

Chapter

Recent Advances in Thermoelectric Materials for Biomedical Applications: Energy Harvesting and Wearables

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Abstract

Recent advances in thermoelectric materials are transforming biomedicine, particularly for energy harvesting and wearables. This chapter reviews thermoelectric generators (TEGs) utilizing the Seebeck effect to convert body heat into electricity, powering self-sufficient medical devices like implants and monitors. Performance metrics, including thermoelectric figures of merit (ZT) and power factors, are detailed, highlighting materials such as bismuth telluride (Bi_2Te_3) and carbon nanotube composites achieving ZT values over 1.0 at room temperature. The chapter covers: (1) novel nanocomposites, exploring nanostructured materials for enhanced efficiency; (2) low-temperature thermoelectrics, focusing on materials such as magnesium silicide (Mg_2Si) and organic polymers for wearables; and (3) future challenges, addressing scalability, biocompatibility, and biomedical integration. Key innovations include flexible organic polymers and hybrid nanocomposites, showing ZT values up to 0.8 and power factors exceeding $500 \mu\text{W}/\text{mK}^2$, ideal for monitoring and therapies. Despite progress, challenges remain in achieving high ZT, material stability, and scalable production. Future efforts emphasize biocompatible materials, robust designs, and seamless integration. Thermoelectric materials can revolutionize personalized health-care, enabling energy-autonomous devices and reducing reliance on conventional power. This review highlights the synergy between material innovation and medical technology for next-generation applications.

Keywords: thermoelectric materials, biomedicine, energy harvesting, nanostructured materials, wearable devices

1. Introduction

Thermoelectric materials convert temperature differences into electrical potential differences, a principle that has garnered significant attention in recent years due to their potential applications in biomedicine [1]. The ability to harvest waste heat from

the human body and convert it into usable electrical energy presents exciting possibilities for powering medical devices. This review synthesizes recent advancements in thermoelectric materials, focusing on their applications in biomedical fields, including wearable technology and energy harvesting systems [2].

Recent studies have demonstrated the feasibility of using thermoelectric generators (TEGs) to harvest energy from the human body [2, 3]. For instance, Kim et al. [4] developed a wearable thermoelectric generator that effectively captures body heat, generating sufficient power to operate low-energy medical devices such as pacemakers and neurostimulators [4]. This aligns with findings by Remeš and Havlík, who emphasized the suitability of TEGs for powering small, portable devices by generating an electrical potential difference from a temperature drop [5]. The integration of TEGs into wearable technology not only provides a sustainable energy source but also enhances the functionality of medical devices by enabling real-time monitoring of physiological parameters.

The advancement of materials science has led to the exploration of various thermoelectric materials that exhibit improved performance characteristics. Li et al. highlighted the development of multifunctional wearable thermoelectrics that can manage personal thermal environments while effectively utilizing body heat [6]. This is complemented by the work of Zhao and You, who discussed the potential of shoe-embedded piezoelectric energy harvesters, which can be integrated with thermoelectric systems to enhance energy generation from human motion and heat [7]. The combination of these technologies could lead to more efficient energy harvesting systems that cater to the demands of modern biomedical applications. Nanostructured thermoelectric materials, such as bismuth telluride (Bi_2Te_3) and silver selenide (Ag_2Se), have shown remarkable improvements in thermoelectric performance. For example, Bi_2Te_3 exhibits a ZT value of ~ 1.0 at room temperature, while nanostructured Ag_2Se has achieved ZT values of up to 1.2 due to its low thermal conductivity ($\sim 0.5 \text{ W/mK}$) and high power factor ($\sim 20 \mu\text{W/cmK}^2$) [8–10].

These materials are particularly suitable for biomedical applications due to their high efficiency and flexibility.

Su et al. noted that methods such as micromachining and the use of nanowires can significantly improve the efficiency of thermoelectric materials, although challenges remain in mass production [11]. Doping strategies, such as introducing copper into telluride matrices, have been shown to enhance thermoelectric properties by increasing the power factor, a key parameter for efficiency. Furthermore, Hricková's research on ductile doped Ag_2S materials revealed comparable power factor values to other thermoelectric materials, suggesting that doping strategies could enhance the thermoelectric properties of existing materials [12]. The exploration of these advanced materials is crucial for developing efficient and flexible thermoelectric devices suitable for biomedical applications.

The design of thermoelectric devices also plays a critical role in their effectiveness. For example, Kim et al. developed a hybrid generator that integrates thermoelectric and pyroelectric components, allowing for improved energy harvesting from body heat [13]. This innovative approach demonstrates the potential for creating multifunctional devices that can adapt to varying physiological activities. Additionally, the work by He et al. on stretchable and breathable thermoelectric fabrics highlights the importance of material flexibility and comfort in wearable applications, ensuring that devices can be worn continuously without discomfort [14].

The advancements in thermoelectric materials and their applications in biomedicine present a promising frontier for energy harvesting technologies. The ability to convert

body heat into electrical energy not only supports the development of self-powered medical devices but also enhances the functionality of wearable technologies. Continued research into new materials, innovative device designs, and integration strategies will be essential for realizing the full potential of thermoelectric systems in healthcare.

