Review

A Review of Elastomer-Based Flexible Thermoelectric Generators: Material Selection, Fabrication Strategies, and Application Prospects

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Received: 5 August 2025; Revised: 27 September 2025; Accepted: 28 September 2025; Published: 30 September 2025

Abstract: Flexible thermoelectric generators (FTEGs) are garnering significant attention for their ability to convert low-grade heat into electricity while maintaining mechanical flexibility, making them ideal for wearable electronics and soft robotics. This review outlines recent advances in elastomer-based FTEGs, with a focus on material selection, structural integration, and scalable fabrication. Emphasis is placed on the development of multifunctional elastomers with enhanced thermoelectric performance, the strategies for embedding fillers to maintain mechanical compliance, and the evolution of interfacial and module-level designs. Furthermore, emerging approaches, such as kirigami-inspired architectures, ionic interfaces, and liquid-metal grids, are explored for their role in improving device endurance and energy output. This review concludes by identifying key challenges, including long-term stability, biocompatibility, and sustainable manufacturing. It also proposes future directions that integrate geometry, chemistry, and computational tools to enable the next generation of deployable, eco-friendly FTEGs.

Keywords: flexible thermoelectric generators (FTEGs); elastomeric composites; stretchable energy harvesting; thermoelectric material integration; wearable electronics

1. Introduction

The rapid adoption of wearable electronics, including health monitoring devices, soft robotics, and smart textiles, has highlighted the emerging need for lightweight, flexible, and autonomous power sources. Among various energy harvesting approaches, flexible thermoelectric generators (FTEGs) have attracted much attention due to their ability to convert body heat into electricity via the Seebeck effect, offering a silent, solid-state, and maintenance-free solution for sustainable and continuous power supply [1]. Their potential to operate without an external charging infrastructure makes them particularly attractive for long-term, body-integrated applications. However, despite their good energy conversion efficiency, conventional thermoelectric materials such as bismuth telluride (Bi_2Te_3) are inherently brittle and rigid, which severely limits their adaptability to stretchable or conformal forms. This mechanical mismatch hinders their direct application in flexible or skin-conforming devices, where the materials must accommodate repeated deformations and maintain close contact with dynamic surfaces.

To overcome these limitations, researchers have incorporated elastomeric materials into the FTEG architecture. Elastomers have a number of key advantages, including high stretchability, biocompatibility, and mechanical elasticity, allowing thermoelectric materials to be integrated into deformable platforms that can withstand significant mechanical strains without compromising performance [2]. A variety of integration strategies have emerged, ranging from liquid metal embedded elastomer (LMEE) composites with excellent conductivity and mechanical durability to aerogel-silicone hybrids for epidermal applications with enhanced comfort and thermal insulation [3]. Elastomers have also been explored as encapsulation layers to improve environmental stability and water resistance [4], and as matrices for modular self-healing systems to extend the life of devices under wear conditions [5]. In addition, elastomer-based substrates have enabled wearable thermoelectric textiles and stretchable modules, expanding the application range of FTEG in clothing, soft robotics, and bio-integrated electronics [6].

Meanwhile, the development of scalable manufacturing techniques (e.g., screen printing, inkjet printing, and roll-to-roll lamination) has opened up new possibilities for large-scale production and commercial deployment of elastomer-based FTEGs [7]. Recent studies have also highlighted the multifunctional role of elastomers, including their contribution to thermal management, such as mitigating local heating and improving temperature uniformity through interface design [8]. In addition, nanomaterial-enhanced elastomers (e.g., elastomers with carbon nanotubes or graphene) have shown significant improvements in electrical conductivity and thermomechanical stability [9].

Recent advancements have also demonstrated novel structural and functional designs for elastomer-based FTEGs. For example, Cao et al. [10] developed a stretchable generator based on screen-printed Bi_2Te_3 embedded in a PDMS matrix. Lee et al. [11] introduced 3D kirigami-inspired thermoelectric modules that retain performance under stretching by decoupling mechanical deformation from the conductive paths. These efforts underline the importance of not only selecting the right elastomeric material but also optimizing the structural integration. Moreover, hybrid integration approaches combining elastomers with emerging materials like MXenes, ionic liquids, or biodegradable polymers are being actively explored further to improve system adaptability and eco-compatibility [12]. The remaining FTEG elastomer references are listed in Table 1.

Table 1. Literature review on elastomer-based thermoelectric generators.

Elastomer	Thermoelectric Material	Key Findings	Applications	Ref.
Silicone + Aerogel	Bi_2Te_3 (P/N)	Aerogel-silicone composite with liquid metal improved thermal insulation and flexibility	Wearable electronics, body heat harvesting	[13]
Self-Healing Elastomer	Bi_2Te_3 (P/N)	Achieved self-healing function with a power density of 3.14 $\mu W \cdot cm^{-2} \cdot K^{-2}$	Stretchable thermoelectric systems	[14]
Silicone-Aerogel Composite	Bi_2Te_3 (P/N)	Power density of 35 $\mu W \cdot cm^{-2}$ on the wrist, suitable for body heat harvesting	Flexible FTEG for wearables	[15]
Silicone Rubber	Bi_2Te_3 + CNT (P)	Exhibited high performance, suitable for wearable applications	Self-healing wearable thermoelectrics	[16]
Silicone Elastomer	Ag_2Se (N) + PEDOT:PSS (P)	Output of 0.63 mV at a 2 °C temperature difference, suitable for wearable applications	Smart textiles	[17]
Elastic Material	Bi_2Te_3 (P/N)	Demonstrated enhanced mechanical stability, suitable for wearable applications	Skin-contact thermoelectric harvesters	[18]
Textile-Based	Bi_2Te_3(P), Ag_2Se(N)	Explored design methods for textile thermoelectric materials, suitable for wearable applications	Broad wearable energy harvesting	[19]
Various Elastomers	Bi_2Te_3 (P/N)	Comprehensive review of wearable thermoelectric generators, covering materials and device design	Flexible power generation	[20]
Various Elastomers	CNT/PEDOT:PSS (P), Ag_2Se (N)	Review of flexible thermoelectric materials and generators, covering theory and applications	Medical wearables, E-skin	[21]
Various Elastomers	Bi_2Te_3 (P/N)	Comprehensive review on the applications of flexible thermoelectric materials	Self-powered sensing devices	[22]

