novel implanted PVDF-PEG device with capacitor storage, measuring 56 mm × 25 mm × 200 µm, was introduced in 2015. An in vitro and an in vivo evaluation was conducted. The in vitro scenario had a maximum power output (Pmax) of 0.681 µW, an open-circuit voltage (Voc) of 10.3 V, and a short-circuit current (Isc) of 400 nA. The in vivo study found that attaching the piezoelectric energy generation (PEG) to the heart of a male domestic pig resulted in the highest current and voltage measurements of 1.5 V and 300 nA, respectively. Shortly after 700 milliseconds at 70 beats per minute, the output power was 30 nanowatts. This implantable polyethylene glycol has shown promise as a future power source for implantable electronic devices with minimal power requirements [29].

A different study on the piezoelectric properties of PVDF showed an output power of 40 nW in vivo and 2.3 µW in vitro [30] and Khan *et al.* [31] describe more PEG materials. The ZnO and PZT output powers are between the nW to µW range. The textiles were encased in ZnO material in order to transform mechanical energy that would otherwise go to waste into electrical energy. Microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) can employ PEG in ZnO as a high-frequency resonator because of its quartz crystal structure.

A study on the piezoelectric properties of polyvinylidene fluoride (PVDF) demonstrated its ability to generate an output power of 40 nW in vivo and 2.3 µW in vitro (30), highlighting its potential for energy harvesting in biomedical applications. Khan *et al.* [31] further explored PEG materials, discussing various developments in the field. Notably, zinc oxide (ZnO) and lead zirconate titanate (PZT) materials were found to produce output powers in the nanowatt to microwatt range. In one approach, textiles were coated with ZnO to harvest mechanical energy, which would otherwise be lost, and convert it into electrical energy. This innovative use of ZnO enables the efficient transformation of mechanical energy from human motion or other dynamic sources. Additionally, because of its quartzite crystal structure, ZnO is suitable for integration into MEMS and NEMS, where it can function as a high-frequency resonator. The piezoelectric properties of ZnO in such systems offer promising applications for powering small-scale biomedical devices and sensors, particularly in scenarios requiring long-term, low-power energy solutions.

Wearable medical devices, such as continuous glucose monitors, electrocardiograms (ECGs), and pulse oximeters, are increasingly being integrated with photovoltaic energy harvesting systems. The advantage of using PV cells in wearable devices lies in the accessibility to ambient light throughout the day, particularly for patients who spend time outdoors or in well-lit environments. Photovoltaic-integrated wearables can reduce the frequency of battery replacements or recharging, thereby improving patient comfort and convenience [32].

A PV cell tailored for use in biomedical implants is part of the design presented in reference [33]. This cell uses 850 nanometres of infrared light, which produces less than 1.06 microwatts per square millimeter of output power. The mouse sample was sandwiched between the LED and the PV cell. Crystalline silicon displays a conversion efficiency of about 15-20%. The size of the solar cell and the amount of light that hits it are directly related to the amount of electrical energy that gets captured. During the day, for example, efficiency levels of 15-20% can be achieved while producing energy levels of up to 100 mW/cm². It is possible to achieve an energy density ranging from 10 to 100 µW/mm² and a conversion efficiency of 8% in an indoor setting. After 40 days of in vivo testing, Haeberlin *et al.* [34] demonstrated that a photovoltaic-driven pacemaker using thin-film silicon materials had a power density of 0.95 mW cm^{-2}.

Underneath pig skin flaps, the photovoltaic cells are exposed to different intensities of light. The median output power that was found was 1963 µW/mm² when the sun was directly overhead, 206 µW/mm² when there was a shade outside, and 4 µW/mm² while it was indoors. Featuring a thin-film amorphous silicon photovoltaic module, this oximeter is flexible. To power this pulse oximeter, engineers created a thin-film lithium-ion battery that is both flexible and durable [35]. The system can be bent and attached to curved surfaces thanks to the PV module and battery's flexible construction.

4. CHALLENGES AND FUTURE DIRECTIONS

Despite the promising potential of photovoltaic energy harvesting for powering medical devices, several significant challenges must be addressed to facilitate its widespread adoption in clinical settings. One of the primary challenges is the efficiency of energy conversion in low-light environments, such as within the human body or in indoor settings where medical devices often operate. PV materials typically require a strong light source to achieve optimal performance, but medical environments often provide limited exposure to natural light, necessitating the development of materials and systems that are efficient even under these suboptimal conditions [5], [36].