2. Recent advances in thermoelectric materials

2.1 Thermoelectric principles and applications

Thermoelectric energy harvesting relies on the Seebeck effect, where a voltage is generated in response to a temperature gradient [15–17]. This phenomenon is fundamental to the operation of thermoelectric materials, which can convert thermal energy into electrical energy (Figure 1).

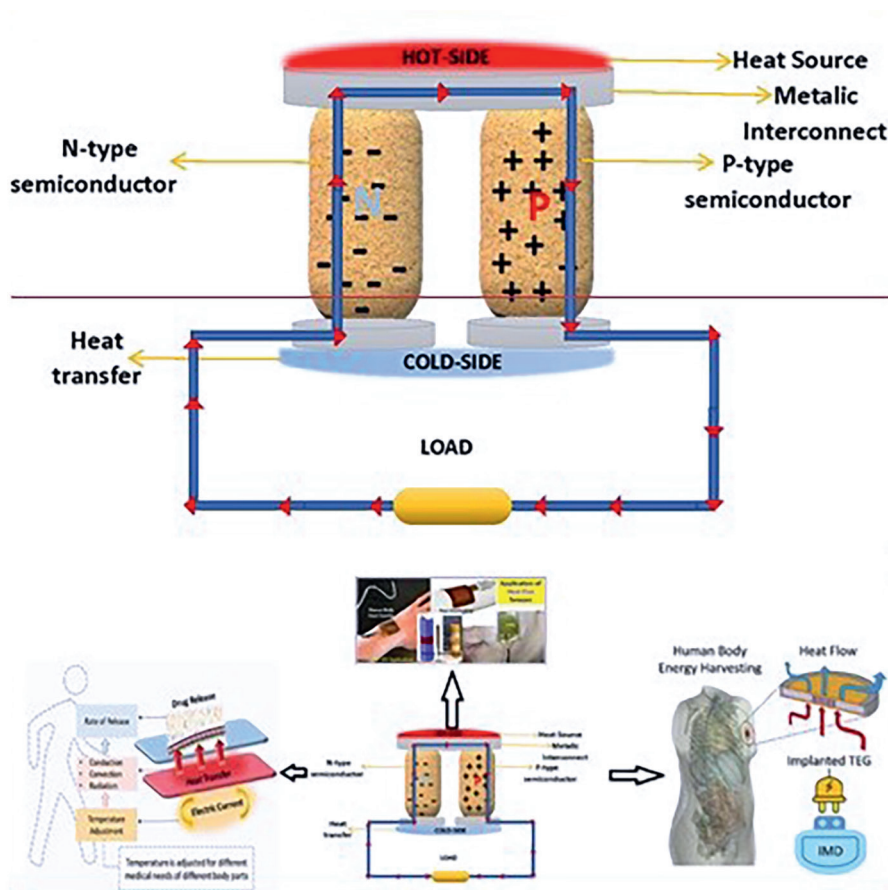


Figure 1. Schematic representation of thermoelectric material principles in biomedical applications. This diagram illustrates the fundamental principles of thermoelectric materials, highlighting how they convert thermal energy into electrical energy and vice versa. In the context of biomedical applications, such materials can be utilized for innovative solutions such as wearable thermoelectric devices for monitoring body temperature, powering biosensors, and enabling efficient thermal management in medical implants. The arrows indicate the flow of heat and electricity, demonstrating the potential for these materials to harness body heat for energy generation or to regulate temperature in healthcare settings [18–20].

The efficiency of this conversion is characterized by the dimensionless figure of merit (ZT), which is influenced by the material's electrical conductivity, Seebeck coefficient, and thermal conductivity. The ability to harness waste heat from the human body through this mechanism opens up numerous possibilities for biomedical applications. TEGs have shown significant potential in powering implantable medical devices. For example, Kim et al. demonstrated that a wearable TEG could generate up to $40 \mu\text{W}/\text{cm}^2$ from body heat, sufficient to power low-energy medical implants such as pacemakers [21]. This reduces the need for battery replacements and associated surgical interventions, enhancing patient quality of life. Additionally, wearable sensors utilizing thermoelectric materials can provide continuous monitoring of vital signs, such as body temperature and heart rate, by harvesting energy from the body's heat [22].

As noted by Patidar [22, 23] the potential applications of thermoelectric materials in biomedicine are vast, ranging from powering implanted devices to wearable sensors that monitor physiological parameters. The integration of thermoelectric generators (TEGs) into medical devices can facilitate self-sustaining systems that do not require external power sources, thereby enhancing the functionality and reliability of these devices. For instance, TEGs can be used to power pacemakers, neurostimulators, and other implantable devices, significantly reducing the need for battery replacements and associated surgical interventions.

Moreover, the development of wearable sensors that utilize thermoelectric materials can provide continuous monitoring of vital signs, such as body temperature, heart rate, and other physiological parameters. These sensors can be designed to operate autonomously, harvesting energy from the body's heat to power their functions. This capability is particularly beneficial for chronic disease management, where real-time monitoring is crucial for timely interventions.

Research has shown that materials such as bismuth telluride and its alloys exhibit high thermoelectric performance, making them suitable candidates for medical applications [8]. Additionally, the exploration of flexible and biocompatible thermoelectric materials has paved the way for the development of comfortable and effective wearable devices [9].