Despite these advances, significant challenges remain in balancing mechanical flexibility with thermoelectric efficiency, achieving stable filler dispersion, and maintaining long-term performance under cyclic mechanical loading. Additionally, device reliability, biocompatibility, and integration with electronics for real-world usage (e.g., wireless data transmission or energy storage) are still evolving [18,23]. Therefore, a comprehensive and targeted review of the role of elastomers in FTEGs is both timely and necessary. Unlike previous reviews that focus on thermoelectric materials or rigid device structures, this article places elastomers at the core of the discussion, emphasizing that they not only serve as mechanical supports but also actively contribute to system performance, durability, and functionality. This review aims to comprehensively introduce the latest progress of elastomer-based FTEG technology, covering aspects such as material selection, composite material fabrication, device architecture, and application scenarios. By critically evaluating existing approaches and identifying ongoing

challenges, this study provides a roadmap for future research on utilizing elastomer materials to realize the next generation of flexible, wearable, and self-powered energy systems.

2. Materials, Integration, Fabrication, and Functionality of FTEG

2.1. Role and Importance of Elastomers in FTEG

Elastomers in FTEG play a fundamental role in the development of flexible thermoelectric generators (FTEGs), primarily by providing mechanical flexibility, stretchability, and structural resilience in dynamic environments. Conventional thermoelectric materials such as Bi_2Te_3 or PbTe are known for their better energy conversion efficiency; however, they are inherently rigid, brittle, and prone to mechanical failure under strain [24,25]. These limitations significantly hinder their application in next-generation wearable or deformable electronics that demand continuous bending, folding, or conformal contact with non-planar surfaces such as human skin or biological tissue.

To address these mechanical constraints, elastomers, characterized by their low Young's modulus, high elongation at break, and excellent elastic recovery, have been widely adopted as flexible substrates, encapsulants, or matrix materials in FTEG systems [26,27]. When used as matrix materials, elastomers enable the uniform dispersion of thermoelectric fillers, including Bi_2Te_3 microparticles, carbon nanotubes (CNTs), graphene, and MXenes, resulting in flexible composite materials that retain thermoelectric functionality while enduring repeated deformation [28]. For instance, Zhang et al. [29] demonstrated that silicone elastomers combined with CNTs form composites with improved stretchability and stable thermoelectric performance under strain cycles. Liu et al. [30] incorporated graphene nanoplatelets into an Ecoflex matrix, achieving enhanced flexibility and conductivity suitable for epidermal electronics. Xu et al. [31] presented fully printed FTEGs utilizing MXene-based inks and vertically integrated thermoelectric chips. They discovered that the integration of MXenes enhanced electrical conductivity and device flexibility, and the FTEGs demonstrated excellent mechanical robustness, reconfigurability, and power output from low-grade heat, highlighting the potential of MXenes for next-generation wearable and flexible energy-harvesting systems.

In addition to their mechanical benefits, elastomers serve essential roles in enhancing device safety and environmental robustness. Their intrinsic electrical insulation prevents short-circuiting between embedded thermoelectric fillers, while their thermal stability assists in managing heat distribution across the generator. Furthermore, elastomer layers can act as protective barriers against moisture, oxidation, and mechanical abrasion, thereby prolonging the lifespan of the device under real-world conditions. Du et al. [13] demonstrated that liquid metal embedded elastomer **(**LMEE) composites maintained stable output across humidity variations and mechanical stretching cycles. Furthermore, elastomers such as polydimethylsiloxane (PDMS) have been widely used for their optical transparency and chemical inertness, making them ideal for hybrid integration with optoelectronic systems [32].

Another critical advantage lies in the biocompatibility and softness of many elastomers, which facilitates direct integration with the human body. These properties are crucial for wearable FTEGs intended for skin-mounted energy harvesting, healthcare monitoring, or biomedical sensing. Advanced formulations using self-healing elastomers or shape-memory polymers have further pushed the boundary, enabling autonomous repair of microcracks or programmed deformation in response to environmental cues, thus enhancing the reliability and functional versatility of FTEGs under complex usage scenarios. Lee et al. [33] developed self-healing thermoelectric modules based on dynamic covalent bonds in polyurethane matrices that restored performance after damage. They proposed a programmable shape-adaptive elastomer system that reconfigured its layout under temperature shifts, optimizing thermal contact with skin surfaces. Elastomers not only provide mechanical support but also enable flexibility, biocompatibility, and protection, making them ideal for wearable FTEGs. Future work should focus on improving filler dispersion, interface design, and self-healing for enhanced durability and performance.