Another challenge is the long-term stability and durability of photovoltaic materials, particularly when used in implantable devices. Over time, PV materials may degrade, reducing their energy conversion efficiency and potentially impacting the reliability of the medical device. Ensuring the longevity of these materials is crucial for the continuous operation of life-saving devices like pacemakers, biosensors, or drug delivery systems. Moreover, the development of flexible and biocompatible PV systems is essential for implantable applications. These systems must not only perform well in energy harvesting but also integrate seamlessly with human tissue, avoiding adverse reactions while maintaining flexibility to adapt to the body's movements [37]-[39].

In addition to technical challenges, regulatory hurdles must be addressed to ensure that PV-integrated medical devices meet strict safety and efficacy standards. Future research should prioritize enhancing the efficiency of photovoltaic materials in low-light conditions and developing advanced, flexible designs suitable for implantation. Exploring new PV materials with improved biocompatibility, flexibility, and long-term durability will also be crucial. Furthermore, integrating advances in energy storage technologies, such as high-efficiency batteries or supercapacitors, will be vital in ensuring that PV-powered medical devices can store harvested energy and function reliably over extended periods without frequent maintenance [5], [40]-[42].

Future research in photovoltaic energy harvesting for medical devices aims to address several key challenges to improve the practicality and efficiency of these systems. One significant direction is enhancing energy conversion under low-light conditions, as many medical devices operate in environments where light exposure is limited, such as within the human body or indoors. This requires advancements in materials and PV cell designs to maximize energy capture in such conditions. Biocompatibility and flexibility of PV materials are also critical for the development of implantable devices. Future innovations may focus on creating thinner, more flexible, and durable PV systems that can integrate seamlessly with biological tissues, minimizing the risk of rejection or complications over long-term use [40]-[45].

Another area of focus is improving the integration of PV systems with energy storage technologies, ensuring a continuous and reliable power supply, even during periods of low light. Additionally, advancements in miniaturization will enable the use of PV systems in smaller, more complex medical devices like MEMS. Finally, addressing regulatory and safety concerns is essential. Future research must ensure that PV-powered medical devices meet stringent clinical standards, paving the way for their widespread adoption in healthcare settings [46]-[49].

5. CONCLUSION

Photovoltaic energy harvesting presents a sustainable and innovative solution for powering medical devices, especially in wearable and implantable applications. By utilizing light to generate electricity, PV systems can potentially extend the lifespan of medical devices like pacemakers, biosensors, and drug delivery systems, minimizing the need for frequent battery replacements or surgical interventions. This not only enhances device longevity but also reduces the frequency of invasive procedures, improving overall patient care and quality of life.

The advancements in PV materials and design strategies are crucial in enabling these benefits. Flexible and biocompatible PV materials allow for seamless integration with the human body, making them ideal for implantable devices. Moreover, miniaturized, and adaptable PV systems offer the possibility of continuous, real-time health monitoring through wearable devices. However, challenges remain, particularly concerning the efficiency of energy conversion in low-light environments, which is critical for the reliability of devices used indoors or within the body.

Addressing issues related to biocompatibility and regulatory approval is also essential for widespread clinical adoption. PV systems must be safe for long-term implantation and meet strict medical device regulations. Therefore, further research is necessary to optimize PV materials, enhance efficiency in low-light conditions, and ensure compliance with medical safety standards, paving the way for the broader use of photovoltaic energy harvesting in healthcare technology.

FUNDING INFORMATION

Authors state there is no funding involved.

AUTHOR CONTRIBUTIONS

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration. The following table provides a summary of the authors' contributions to this research paper.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Hamza Abu Owida	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	
Basem Abu Izneid	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			
Nidal Turab	✓				✓	✓	✓		✓		✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that supports the findings of this study are available from the corresponding author, [HAO], upon reasonable request.