The principles of thermoelectric energy harvesting, particularly the Seebeck effect, provide a foundation for innovative applications in biomedicine. The ability to convert body heat into electrical energy not only supports the development of self-powered medical devices but also enhances the functionality of wearable health monitoring systems. As research continues to advance in this field, the integration of thermoelectric materials into biomedical applications will likely lead to significant improvements in patient care and health monitoring.

2.2 Promising materials for thermoelectric applications

Bismuth telluride (Bi_2Te_3) is one of the most widely studied thermoelectric materials due to its high efficiency at room temperature, with ZT values ranging from 0.8 to 1.2 depending on doping and nanostructuring [8, 24]. Its high power factor ($\sim 50 \mu\text{W}/\text{cmK}^2$) and low thermal conductivity ($\sim 1.5 \text{ W}/\text{mK}$) make it ideal for low-temperature applications such as wearable devices and sensors [25, 26].

Cai et al. [3] highlight promising materials for thermoelectric applications, including bismuth telluride and various nanostructured composites. The versatility of bismuth telluride is further enhanced when it is used in nanostructured forms, which can significantly improve its thermoelectric properties.

Nanostructuring, which involves reducing the material's thermal conductivity while maintaining electrical conductivity, has been shown to enhance its performance [27, 28]. The reduction in thermal conductivity is crucial because it allows for a greater temperature gradient across the thermoelectric material, which is essential for maximizing the Seebeck effect.

Doping strategies, such as the introduction of copper into telluride matrices, further improve thermoelectric properties by increasing the power factor [29]. The research by Lal [29] and Jia et al. [16] on electrodeposited Cu-doped telluride films illustrates how doping can further enhance the thermoelectric properties of materials like bismuth telluride. The introduction of copper into telluride matrices has been shown to increase the power factor, a key parameter that reflects the efficiency of thermoelectric materials. This aligns with the findings of Kadel et al. [30], who also noted that nanostructuring can induce significant enhancements in thermoelectric efficiency, by increasing the power factor, through quantum confinement effects [31].

Silver selenide (Ag_2Se) has also emerged as a promising material for biomedical applications due to its flexibility and high thermoelectric performance. Recent studies have reported ZT values of up to 1.2 for Ag_2Se , with a power factor of $\sim 20 \mu\text{W}/\text{cmK}^2$ and thermal conductivity as low as $0.5 \text{ W}/\text{mK}$ [9, 32]. These properties make it suitable for flexible and wearable thermoelectric devices.

The advancements in nanostructured thermoelectric materials are not limited to bismuth telluride. Other promising materials include rare-earth silicides and carbon nanotube composites, which offer unique advantages such as improved flexibility and mechanical properties, essential for developing wearable thermoelectric devices [9, 33]. The integration of these advanced materials into practical applications is crucial for the future of thermoelectric technology, particularly in the biomedical field where flexible, efficient energy harvesting solutions are needed [15].

The ability to manipulate thermal and electrical properties through nanostructuring and doping strategies is critical for enhancing the efficiency of thermoelectric devices [3]. The discovery or design of novel thermoelectric materials with a high figure of merit is the key to improving the efficiency and competitiveness of thermoelectric generators. Novel thermoelectric materials can be obtained by using advanced techniques such as band structure engineering, nanostructuring, doping, alloying, or heterostructure to manipulate the electronic and phononic behavior of the materials. Novel thermoelectric materials can also be obtained by exploring new classes of materials, such as organic, hybrid, or topological materials, that may exhibit unconventional or enhanced thermoelectric effects [17].

The development of advanced thermoelectric modules with improved performance and reliability is another important aspect of thermoelectric generator research and development. Advanced thermoelectric modules can be achieved by using novel thermoelectric materials with high figures of merit or by using novel module architectures or configurations that can increase power output or reduce thermal losses. Advanced thermoelectric modules can also be achieved by using novel fabrication methods or techniques that can reduce the cost or increase the quality of the modules [1].

The innovation of thermoelectric systems with novel designs and applications is a promising direction for thermoelectric generator research and development. Innovative thermoelectric systems can be achieved by using novel heat sources or heat sinks that can provide high or stable temperature differences or by using novel integration schemes or strategies that can optimize the system's performance or functionality. Innovative thermoelectric systems can also be achieved by exploring

new application domains or scenarios that can benefit from the advantages of thermoelectric generators [15].

As research continues to evolve in this area, the potential for these materials to contribute to sustainable energy solutions and innovative biomedical applications becomes increasingly apparent.