In addition, several studies emphasized the multifunctionality of elastomer composites. For example, Xu et al. [34] developed multifunctional elastomer thermoelectric composites with tunable stiffness for conformal integration with human joints. Jin et al. [1] reported elastomer-supported modular TEG arrays capable of powering IoT sensors under variable mechanical loads. These findings indicate that elastomers are not merely passive mechanical supports but are integral to the multifunctional design of FTEGs, bridging the gap between rigid energy materials and the soft dynamic requirements of emerging wearable and bio-integrated electronics.

In summary, elastomers are crucial to FTEG systems, offering mechanical stretchability, resilience, and biocompatibility for wearable applications. They address the brittleness of conventional thermoelectric materials like Bi_2Te_3 by serving as substrates or matrices that can endure repeated deformation. Elastomers enhance safety and environmental resistance through insulation and moisture protection, while also enabling uniform dispersion of fillers such as CNTs, graphene, or MXenes. Additionally, their softness and adaptability support integration

with skin, making them suitable for bioelectronics. Advanced elastomers with self-healing or programmable shape-memory properties further expand FTEG's versatility, emphasizing their active, multifunctional role in next-generation energy systems.

2.2. Types of Elastomers and Their Properties

A wide variety of elastomers have been explored in the development of FTEGs, each contributing uniquely to mechanical performance, thermal stability, biocompatibility, and process compatibility. Among the most widely used materials are polydimethylsiloxane (PDMS), polyurethane (PU), Ecoflex, and thermoplastic elastomers (TPEs), which differ significantly in terms of their chemical structure, stretchability, and suitability for integration with thermoelectric systems [35,36].

2.2.1. Polydimethylsiloxane (PDMS)

PDMS is particularly favored due to its transparency, biocompatibility, and ease of processing [37]. It offers excellent chemical and thermal stability, ensuring reliable operation over a broad temperature range. However, its intrinsic stretchability is relatively limited, typically below 150%, which may constrain its application in highly deformable or dynamic systems unless it is reinforced with flexible fillers or blended with more elastic polymers.

2.2.2. Polyurethane (PU)

Polyurethane (PU) has emerged as one of the most versatile elastomers in FTEG research due to its excellent balance of mechanical strength, flexibility, and chemical tunability [38]. PU consists of alternating soft and hard segments, which can be molecularly tailored to produce a wide range of mechanical behaviors, from soft and highly elastic foams to tough and rubber-like solids. This tunable morphology allows PU to exhibit high strain tolerance, typically exceeding 300%, and excellent mechanical durability under cyclic deformation. This makes it particularly suitable for applications where the device is subjected to frequent stretching, bending, or twisting. Its abrasion resistance and toughness also make it a compelling choice for integration into dynamic wearable devices, robotic skins, or joint-mounted sensors, where long-term stability is critical [39].

Furthermore, PU exhibits excellent adhesion to both organic and inorganic surfaces, enabling robust bonding with thermoelectric fillers such as carbon nanotubes, graphene, or Bi_2Te_3 particles. This interfacial compatibility enhances filler dispersion and facilitates the formation of conductive percolation networks within the composite matrix [40]. For example, Wu et al. [41] demonstrated a stretchable thermoelectric nanocomposite by dispersing carbon nanotubes into a PU matrix, achieving both electrical conductivity and mechanical flexibility. Cao et al. [42] developed a screen-printable FTEG using PU-based inks and found that the polymer matrix not only stabilized the ink but also provided mechanical compliance during deformation.

In biomedical and skin-contact applications, PU's biocompatibility and hydrophilic tunability are especially advantageous. By adjusting the ratio of hard-to-soft segments or incorporating specific functional groups, PU can be modified to achieve desirable moisture permeability, surface softness, or antibacterial properties, enabling safe and comfortable long-term contact with human skin [43]. Recent developments in PU-based nanocomposites have also demonstrated the ability to co-engineer thermoelectric and mechanical properties, for example, by incorporating conductive nanofillers in aligned or gradient structures, or by applying microstructural patterning techniques such as electrospinning or freeze casting. These advancements highlight PU's potential as a foundation material for high-performance, multifunctional FTEGs that demand both electrical efficiency and mechanical resilience.

2.2.3. Ecoflex

Ecoflex, an ultra-soft silicone-based elastomer, stands out for its exceptional stretchability, reaching up to 600%, and its low elastic modulus [44]. These properties make it ideal for applications requiring high comfort and compliance, such as epidermal electronics or implantable biomedical devices. Despite these benefits, Ecoflex generally suffers from lower mechanical durability, necessitating additional structural support or encapsulation for long-term reliability. Thermoplastic elastomers, such as styrenic block copolymers and thermoplastic polyurethanes, combine the flexibility of rubber-like materials with the thermal processability of plastics [45]. Their compatibility with scalable manufacturing methods, such as extrusion, injection molding, and 3D printing, positions them as promising candidates for large-scale FTEG fabrication, especially when both mechanical resilience and manufacturing throughput are required.