REFERENCES

[1] Y. H. Joung, "Development of implantable medical devices: from an engineering perspective," *International Neurourology Journal*, vol. 17, no. 3, pp. 98–106, 2013, doi: 10.5213/inj.2013.17.3.98.
[2] F. T. Ahamad, N. F. A. Malek, F. S. Roslan, N. Saidin, R. Islam, and N. E. L. Qasem, "Enhanced antenna performance at 3.5 GHz with a compact and intelligent reflecting surface," *IIUM Engineering Journal*, vol. 25, no. 2, pp. 179–195, 2024, doi: 10.31436/iiumej.v25i2.2954.
[3] H. A. Owida, J. I. Al-Nabulsi, N. M. Turab, F. Alnaimat, H. Rababah, and M. Y. Shakour, "Autocharging techniques for implantable medical applications," *International Journal of Biomaterials*, vol. 2021, 2021, doi: 10.1155/2021/6074657.
[4] B. Upendra, B. Panigrahi, K. Singh, and G. R. Sabareesh, "Recent advancements in piezoelectric energy harvesting for implantable medical devices," *Journal of Intelligent Material Systems and Structures*, vol. 35, no. 2, pp. 129–155, 2024, doi: 10.1177/1045389X231200144.
[5] J. Zhao *et al.*, "Self-powered implantable medical devices: photovoltaic energy harvesting review," *Advanced Healthcare Materials*, vol. 9, no. 17, 2020, doi: 10.1002/adhm.202000779.
[6] D. Hao *et al.*, "Solar energy harvesting technologies for PV self-powered applications: a comprehensive review," *Renewable Energy*, vol. 188, pp. 678–697, 2022, doi: 10.1016/j.renene.2022.02.066.
[7] S. Hwang and T. Yasuda, "Indoor photovoltaic energy harvesting based on semiconducting π-conjugated polymers and oligomeric materials toward future IoT applications," *Polymer Journal*, vol. 55, no. 4, pp. 297–316, 2023, doi: 10.1038/s41428-022-00727-8.
[8] A. S. Al-Ezzi and M. N. M. Ansari, "Photovoltaic solar cells: a review," *Applied System Innovation*, vol. 5, no. 4, 2022, doi: 10.3390/asi5040067.
[9] A. R. Jordehi, "Parameter estimation of solar photovoltaic (PV) cells: a review," *Renewable and Sustainable Energy Reviews*, vol. 61, pp. 354–371, 2016, doi: 10.1016/j.rser.2016.03.049.
[10] J. Pastuszak and P. Węgierek, "Photovoltaic cell generations and current research directions for their development," *Materials*, vol. 15(16), p. 5542, 2022.
[11] M. M. H. Shuvo, T. Titirsha, N. Amin, and S. K. Islam, "Energy harvesting in implantable and wearable medical devices for enduring precision healthcare," *Energies*, vol. 15, no. 20, 2022, doi: 10.3390/en15207495.
[12] P. Verlinden *et al.*, "Photovoltaic device innovation for a solar future," *Device*, vol. 1, no. 1, 2023, doi: 10.1016/j.device.2023.100013.
[13] M. Dada and P. Popoola, "Recent advances in solar photovoltaic materials and systems for energy storage applications: a review," *Beni-Suef University Journal of Basic and Applied Sciences*, vol. 12, no. 1, p. 66, Jul. 2023, doi: 10.1186/s43088-023-00405-5.
[14] M. Alkhawatrah, "Energy-harvesting cooperative NOMA in IoT networks," *Modelling and Simulation in Engineering*, vol. 2024, 2024, doi: 10.1155/2024/1043973.
[15] M. A. Fazal and S. Rubaiee, "Progress of PV cell technology: feasibility of building materials, cost, performance, and stability," *Solar Energy*, vol. 258, pp. 203–219, 2023, doi: 10.1016/j.solener.2023.04.066.
[16] T. S. Liang *et al.*, "A review of crystalline silicon bifacial photovoltaic performance characterisation and simulation," *Energy and Environmental Science*, vol. 12, no. 1, pp. 116–148, 2019, doi: 10.1039/c8ee02184h.
[17] Y. Zhan *et al.*, "Multi-layer transparent electrodes for high performance bifacial perovskite solar cells," *Surfaces and Interfaces*, vol. 44, 2024, doi: 10.1016/j.surfin.2023.103765.
[18] R. Santbergen and R. J. C. van Zolingen, "The absorption factor of crystalline silicon PV cells: a numerical and experimental study," *Solar Energy Materials and Solar Cells*, vol. 92, no. 4, pp. 432–444, 2008, doi: 10.1016/j.solmat.2007.10.005.