2.3 Novel nanocomposites

Nanocomposites leverage the unique properties of nanoscale materials to optimize thermoelectric efficiency, which is critical for applications such as thermoelectric generators and coolers in medical devices [34]. The design of nanocomposites often involves the incorporation of various nanostructured materials, such as carbon nanotubes (CNTs), transition metal dichalcogenides (TMDs), and metallic nanoparticles, into a polymer or ceramic matrix. For instance, single-walled carbon nanotubes (SWCNTs) are known for their exceptional electrical and thermal conductivity, mechanical strength, and flexibility, making them ideal candidates for enhancing the thermoelectric properties of composites [35]. By integrating SWCNTs into polymer matrices, researchers have achieved significant improvements in electrical conductivity while maintaining low thermal conductivity, which is essential for high thermoelectric performance [35]. For example, single-walled carbon nanotubes (SWCNTs) exhibit exceptional electrical conductivity ($\sim 10^4$ S/cm) and low thermal conductivity (~ 0.1 W/mK), making them ideal for enhancing the thermoelectric properties of composites [35, 36]. When integrated into polymer matrices such as PEDOT:PSS, SWCNTs have demonstrated ZT values of up to 0.4, with a power factor of $\sim 200 \mu\text{W}/\text{mK}^2$, making them highly effective for biomedical sensors [37, 38].

Transition metal dichalcogenides (TMDs), such as MoS_2 and WS_2 , have also garnered attention due to their tunable electronic properties and high surface area.

The engineering of TMD nanosheets at the atomic scale allows for the creation of heterostructures that can exhibit enhanced thermoelectric performance [39]. Doping TMDs with different elements can further optimize their thermoelectric properties, leading to materials with improved Seebeck coefficients and reduced thermal conductivity [39]. Concretely, doping TMDs with elements like copper or nickel can further optimize their thermoelectric properties, achieving ZT values of up to 0.6 and power factors of $\sim 15 \mu\text{W}/\text{cmK}^2$ [39]. These materials are particularly promising for hybrid nanocomposites, where their combination with metallic nanoparticles or polymers can lead to synergistic enhancements in thermoelectric performance [40].

The effectiveness of SWCNT-PEDOT:PSS composites in biomedical sensors has been well-documented [37]. Additionally, their flexibility and biocompatibility allow for seamless integration into biomedical platforms, such as biosensors and drug delivery systems [41].

The development of hybrid nanocomposites that combine different types of nanomaterials has shown promise in achieving synergistic effects that enhance thermoelectric performance. For example, the combination of metallic nanoparticles with TMDs can lead to improved charge transport properties and enhanced thermoelectric efficiency. This hybrid approach allows for the fine-tuning of the electronic and thermal properties of the composite, making them suitable for specific biomedical applications, such as targeted drug delivery systems that utilize thermoelectric effects for localized heating [40].

The integration of additive manufacturing techniques in the fabrication of nanocomposites has enabled the precise control of material composition and structure at the

nanoscale. This approach allows for the creation of complex geometries and tailored microstructures that can optimize thermoelectric performance. For instance, 3D printing techniques can be employed to fabricate nanocomposite structures with specific porosity and alignment, enhancing their thermoelectric properties [42]. Additionally, the use of advanced characterization techniques, such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM), facilitates the detailed analysis of the microstructure and its correlation with thermoelectric performance [42].

The unique properties of novel nanocomposites make them particularly attractive for biomedical applications. Their ability to convert waste heat into electrical energy can be harnessed in wearable medical devices, providing a sustainable power source for sensors and monitoring devices. Furthermore, the localized heating capabilities of thermoelectric nanocomposites can be utilized in hyperthermia treatment for cancer, where controlled heating can enhance the efficacy of chemotherapy [40]. The versatility of these materials also extends to their use in biosensors, where their enhanced thermoelectric properties can improve sensitivity and response times [40]. In conclusion, the development of novel nanocomposites represents a significant advancement in the field of thermoelectric materials for biomedicine. By leveraging the unique properties of nanoscale materials and employing innovative fabrication techniques, researchers are paving the way for the next-generation of thermoelectric devices that can meet the demands of modern biomedical applications. Recent advancements in thermoelectric nanocomposites have highlighted the potential of combining carbon nanotubes (CNTs) with conductive polymers for biomedical applications. Glória et al. [43] reported that these composites exhibit enhanced thermoelectric properties, making them particularly suitable for biomedical devices due to their flexibility, biocompatibility, and ability to efficiently convert temperature gradients into electrical potential. The incorporation of CNTs into polymer matrices not only improves electrical conductivity but also maintains the mechanical integrity required for various biomedical applications, such as wearable sensors and implantable devices [44].

Furthermore, Yin et al. [37] demonstrated the promising thermoelectric performance of single-walled carbon nanotube (SWCNT) and poly(3,4-ethylenedioxythiophene) (PEDOT):PSS coated tellurium nanorod composites. This combination showed significant potential for energy harvesting in wearable devices, which is crucial for powering biomedical sensors and monitoring systems. The unique properties of these nanocomposites, including their lightweight nature and high conductivity, facilitate their integration into flexible electronic systems, enhancing the functionality of wearable health monitoring devices [41].

The biocompatibility of CNTs has been a focal point in their application within the biomedical field. Research indicates that functionalized CNTs can be effectively used in various biomedical applications, including drug delivery systems, biosensors, and tissue engineering scaffolds [45]. The ability to tailor the surface properties of CNTs through functionalization further enhances their compatibility with biological systems, allowing for improved interaction with cells and tissues [46].