2.2.4. Thermoplastic Elastomers (TPEs)

TEGs integrated with thermoplastic elastomers represent a compelling frontier in wearable electronics. These hybrid devices harness body heat and convert it into electricity, enabling continuous, battery-free operation of low-power electronics. The use of thermoplastic elastomers enhances mechanical flexibility and stretchability, making the TEGs conformable to dynamic human motion without performance degradation. For instance, embedding inorganic thermoelectric materials like Bi_2Te_3 or poly(3,4-ethylenedioxythiophene):polystyrenesulfonate (PEDOT:PSS) stretchable matrices [46] improves both energy harvesting and mechanical durability. Chang et al. [47] presented an FTEG constructed using a TPE matrix that embeds n-type and p-type Bi_2Te_3-based particles. The adopted TPE material was styrene-ethylene-butylene-styrene (SEBS). The TPE provided mechanical stretchability and durability while maintaining thermal and electrical pathways. The resulting FTEG achieved reliable power output under deformation, making it suitable for wearable energy harvesting. Jeong et al. [48] reported a stretchable TEG utilizing thermoplastic elastomer (TPE), specifically thermoplastic polyurethane, as a flexible substrate, combined with rigid thermoelectric materials—specifically, Bi_2Te_3-based p-type and n-type legs. These legs were embedded in an island-bridge configuration to maintain electrical performance under mechanical deformation. Liquid metal interconnects were used to ensure stretchable conductivity between thermoelectric islands. The TPE provided elasticity and durability, allowing the TEG to conform to body movements while maintaining a stable power output.

Selecting an appropriate elastomer for FTEG integration requires balancing several interrelated factors. Mechanical compliance is essential to ensure that the device maintains structural integrity under strain. At the same time, compatibility with fabrication methods such as screen printing, casting, or roll-to-roll processing must be considered to enable efficient production. From a device performance perspective, thermal and electrical properties, including insulation behavior, thermal conductivity, and interfacial adhesion, must align with the operational needs of the thermoelectric system. In wearable and biomedical applications, biocompatibility becomes particularly critical to ensure safe long-term contact with the skin or tissue. Moreover, the ability of an elastomer to effectively interact with thermoelectric fillers greatly influences the dispersion quality and percolation network formation, both of which are key to maintaining high electrical conductivity and power factor in the composite. To address the complex demands of modern FTEG applications, current research has increasingly turned to the development of hybrid elastomer systems [49], nanocomposite formulations [50], and multifunctional elastomers [13], such as self-healing, biodegradable, or stimuli-responsive variants, that can offer greater adaptability for next-generation wearable energy harvesting platforms.

2.3. FTEG Fabrication

The fabrication of elastomer-based FTEGs has advanced toward the integration of high-performance thermoelectric materials with stretchable and biocompatible matrices, aiming to deliver mechanically robust systems capable of efficient energy conversion under dynamic conditions. Figure 1 illustrates five representative FTEG configurations, each with distinct material combinations, fabrication features, and application potentials.

In Figure 1a, a multilayered FTEG architecture is demonstrated using PDMS as the elastomeric substrate. This design incorporates Ag_2Se (n-type) and poly(3,4-ethylenedioxythiophene): polystyrene sulfonate (PEDOT: PSS)/multiwalled carbon nanotube (MWCNT) (p-type) composites as thermoelectric legs. To enhance both electrical conductivity and mechanical compliance, eutectic gallium-indium (EGaIn) liquid metal electrodes are embedded between PDMS layers, forming soft and conductive interconnects that reduce interfacial resistance. This configuration enables high output performance and flexibility, making it well-suited for dynamic energy harvesting [51]. Figure 1b presents an alternative fabrication approach that utilizes Ecoflex-gelatin-based ionic elastomers. The flexible frames and encapsulating layers are fabricated via mold-assisted casting and soft lithography, enabling scalable production with excellent conformability. These FTEGs are optimized for harvesting body heat and exhibit high adaptability on curved surfaces, such as human skin, making them ideal for wearable thermal energy harvesting [52]. In Figure 1c, a photothermal-assisted FTEG is depicted, which incorporates a MoS_2/polyurethane composite as a photothermal layer. When exposed to infrared (IR) radiation, the photothermal layer generates localized heat, inducing a temperature gradient across the attached thermoelectric elements. This strategy facilitates remote energy harvesting and is particularly promising for self-powered optoelectronic systems [53].