[19] E. R. Costals *et al.*, "Atomic layer deposition of vanadium oxide films for crystalline silicon solar cells," *Materials Advances*, vol. 3, no. 1, pp. 337–345, 2022, doi: 10.1039/d1ma00812a.
[20] C. Han *et al.*, "Controllable simultaneous bifacial cu-plating for high-efficiency crystalline silicon solar cells," *Solar RRL*, vol. 6, no. 6, 2022, doi: 10.1002/solr.202100810.
[21] S. Venkatesan, W. H. Lin, T. H. Hsu, H. Teng, and Y. L. Lee, "Indoor dye-sensitized solar cells with efficiencies surpassing 26% using polymeric counter electrodes," *ACS Sustainable Chemistry and Engineering*, vol. 10, no. 7, pp. 2473–2483, 2022, doi: 10.1021/acssuschemeng.1c07626.
[22] D. Devadiga, M. Selvakumar, P. Shetty, and M. S. Santosh, "The integration of flexible dye-sensitized solar cells and storage devices towards wearable self-charging power systems: a review," *Renewable and Sustainable Energy Reviews*, vol. 159, 2022, doi: 10.1016/j.rser.2022.112252.
[23] I. Dragutan, V. Dragutan, and A. Demonceau, "Special issue on ruthenium complexes," *Molecules*, vol. 22, no. 2, 2017, doi: 10.3390/molecules22020255.
[24] S. C. Yadav, A. Sharma, R. S. Devan, and P. M. Shirage, "Role of different counter electrodes on performance of tio2 based dye-sensitized solar cell (dssc) fabricated with dye extracted from hibiscus sabdariffa as sensitizer," *Optical Materials*, vol. 124, 2022, doi: 10.1016/j.optmat.2022.112066.
[25] T. M. W. J. Bandara, J. M. C. Hansadi, and F. Bella, "A review of textile dye-sensitized solar cells for wearable electronics," *Ionics*, vol. 28, no. 6, pp. 2563–2583, 2022, doi: 10.1007/s11581-022-04582-8.
[26] R. Zhu, E. Pan, and A. K. Roy, "Molecular dynamics study of the stress-strain behavior of carbon-nanotube reinforced epon 862 composites," *Materials Science and Engineering: A*, vol. 447, no. 1–2, pp. 51–57, 2007, doi: 10.1016/j.msea.2006.10.054.
[27] G. Sui, W. Zhong, X. Yang, and S. Zhao, "Processing and material characteristics of a carbon-nanotube-reinforced natural rubber," *Macromolecular Materials and Engineering*, vol. 292, no. 9, pp. 1020–1026, 2007, doi: 10.1002/mame.200700126.
[28] V. Abhinav *et al.*, "Advancements in wearable and implantable biomems devices: transforming healthcare through technology," *Micromachines*, vol. 16, no. 5, p. 522, Apr. 2025, doi: 10.3390/mi16050522.
[29] Z. Zhang, Y. Gu, S. Wang, M. Li, J. Bi, and Z. Zhang, "Enhancement of dielectric and electrical properties in bt/sic/PVDF three-phase composite through microstructure tailoring," *Composites Part A: Applied Science and Manufacturing*, vol. 74, pp. 88–95, 2015, doi: 10.1016/j.compositesa.2015.04.002.
[30] X. Cheng *et al.*, "Implantable and self-powered blood pressure monitoring based on a piezoelectric thin film: simulated, in vitro and in vivo studies," *Nano Energy*, vol. 22, pp. 453–460, 2016, doi: 10.1016/j.nanoen.2016.02.037.
[31] A. Khan, Z. Abas, H. Soo Kim, and I. K. Oh, "Piezoelectric thin films: an integrated review of transducers and energy harvesting," *Smart Materials and Structures*, vol. 25, no. 5, 2016, doi: 10.1088/0964-1726/25/5/053002.
[32] E. Moon, D. Blaauw, and J. D. Phillips, "Subcutaneous photovoltaic infrared energy harvesting for bio-implantable devices," *IEEE transactions on electron devices*, vol. 64, no. 5, pp. 2432–2437, May 2017.
[33] Y. Tanaka, T. Miyoshi, and Y. Suzuki, "Stochastic model of human arm swing toward standard testing for rotational energy harvester," *Journal of Physics: Conference Series*, vol. 1407, no. 1, 2019, doi: 10.1088/1742-6596/1407/1/012033.
[34] A. Haeberlin *et al.*, "The first batteryless, solar-powered cardiac pacemaker," *Heart Rhythm*, vol. 12, no. 6, pp. 1317–1323, 2015, doi: 10.1016/j.hrthm.2015.02.032.
[35] A. E. Ostfeld, A. M. Gaikwad, Y. Khan, and A. C. Arias, "High-performance flexible energy storage and harvesting system for wearable electronics," *Scientific Reports*, vol. 6, 2016, doi: 10.1038/srep26122.
[36] S. Zhao, C. Fang, J. Yang, and M. Sawan, "Emerging energy-efficient bio signal-dedicated circuit techniques: a tutorial brief," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 69, no. 6, pp. 2592–2597, 2022, doi: 10.1109/TCSII.2022.3169004.