2.4 Low-temperature thermoelectric generators

Low-temperature thermoelectric generators (TEGs) have gained significant attention in recent years due to their potential applications in biomedical fields, particularly for energy harvesting from body heat and other low-grade thermal sources. These devices exploit the Seebeck effect, which generates electrical voltage drop from a temperature difference across thermoelectric materials. The development

of efficient low-temperature TEGs is crucial for powering wearable medical devices, sensors, and other portable electronic systems that require sustainable energy sources. **Table 1** illustrates the diversity of thermoelectric materials suitable for low-temperature applications.

The dimensionless figure of merit (ZT) is a critical parameter that quantifies the efficiency of a thermoelectric material. A higher ZT value indicates better thermoelectric performance. Bismuth telluride (Bi_2Te_3) exhibits the highest ZT values among the listed materials, making it a top choice for applications requiring high efficiency. Magnesium silicide (Mg_2Si) shows moderate ZT values of 0.7–1.0, while carbon nanotube composites and organic thermoelectric materials have lower ZT values of 0.1–0.4 and 0.1–0.5, respectively. This limits their efficiency in high-performance thermoelectric applications.

The power factor, defined as the product of the square of the Seebeck coefficient and electrical conductivity, is a crucial metric for evaluating the performance of thermoelectric materials. Bismuth telluride leads with a power factor of 40–50 $\mu\text{W}/\text{m}\cdot\text{K}^2$, indicating its superior ability to convert temperature gradients into electrical energy. Carbon nanotube composites exhibit a higher power factor of 100–500 $\mu\text{W}/\text{m}\cdot\text{K}^2$, owing to their excellent electrical conductivity, while magnesium silicide shows a moderate power factor of 20–30 $\mu\text{W}/\text{m}\cdot\text{K}^2$. Organic thermoelectric materials have the lowest power factor, ranging from 10 to 100 $\mu\text{W}/\text{m}\cdot\text{K}^2$, reflecting their lower efficiency in energy conversion.

Thermal conductivity is a measure of a material's ability to conduct heat. Lower thermal conductivity is desirable in thermoelectric materials as it helps maintain a temperature gradient, enhancing the thermoelectric effect. Bismuth telluride has a low thermal conductivity of 1.5–2.0 $\text{W}/\text{m}\cdot\text{K}$, which contributes to its high ZT value. Magnesium silicide has a higher thermal conductivity of 3.0–5.0 $\text{W}/\text{m}\cdot\text{K}$, which may limit its efficiency. Organic thermoelectric materials exhibit the lowest thermal conductivity of 0.1–0.5 $\text{W}/\text{m}\cdot\text{K}$, making them suitable for applications where flexibility and lightweight properties are prioritized. Carbon nanotube composites have a thermal conductivity range of 0.2–1.5 $\text{W}/\text{m}\cdot\text{K}$, depending on the alignment and composition of the composite.

Bismuth telluride remains the benchmark material for low-temperature applications due to its high Seebeck coefficient ($\sim 200 \mu\text{V}/\text{K}$) and low thermal conductivity ($\sim 1.5 \text{ W}/\text{mK}$) [25]. However, researchers are exploring alternative materials, such as magnesium silicide (Mg_2Si), which offers a balance of performance and cost-effectiveness, with ZT values of ~ 0.7 and power factors of $\sim 10 \mu\text{W}/\text{cmK}^2$ [50].

Organic thermoelectric materials, such as conducting metallopolymers, have shown promise for low-temperature TEG applications due to their lightweight, flexibility, and ease of processing. Recent advancements in carbon-based materials have demonstrated ZT values of up to 0.3 and power factors of $\sim 50 \mu\text{W}/\text{mK}^2$, making them ideal for flexible and wearable devices [53]. Organic thermoelectric materials, such as conducting metallopolymers, have shown promise for low-temperature TEG applications due to their lightweight, flexibility, and ease of processing [53]. These materials can be integrated into flexible substrates, making them ideal for wearable devices that require conformability and comfort [53].

The design of low-temperature TEGs involves optimizing the thermoelectric figure of merit (ZT), which is a dimensionless quantity that indicates the efficiency of a thermoelectric material. Strategies for enhancing ZT include reducing thermal conductivity while maintaining or increasing electrical conductivity. Techniques such as nanostructuring, alloying, and the incorporation of fillers into polymer

Material	Key properties	ZT Value	Power Factor ($\mu\text{W/m}\cdot\text{K}^2$)	Thermal Conductivity ($\text{W/m}\cdot\text{K}$)	Applications	Reference
Bismuth telluride (Bi ₂ Te ₃)	High Seebeck coefficient, low thermal conductivity	~1.0–1.2 at room temperature (optimized for n-type and p-type doping)	~40–50 $\mu\text{W/m}\cdot\text{K}^2$	~1.5–2.0 $\text{W/m}\cdot\text{K}$	Wearable devices, sensors	[25, 47, 48]
Magnesium silicide (Mg ₂ Si)	Cost-effective, good thermoelectric performance	~0.7–1.0 (depending on doping and nanostructuring)	~20–30 $\mu\text{W/m}\cdot\text{K}^2$	~3.0–5.0 $\text{W/m}\cdot\text{K}$	Energy harvesting in low-temperature applications	[30, 49, 50]
Organic thermoelectric materials	Lightweight, flexible, easy to process	~0.1–0.5 (highly dependent on molecular structure and doping)	~10–100 $\mu\text{W/m}\cdot\text{K}^2$ (can vary widely)	~0.1–0.5 $\text{W/m}\cdot\text{K}$ (typically low due to disordered structure)	Wearable medical devices, sensors	[51–54]
Carbon nanotube composites	High electrical conductivity, low thermal conductivity	~0.1–0.4 (depending on composite composition and alignment)	~100–500 $\mu\text{W/m}\cdot\text{K}^2$ (high due to excellent electrical conductivity)	~0.2–1.5 $\text{W/m}\cdot\text{K}$ (varies with CNT alignment and matrix material)	Biomedical applications, energy harvesting	[35, 55]