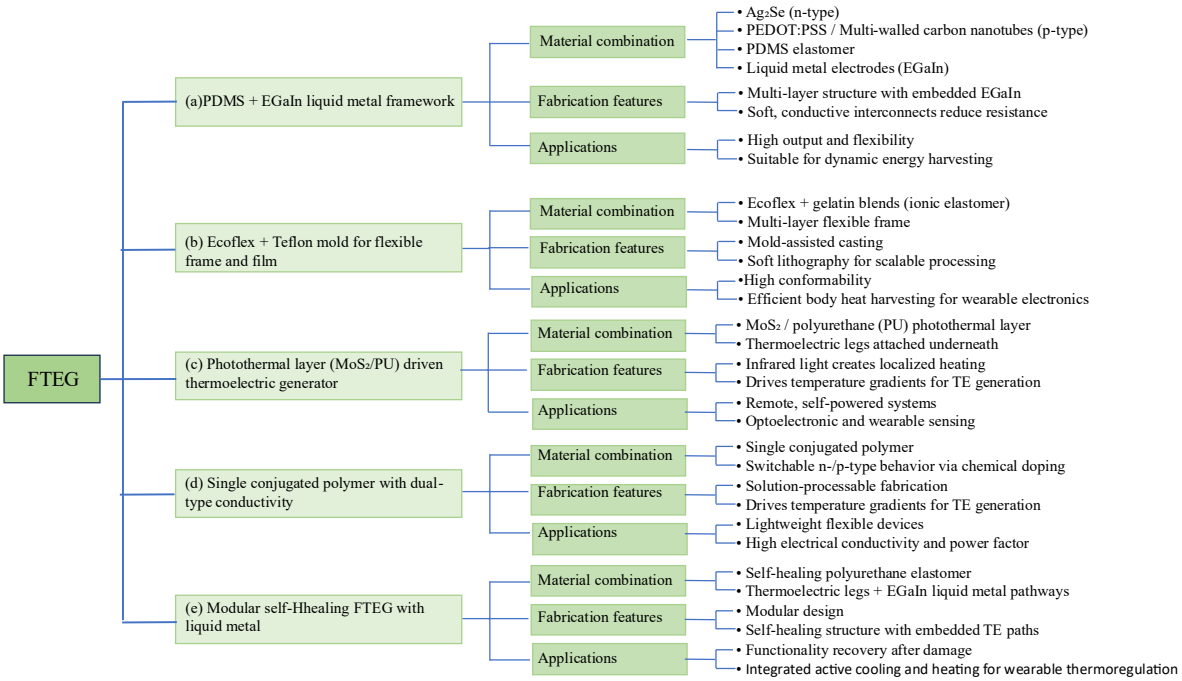

Figure 1. Representative fabrication strategies of elastomer-based FTEGs, highlighting material combinations, fabrication features, and application scenarios.

Figure 1d illustrates a fabrication method based on a single conjugated polymer capable of dual-type conductivity. Through chemical doping, the polymer can exhibit both n-type and p-type behavior, allowing for solution-processable fabrication on flexible substrates. This eliminates the need for separate n- and p-type legs, significantly simplifying device architecture while achieving high conductivity and power factors suitable for lightweight and flexible electronics [54]. Figure 1e shows a modular, self-healing FTEG fabricated using a self-healing polyurethane elastomer integrated with embedded thermoelectric legs and interconnected EGaIn liquid metal pathways. This design supports mechanical self-recovery after damage and further enables active thermal regulation through built-in heating and cooling functionalities, expanding its utility in wearable thermoregulation systems [14].

Taken together, these fabrication strategies underscore the ongoing evolution of FTEG technologies toward soft, scalable, and multifunctional platforms that are increasingly adaptable for real-world, body-integrated energy harvesting applications.

2.4. Integration Strategies and Challenges

The integration of thermoelectric materials with elastomers is a pivotal step in the development of FTEGs, aiming to combine high energy conversion efficiency with mechanical compliance. However, this integration presents significant engineering and materials science challenges, particularly in achieving synergistic performance without sacrificing either thermoelectric or mechanical properties.

Common strategies for integration include physical blending, in-situ polymerization, and layer-by-layer (LbL) stacking [55]. Physical blending involves dispersing TE fillers (e.g., Bi_2Te_3 particles, carbon nanotubes, or nanowires) directly into an elastomer matrix such as PDMS, Ecoflex, or thermoplastic polyurethane (TPU). While this method is relatively straightforward and scalable, it often suffers from agglomeration of the fillers, leading to non-uniform properties [56,57]. In-situ polymerization enables better interfacial bonding by polymerizing the elastomer around the filler particles, which improves filler dispersion and interfacial adhesion but may be limited by processing conditions and reaction compatibility. LbL stacking, on the other hand, assembles TE and elastomer layers sequentially, offering structural control and modularity, but may introduce interface resistance and delamination risks if adhesion is insufficient [55].

Key design considerations for all integration strategies include:

(1) Interfacial compatibility: Strong adhesion between TE fillers and elastomeric matrix is essential to prevent interfacial delamination, especially under repeated bending or stretching cycles. Surface modification of fillers, such as silane coupling agents or π-π interaction-enhancing treatments, is often employed to improve compatibility [58]. To maintain high power factors during mechanical deformation, percolative networks of conductive fillers must remain intact. This is particularly challenging at low filler loading, where

stretchability is favored but electrical performance diminishes [59].

(2) Thermal conductivity matching: Discontinuities in thermal conductivity at the filler-atrix interface can lead to heat losses and efficiency reduction. Strategies such as incorporating thermally conductive but electrically insulating fillers (e.g., boron nitride) or engineering graded interfaces have been proposed to mitigate this issue [60].

Despite the promising functionalities offered by elastomers, several critical trade-offs must be navigated. Elastomers are typically electrical and thermal insulators, necessitating high filler content to achieve functional TE properties. However, excessive loading reduces mechanical compliance, introduces brittleness, and may hinder processing [61,62]. To overcome these limitations, researchers have developed composite strategies that combine elastomers with thermoelectric fillers and engineered architectures. Rather than relying solely on increasing filler content, these approaches focus on optimizing the spatial arrangement, interfacial bonding, and device geometry to balance mechanical flexibility with thermoelectric performance. Recent advancements in FTEG design focus on enhancing stretchability, integration, and reliability. In Figure 2, strategies include PDMS-based vertical stacking with liquid metal electrodes for conformability Figure 2a, Ecoflex-assisted modular fabrication for scalability Figure 2b, self-healing systems using dynamic polymers and liquid metal interconnects for durability Figure 2c, and planar architectures with improved thermal interfaces for performance optimization Figure 2d. These approaches collectively support the development of robust, wearable energy-harvesting devices.