[37] D. Hemapriya, P. Viswanath, V. M. Mithra, S. Nagalakshmi, and G. Umarani, "Wearable medical devices - design challenges and issues," *IEEE International Conference on Innovations in Green Energy and Healthcare Technologies - 2017, IGEHT 2017*, 2017, doi: 10.1109/IGEHT.2017.8094096.
[38] K. Bazaka and M. V. Jacob, "Implantable devices: issues and challenges," *Electronics (Switzerland)*, vol. 2, no. 1, 2012, doi: 10.3390/electronics2010001.
[39] D. Yogev, T. Goldberg, A. Arami, S. Tejman-Yarden, T. E. Winkler, and B. M. Maoz, "Current state of the art and future directions for implantable sensors in medical technology: clinical needs and engineering challenges," *APL Bioengineering*, vol. 7, no. 3, 2023, doi: 10.1063/5.0152290.
[40] Z. Gao *et al.*, "Advanced energy harvesters and energy storage for powering wearable and implantable medical devices," *Advanced Materials*, vol. 36, no. 42, 2024, doi: 10.1002/adma.202404492.
[41] Z. Zheng, R. Zhu, I. Peng, Z. Xu, and Y. Jiang, "Wearable and implantable biosensors: mechanisms and applications in closed-loop therapeutic systems," *Journal of Materials Chemistry B*, vol. 12, no. 35, pp. 8577–8604, 2024, doi: 10.1039/d4tb00782d.
[42] T. Ghomian and S. Mehraeen, "Survey of energy scavenging for wearable and implantable devices," *Energy*, vol. 178, pp. 33–49, 2019, doi: 10.1016/j.energy.2019.04.088.
[43] S. F. A. Abuowaida, H. Y. Chan, N. F. F. Alshdaifat, and L. Abualigah, "A novel instance segmentation algorithm based on improved deep learning algorithm for multi-object images," *Jordanian Journal of Computers and Information Technology*, vol. 7, no. 1, pp. 74–88, 2021, doi: 10.5455/jjcit.71-1603701313.
[44] N. F. F. Alshdaifat, M. A. Osman, and A. Z. Talib, "An improved multi-object instance segmentation based on deep learning," *Kuwait Journal of Science*, vol. 49, no. 2, 2022, doi: 10.48129/kjs.10879.
[45] S. F. A. Abuowaida and H. Y. Chan, "Improved deep learning architecture for depth estimation from single image," *Jordanian Journal of Computers and Information Technology*, vol. 6, no. 4, pp. 434–445, 2020, doi: 10.5455/jjcit.71-1593368945.
[46] B. Al-naami, H. Fraihat, H. A. Owida, K. Al-hamad, R. De Fazio, and P. Visconti, "Automated detection of left bundle branch block from ecg signal utilizing the maximal overlap discrete wavelet transform with anfis," *Computers*, vol. 11, no. 6, 2022, doi: 10.3390/computers11060093.
[47] M. Arabiat, S. Abuowaida, A. Al-Momani, N. Alshdaifat, and H. Y. Chan, "Depth estimation method based on residual networks and se-net model," *Journal of Theoretical and Applied Information Technology*, vol. 102, no. 3, pp. 866–871, 2024.
[48] S. Abuowaida *et al.*, "Proposed enhanced feature extraction for multi-food detection method," *Journal of Theoretical and Applied Information Technology*, vol. 101, no. 24, pp. 8140–8146, 2023.
[49] A. Al-Momani, M. N. Al-Refai, S. Abuowaida, M. Arabiat, N. Alshdaifat, and M. N. A. Rahman, "The effect of technological context on smart home adoption in Jordan," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 33, no. 2, pp. 1186–1195, 2024, doi: 10.11591/ijeecs.v33.i2.pp1186-1195.

BIOGRAPHIES OF AUTHORS

Hamza Abu Owida received Ph.D. in Biomedical Engineering. He is an assistant professor in the Medical Engineering Department at Al-Ahliyya Amman University, Jordan. His research interests focused on biomedical sensors, nanotechnology, and tissue engineering. He can be contacted at email: h.abuowida@ammanu.edu.jo.

Basem Abu Izneid received his Ph.D. in mechatronics from University Science Malaysia. His research interests focused on robotics and artificial intelligence, and biomedical sensors. He is an assistant professor at the Robotics and Artificial Intelligence Engineering Department, Al-Ahliyya Amman University, Jordan. He has authored 40+ publications. He can be contacted at email: b.izneid@ammanu.edu.jo.

Nidal Turab received his Ph.D. in computer science. He is a professor in the Networks and Cyber Security Department at Al-Ahliyya Amman University, Jordan. His research interests include WLAN security, computer network security, cloud computing security, e-learning, and internet of things. He can be contacted at email: n.turab@ammanu.edu.jo.