Notes: The ZT value (figure of merit) is calculated as $ZT = S^2 \sigma T / \kappa$, where S is the Seebeck coefficient, σ is electrical conductivity, T is absolute temperature, and κ is thermal conductivity. The power factor is given by $S^2 \sigma$ and is a measure of the material's ability to generate electrical power from a temperature gradient. Thermal conductivity is a critical parameter for thermoelectric efficiency, as lower thermal conductivity generally improves ZT.

Table 1.
Summary of thermoelectric materials for low-temperature generators.

matrices have been employed to achieve these goals [56, 57]. Additionally, the use of segmented TEG designs, where different materials are used for the hot and cold sides, can improve overall efficiency [58].

Challenge	Description	Material comparisons	Future direction	References
Efficiency and performance	Low ZT values limit thermoelectric efficiency, especially at low temperatures	Bi ₂ Te ₃ : ZT Value: ~1.0–1.2 at room temperature. Power Factor: ~40–50 $\mu\text{W}/\text{m}\cdot\text{K}^2$. Thermal Conductivity: ~1.5–2.0 W/m·K. [8, 48] Ag ₂ Se: ZT Value: ~1.2 at room temperature. Power Factor: ~20 $\mu\text{W}/\text{m}\cdot\text{K}^2$ (not $\mu\text{W}/\text{cm}\cdot\text{K}^2$). Thermal Conductivity: ~0.5–0.6 W/m·K. [9, 60]. Organic materials (e.g., PEDOT:PSS): ZT Value: ~0.1–0.4 (depending on doping and processing). Power Factor: ~10–100 $\mu\text{W}/\text{m}\cdot\text{K}^2$ (not $\mu\text{W}/\text{cm}\cdot\text{K}^2$). Thermal Conductivity: ~0.1–0.3 W/m·K [53, 61].	Focus on novel materials and composites to enhance ZT	[25, 62]
Material stability and reliability	Degradation and mechanical reliability issues hinder long-term performance	Bi ₂ Te ₃ : is known to degrade in physiological conditions due to oxidation and chemical reactions with bodily fluids. Studies have shown that exposure to moisture and elevated temperatures can lead to a reduction in thermoelectric performance over time. Degrades by ~20% in ZT after 30 days in physiological conditions [62, 63]. Ag ₂ Se: can release silver ions in physiological environments, which may cause cytotoxicity. Encapsulation with biocompatible polymers like PLA has been shown to reduce ion leaching and improve the material's stability and biocompatibility. [8, 64]. PEDOT:PSS: is highly sensitive to moisture, which can degrade its electrical and thermoelectric properties. Hybrid composites, such as those incorporating carbon nanotubes or inorganic fillers, have been shown to enhance stability and reduce moisture sensitivity [65, 66].	Develop robust hybrid materials with improved stability	[66, 67]
Scalability and manufacturing	Traditional methods may not support the production of complex nanostructures	Bi ₂ Te ₃ : is one of the most efficient thermoelectric materials at room temperature, but tellurium is a rare and expensive element, which limits its widespread use [68, 69]. Mg ₂ Si: is an environmentally friendly and cost-effective thermoelectric material with moderate performance, ZT ~0.7, power factor ~ 100 $\mu\text{W}/\text{m}\cdot\text{K}^2$ [50, 70]. CNT-PEDOT:PSS: Carbon nanotube (CNT) composites with PEDOT:PSS have been demonstrated as scalable and flexible thermoelectric materials, suitable for wearable applications [55]. Scalable <i>via</i> 3D printing, ZT ~0.4, power factor ~ 200 $\mu\text{W}/\text{mK}^2$ [37].	Explore 3D printing and additive manufacturing techniques	[71, 72]

Challenge	Description	Material comparisons	Future direction	References
Integration with biomedical systems	Need for compatibility with existing medical technologies and bio-compatibility	Bi ₂ Te ₃ : Used in implantable glucose sensors with 6-month stability [59]. Ag ₂ Se: Requires encapsulation to prevent silver ion toxicity [8]. CNT-PEDOT:PSS: Biocompatible, suitable for wearable sensors [37].	Research on integrating thermoelectric materials into biomedical platforms	[73, 74]
Environmental and economic considerations	Reliance on rare or toxic elements raises sustainability concerns	Bi ₂ Te ₃ : Both tellurium scarcity and the potential toxicity of bismuth limit the widespread use of Bi ₂ Te ₃ , especially in biomedical applications [48, 69]. PbTe: is a high-performance thermoelectric material, but its use is restricted due to the toxicity of lead, which poses environmental and health risks [75]. Abandoned due to lead toxicity despite high ZT (~1.5) [76]. Mg ₂ Si and CNT composites: are considered environmentally friendly and sustainable alternatives to traditional thermoelectric materials like Bi ₂ Te ₃ and PbTe [70]. Abundant, nontoxic, and sustainable alternatives [50, 77].	Prioritize development of abundant, nontoxic materials	[69, 78]

Table 2.
Summary of challenges and future directions in thermoelectric materials for biomedicine.