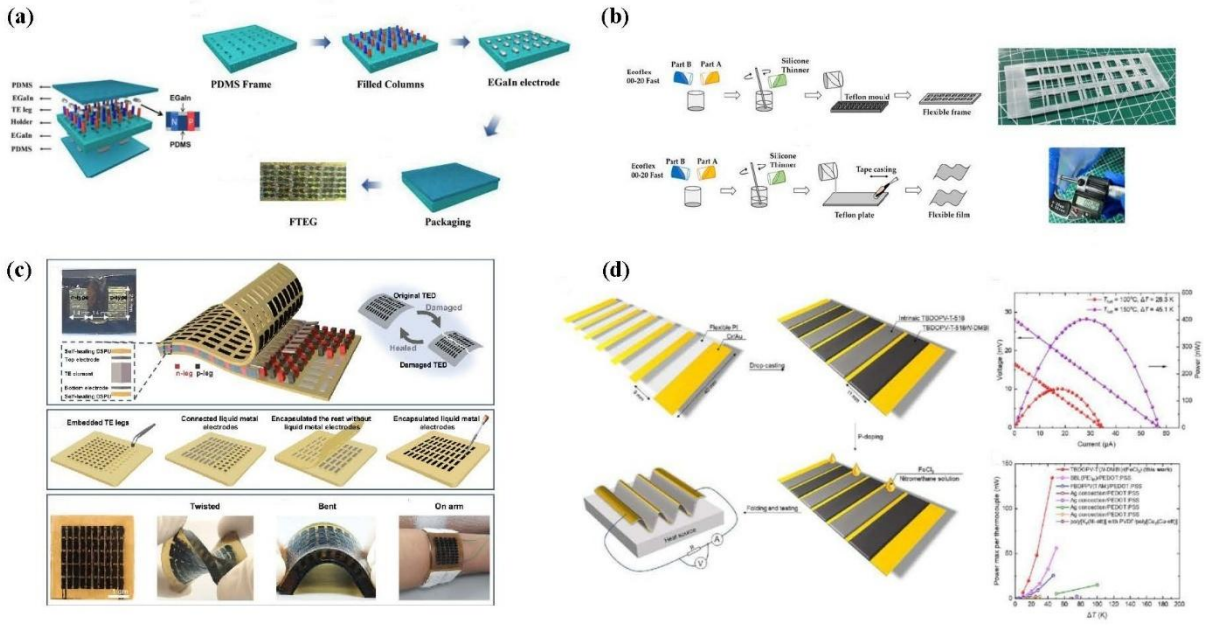

Figure 2. Recent structural and fabrication strategies for FTEGs. (**a**) multilayer fabrication on PDMS base [51], (**b**) Ecoflex-based flexible structure and film fabrication [52], (**c**) self-healing FTEG design and flexibility test [14], and (**d**) device architecture and performance evaluation [54].

Moreover, fabrication scalability is a pressing concern. Techniques such as screen printing, 3D printing, inkjet printing, and roll-to-roll (R2R) lamination have emerged as viable routes for producing large-area or complex-pattern FTEG devices [63]. Nonetheless, ensuring consistent filler dispersion, controlled rheology, and strong layer adhesion during these processes demands significant formulation and process optimization. Next-generation integration approaches are increasingly centered on hierarchical architectures, such as interlocked or kirigami-inspired mesh structures, which allow for localized strain accommodation while preserving global conductivity [64]. Gradient interfaces, where filler concentration or stiffness varies gradually across the composite, help alleviate stress concentration and improve mechanical reliability. Additionally, the development of multifunctional composites, capable of concurrent energy harvesting, strain sensing, or self-healing, represents a frontier in wearable and bio-integrated TE applications. Ultimately, successful integration strategies must transcend simple mechanical blending and address the complex interplay between structure, property, and processing, ensuring that FTEGs meet the stringent demands of real-world deployment, particularly in wearable electronics, biomedical sensing, and low-power autonomous systems. A comparative summary of key elastomer-integration approaches, their strategies, and applications is provided in Table 2.

Table 2. Comparative overview of elastomer-integrated thermoelectric generators.

Elastomer Type	Integration Strategy	Major Insights	Applications	Ref.
Liquid Metal Embedded Elastomer (LMEE)	Composite of liquid metal with elastomer, integrating Bi_2Te_3 thermoelectric elements	Achieved a power density of 86.6 μW·cm^{-2} at ΔT = 60 °C with stretchability over 50%	Wearable electronics, robotics	[33]
Silicone-Aerogel Composite	E*GaIn liquid metal interconnection, reducing thermal conductivity	Power density of 35 μW·cm^{-2} on the wrist, suitable for body heat harvesting	Health monitoring, wearable devices	[17]
Silicone Rubber	Simple fabrication process for high-performance FTEG	Exhibited high performance, suitable for wearable applications	Wearable thermoelectric devices	[65]
Silicone Elastomer	Used as an encapsulation material, combined with conductive textile electrodes	Output of 0.63 mV at a 2 °C temperature difference, suitable for wearable applications	Wearable thermoelectric devices	[66]
Elastic Material	Provides reversible bending for enhanced mechanical stability	Demonstrated enhanced mechanical stability, suitable for wearable applications	Wearable thermoelectric devices	[67]
Self-Healing Elastomer	Modular assembly, integrating cooling and heating functions	Achieved self-healing function with a power density of 3.14 μW·cm^{-2}·K^{-2}	Wearable power sources, thermal management	[68]
Textile-Based	Fabrication of thermoelectric fibers and textiles	Explored design methods for textile thermoelectric materials, suitable for wearable applications	Wearable electronics	[20]
Various Elastomers	Reviewed design and application of thermoelectric modules	Comprehensive review of wearable thermoelectric generators, covering materials and device design	Wearable thermoelectric devices	[22]
Various Elastomers	Discussed advancements in flexible thermoelectric materials and generators	Review of flexible thermoelectric materials and generators, covering theory and applications	Wearable electronics	[21]
Various Elastomers	Explored applications of flexible thermoelectric materials and devices	Comprehensive review on the applications of flexible thermoelectric materials	Wearable electronics	[69]

E*: eutectic.

3. Future Work and Research Directions

3.1. Material Innovation and Multifunctional Elastomers

The pursuit of novel elastomeric materials with enhanced mechanical, electrical, and multifunctional properties remains a key direction for advancing FTEGs. While traditional elastomers like PDMS, PU, and Ecoflex offer valuable baseline properties, their limitations in electrical insulation, thermal conductivity, and long-term stability under cyclic strain necessitate further material innovation [37]. Recent trends point toward the development of hybrid elastomers that combine multiple functionalities such as self-healing, biodegradability, recyclability, and responsiveness to external stimuli (e.g., heat, light, or humidity) [70]. For instance, Song et al. [71] demonstrated that incorporating reversible Diels-Alder bonds into elastomers enabled autonomous healing of microcracks, significantly improving the reliability and lifespan of thermoelectric devices. In parallel, Guo et al. [72] developed poly(glycerol sebacate) (PGS)-based elastomers suitable for transient electronics and biomedical applications due to their controlled environmental degradation.

Advanced nanocomposite elastomers that integrate carbon-based fillers such as graphene, carbon nanotubes, and MXenes [73] or ceramic particles like boron nitride into polymer matrices have shown marked improvements in thermal conductivity, electrical output, and mechanical resilience. Xu et al. [74] constructed three-dimensional filler networks to enhance thermoelectric performance under strain, focusing on interface engineering to optimize polymer-filler compatibility and reduce electrical resistance. In one example, Shalil and Balandin [75] developed

graphene–multilayer-graphene epoxy composites that significantly improved cross-plane thermal conductivity, establishing their promise as high-performance thermal interface materials. Furthermore, Zheng et al. [76] independently developed filler alignment techniques, including shear-induced processing and electrospinning, to boost anisotropic conductivity in composite systems.

Research has also shifted toward programmable and stimuli-responsive elastomers. Zadan et al. [77] demonstrated shape-memory elastomers that adapt their shape in response to heat, enabling better mechanical conformation in wearable platforms. Park et al. [78] and Feng et al. [79] separately worked on functionalizing elastomers with ionic liquids or ionomers, reporting improved electrothermal responsiveness and more stable interfacial charge transport. Efforts are also being directed toward scalable synthesis routes for these advanced elastomers. Li et al. [80] proposed solvent-free polymerization and renewable monomer approaches that enhance batch consistency while aligning with environmental sustainability goals. In addition, Xie et al. [81] promoted green chemistry routes for large-scale fabrication without compromising material quality. The convergence of material chemistry, nanotechnology, and polymer engineering is expected to yield next-generation elastomers that are not only mechanically robust and biocompatible, but also multifunctional-paving the way for FTEGs that are adaptive, autonomous, and seamlessly integrated into complex environments.

3.2. Advanced Integration Architectures and Interface Engineering

3.2.1. Transition from Traditional Composite Materials to Structured Microstructures

Although dispersion-based (random filler) and laminated composites laid the groundwork for FTEGs, Jeong et al. [82] convincingly showed that these early systems failed once tensile strain introduced filler agglomeration, interfacial voiding, and cascading performance loss. In response, the community progressively shifted its focus from "mix-and-stack" recipes to architected microstructures and purpose-built interfaces that could simultaneously sustain deformation, preserve percolation, and manage heat flow.

3.2.2. Interface-Toughening Approaches

With macroscopic compliance secured, investigators focused on the filler-matrix interface, long recognized as the "Achilles' heel" of stretchable composites. Lv et al. [83] fabricated through-thickness gradients in filler loading and crosslink density; the concomitant modulus gradient dissipated interfacial shear and delayed crack propagation beyond 1000 bending cycles. Wang et al. [84] inserted 20 nm polydopamine buffer layers and silane coupling agents, which dropped contact resistance by ~25% and suppressed delamination during 5000 stretch cycles. Gilbert et al. [85] took a chemical-adhesive route, grafting catechol moieties onto polyurethane; π–π and hydrogen-bond networks "locked" Bi_2Te_3 platelets into place and limited resistance drift to <3% over 10,000 cycles. Chen et al. [86] injected eutectic gallium-indium (Ga–In) into Ecoflex microchannels, forming a self-healing conductive network that restored over 95% of its conductivity within 60 s after mechanical rupture.

3.2.3. Critical Assessment and Future Outlook

Geometry-derived strain relief supplies the "hardware" for mechanical endurance, while chemical or physical interphases provide the "software" that maintains electron/phonon coupling under repeated deformation. Module-scale matching and digital design complete the ecosystem, producing FTEGs that withstand >20,000 cycles at 100% strain and deliver >15 $\mu W \cdot cm^{-2}$ in realistic, motion-rich environments [87].

Challenges remain, notably scalable manufacturing of 3D micro-architectures, long-term stability under sweat or UV exposure, and closed-loop coupling with energy-storage components. Addressing these gaps will likely require hybrid strategies that merge additive manufacturing, responsive interfacial chemistries, and AI-assisted lifecycle prediction. Nevertheless, the four-pillar framework of geometry, interface, integration, and computation already provides a robust roadmap for transforming laboratory FTEGs into deployable power supplies for on-body sensing, soft robotics, and the Internet of Things (IoT). Table 3 synthesizes key challenges and corresponding strategies found within the literature into one cohesive table.