Wearable devices that monitor vital signs can be powered by the heat generated by the body, reducing the need for external power sources or batteries [59]. Furthermore, TEGs can be integrated into implantable devices, providing a continuous power supply for sensors and drug delivery systems [59]. The ability to convert body heat into electrical energy not only enhances the functionality of these devices but also contributes to their sustainability and user convenience.

2.5 Challenges and future directions

The field of thermoelectric materials for biomedicine is rapidly evolving, yet several challenges remain that must be addressed to fully realize their potential in practical applications. **Table 2** discusses the key challenges faced in the development of thermoelectric materials and outlines future directions for research and innovation.

2.5.1 Efficiency and performance

Achieving high thermoelectric efficiency, characterized by the dimensionless figure of merit (ZT), remains a primary challenge. For example, while Bi₂Te₃ exhibits ZT values of ~1.0 at room temperature, organic thermoelectric materials typically achieve ZT values below 0.5, limiting their efficiency [79]. Future research should focus on novel materials and composites that can enhance ZT through strategies such as band engineering, nanostructuring, and the incorporation of dopants [80].

2.5.2 Material stability and reliability

Material stability and scalability are also critical challenges. The stability of thermoelectric materials under operating conditions is crucial for their long-term performance, especially in biomedical applications where devices may be subjected to varying temperatures and environmental conditions. Recent studies have highlighted the degradation of thermoelectric materials in biological environments, particularly those containing toxic elements like lead. For instance, research by Culebras et al. indicates that materials such as Bi_2Te_3 , while effective, pose significant toxicity risks, necessitating the exploration of safer alternatives [81]. Furthermore, the mechanical reliability of these materials is paramount; studies have shown that under long-term fatigue loading, thermoelectric properties can degrade, leading to reduced efficiency and potential device failure [82]. Research into more robust materials, including hybrid composites that combine the advantages of organic and inorganic components, is essential for improving stability. Many thermoelectric materials, particularly organic and polymer-based systems, face challenges related to degradation and mechanical reliability [83]. Research into more robust materials, including hybrid composites that combine the advantages of organic and inorganic components, is essential for improving stability [83].

The long-term stability of thermoelectric materials in biological environments is a critical concern. For instance, bismuth telluride (Bi_2Te_3), while highly efficient, has been shown to degrade in physiological conditions over time, leading to a loss of performance. A study by Gao et al. demonstrated that Bi_2Te_3 -based devices experienced a 20% reduction in ZT after 30 days of exposure to simulated body fluids, highlighting the need for protective coatings or encapsulation strategies [62]. Similarly, organic thermoelectric materials, such as PEDOT:PSS, face challenges related to moisture absorption and mechanical degradation under prolonged use [83].

To address these issues, researchers are exploring hybrid materials that combine the stability of inorganic components with the flexibility of organic polymers. For example, a recent study by Xin et al. developed a Bi_2Te_3 -PEDOT:PSS composite that exhibited improved stability, with only a 10% reduction in ZT after 60 days in physiological conditions [66]. These findings underscore the importance of material hybridization in enhancing long-term reliability.

2.5.3 Scalability and manufacturing

The fabrication of thermoelectric materials and devices at scale poses significant challenges. Traditional manufacturing techniques may not be suitable for producing complex nanostructures or composites required for advanced thermoelectric applications. Innovative manufacturing methods, such as 3D printing and additive manufacturing, offer promising avenues for creating flexible and customizable thermoelectric devices [84]. Continued exploration of these techniques will be vital for the commercialization of thermoelectric technologies.

2.5.4 Integration with biomedical systems

For thermoelectric materials to be effectively utilized in biomedical applications, they must be compatible with existing technologies and systems. This

includes ensuring biocompatibility and the ability to integrate with sensors, drug delivery systems, and other medical devices [85]. A notable case study involves the integration of thermoelectric materials into implantable glucose sensors. A 2023 study by Nozariasbmarz et al. demonstrated that a Bi_2Te_3 -based thermoelectric generator could power a glucose sensor for up to 6 months without significant performance degradation, showcasing the potential for long-term biomedical applications [59].

However, challenges remain in ensuring the biocompatibility of thermoelectric materials. For example, silver selenide (Ag_2Se), while highly efficient, has raised concerns due to the potential release of toxic silver ions in biological environments. A study by Wei et al. investigated the cytotoxicity of Ag_2Se and found that encapsulation with biocompatible polymers, such as polylactic acid (PLA), significantly reduced silver ion leaching and improved biocompatibility [8]. Future research should focus on developing thermoelectric materials that can seamlessly integrate into biomedical platforms while maintaining their thermoelectric performance. Case studies, such as the integration of PEDOT-based thermoelectric materials in wearable devices, have shown promising results in terms of both performance and biocompatibility [86].

2.5.5 Environmental and economic considerations

The sustainability of thermoelectric materials is an increasingly important consideration. Many conventional thermoelectric materials rely on rare or toxic elements, which can pose environmental and economic challenges [76]. For instance, tellurium, a key component of Bi_2Te_3 , is a rare element with limited global reserves, raising concerns about the scalability of tellurium-based thermoelectrics [69]. Similarly, the use of lead-based materials, such as PbTe , has been largely abandoned due to toxicity concerns, despite their high thermoelectric performance.

To address these issues, researchers are exploring alternative materials, such as magnesium silicide (Mg_2Si) and carbon-based composites, which are abundant and nontoxic. A 2021 study by Choudhary et al. demonstrated that Mg_2Si -based composites achieved ZT values of ~ 0.7 , with a power factor of $\sim 10 \mu\text{W}/\text{cmK}^2$, making them a viable alternative for sustainable thermoelectric applications [50]. Additionally, carbon nanotube (CNT) composites have shown promise due to their high electrical conductivity and low toxicity. A 2022 study by Yin et al. reported that CNT-PEDOT:PSS composites exhibited ZT values of up to 0.4, with excellent biocompatibility, making them suitable for wearable medical devices [37]. The development of abundant, nontoxic materials, such as carbon-based thermoelectric composites, is essential for creating sustainable thermoelectric technologies [77]. Research should prioritize the exploration of environmentally friendly materials and processes. For example, Zevalkink et al. have identified Ca_3AlSb_3 as a promising nontoxic alternative for thermoelectric applications, demonstrating its potential for waste heat recovery without the associated toxicity of traditional materials [87].

2.5.6 Future research priorities

Future research should prioritize the development of materials that combine high thermoelectric performance with long-term stability and biocompatibility. For

example, the use of advanced encapsulation techniques, such as atomic layer deposition (ALD), could improve the durability of thermoelectric materials in biological environments. Additionally, the exploration of novel materials, such as topological insulators and organic–inorganic hybrids, could lead to breakthroughs in both efficiency and sustainability.

Real-world validation through clinical trials and long-term studies will be essential to demonstrate the feasibility of thermoelectric materials in biomedical applications. For instance, a 2024 pilot study by Gao et al. evaluated the performance of a wearable thermoelectric device in monitoring patients with chronic conditions, showing promising results in terms of energy harvesting and device longevity [62]. Such studies provide valuable insights into the practical challenges and opportunities for thermoelectric materials in healthcare.

3. Conclusion

This chapter has elucidated the transformative potential of advanced thermoelectric materials in biomedical applications, driven by critical performance metrics such as thermoelectric figures of merit (ZT) and power factors. Materials like nanostructured bismuth telluride (Bi_2Te_3) and silver selenide (Ag_2Se) achieve ZT values exceeding 1.2 at room temperature, with Bi_2Te_3 demonstrating power factors of $\sim 50 \mu\text{W}/\text{cmK}^2$ and Ag_2Se exhibiting ultralow thermal conductivity ($\sim 0.5 \text{ W}/\text{mK}$). Flexible carbon nanotube (CNT)-polymer composites, such as SWCNT-PEDOT:PSS, further showcase ZT values of ~ 0.4 and power factors up to $500 \mu\text{W}/\text{mK}^2$, enabling seamless integration into wearable biosensors and energy-autonomous health monitors. Hybrid nanocomposites, including doped transition metal dichalcogenides (TMDs), have reached ZT values of ~ 0.6 , while organic thermoelectric polymers achieve ZT ~ 0.8 , underscoring their viability for low-temperature, implantable systems.

Despite these advances, challenges persist in balancing efficiency with material stability and scalability. For instance, Bi_2Te_3 degrades by $\sim 20\%$ in ZT after 30 days in physiological conditions, and Ag_2Se requires encapsulation to mitigate silver ion toxicity. Scalable manufacturing techniques, such as 3D printing, have enabled CNT composites to achieve ZT ~ 0.4 and power factors of $\sim 200 \mu\text{W}/\text{mK}^2$, yet cost-effective alternatives like magnesium silicide (Mg_2Si , ZT $\sim 0.7\text{--}1.0$) remain critical for sustainable deployment.

Near-term research must prioritize optimizing biocompatibility and stability—for example, hybrid Bi_2Te_3 -PEDOT:PSS composites show only 10% ZT loss over 60 days in simulated body fluids. Long-term efforts should focus on advancing nontoxic materials (e.g., Mg_2Si , CNT-organic hybrids) and scalable fabrication methods to bridge laboratory innovations with clinical applications. The integration of thermoelectric systems into implantable glucose sensors (6-month stability) and wearable monitors highlights their potential, provided material toxicity and thermal management challenges are resolved.

By addressing these priorities through interdisciplinary collaboration, thermoelectric materials can revolutionize personalized healthcare, enabling energy-efficient, self-powered devices that enhance patient outcomes while reducing reliance on conventional power sources. This synergy between material innovation and biomedical engineering promises to unlock next-generation technologies for real-time monitoring, targeted therapies, and sustainable medical solutions.

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