A system-level validation of these integration principles was provided by Liang et al. [88], who demonstrated a multimodal health-monitoring bracelet powered entirely by FTEGs. The device combined flexible TE modules with optimized energy management circuitry, achieving a high on-body power density of 153.3 mW cm^{-2} from an ultralow self-startup voltage of 20 mV. By supporting continuous, battery-free monitoring of physiological and environmental parameters, this example highlights how FTEGs can transition from laboratory concepts to robust, application-ready platforms, while also revealing the persistent challenge of matching low-voltage outputs with power conditioning electronics.

Table 3. Literature-reported strategies for addressing long-term stability, biocompatibility, and sustainable manufacturing in elastomer-based FTEGs.

Key Challenge	Failure Mode/Concern	Strategy	Addressed Aspect	Quantitative/Reported Effectiveness	Ref.
Long-term stability	Interfacial debonding under cyclic strain	Polydopamine buffer (20 nm) + silane coupling	Strengthens filler–matrix adhesion; suppresses delamination	Contact resistance ~25%; stable for 5000 cycles	[84]
	Progressive resistance drift	Catechol-grafted polyurethane (π–π & H-bonds)	Locks Bi_2Te_3 platelets; maintains conductivity	Resistance drift limited to <3% over 10,000 cycles	[85]
	Crack initiation and propagation	Through-thickness modulus gradient (filler & crosslink)	Dissipates shear stress; delays crack growth	Stable performance beyond 1000 bends	[83]
	Open circuits after rupture	LM (Ga–In) microchannel interconnects	Provides self-healing conductive pathways	>95% conductivity restored within 60 s	[86]
Biocompatibility	Skin irritation & cytotoxicity	Functionalized PU (antibacterial, hydrophilic groups)	Reduces cytotoxicity; improves skin safety	Reported safe for prolonged skin contact	[43]
	Lack of epidermal comfort under stretch	Ecoflex elastomer	High compliance & softness; mimics skin mechanics	Stretchability up to ~600% without failure	[44]
	Sweat, heat, & moisture exposure	PDMS / silicone encapsulation	Prevents degradation from sweat & heat	Enhanced stability during on-body wear tests	[89]
Sustainable manufacturing	Energy-intensive, solvent-heavy processing	Solvent-free polymerization & renewable monomers	Lowers environmental impact; greener chemistry	Improved reproducibility and sustainability	[80]
	Scalability & high-throughput fabrication	Screen printing, aerosol jet, roll-to-roll (R2R)	Enables mass production at low cost	Screen-printed PU/CNT inks: stable output & stretchability	[50]
	Limited structural programmability	Direct ink writing (DIW) with in-situ curing	Enables programmable filler architecture & gradients	Demonstrated tunable thermal gradients in devices	[90]
	Lifecycle & end-of-life concerns	Lifecycle assessment & eco-design	Identifies hotspots; guides recycling strategies	LCA highlighted recyclability/end-of-life as critical	[91]

Beyond elastomeric composites, high-entropy thermoelectric materials represent an emerging solution where configurational entropy stabilizes multi-element phases and enhances phonon scattering. Tang et al. [92] demonstrated that such entropy-engineered systems can achieve competitive zT values without compromising electrical transport. Although not elastomer-based, the concept of entropy-driven stabilization parallels the role of chain dynamics and filler dispersion in elastomer composites [93]. Future efforts could explore embedding nanoscale high-entropy fillers into elastomer matrices, combining entropy-engineered thermal management with the mechanical compliance of soft systems to expand the design space for sustainable FTEGs.

3.3. Scalable Fabrication and Application-Oriented Optimization

Achieving real-world deployment of elastomer-based FTEGs depends not only on material performance but also on scalable, cost-effective, and reproducible fabrication techniques. Conventional lab-scale methods, such as drop-casting or spin-coating, though effective for proof-of-concept studies, are not suitable for mass production [94].

Emerging scalable methods include screen printing, inkjet printing, aerosol jet printing, and roll-to-roll (R2R) lamination, which allow rapid deposition of thermoelectric composites onto flexible substrates with high resolution and throughout [95]. For example, screen-printed PU/CNT thermoelectric inks have been used to fabricate conformal energy harvesters with excellent stretchability and output power [50]. Ink formulation and rheological control are essential for these methods to ensure uniform filler dispersion, film integrity, and interface adhesion. Hybrid processing approaches, such as combining 3D printing with in-situ curing or laser patterning, enable the

construction of complex architectures with spatially controlled properties [90]. For instance, direct-ink-writing of elastomer-thermoelectric inks enables layer-by-layer construction of stretchable devices with programmable thermal gradients and mechanical responses.

Beyond fabrication, application-oriented optimization is crucial. In wearable applications, devices must withstand sweat, temperature fluctuation, and mechanical stress while maintaining performance. Encapsulation strategies using biocompatible elastomers, breathable membranes, or hydrophobic coatings help improve comfort and durability [89]. In biomedical contexts, sterilization compatibility and long-term skin contact must be verified through cytotoxicity and irritation tests. Power conditioning circuits, storage systems, and wireless transmission modules must be integrated to deliver usable energy. Recent developments have introduced FTEG-based systems that autonomously power biosensors, motion detectors, or wireless nodes using only body heat [96]. These systems require co-optimization of power output, mechanical resilience, and energy management circuitry.

Future efforts should also focus on lifecycle assessment, cost analysis, and eco-design of FTEGs, especially for disposable or biodegradable devices. Sustainable material selection, energy-efficient manufacturing, and end-of-life recyclability will become critical as flexible thermoelectric devices move toward commercial adoption [91].

4. Conclusions

Elastomer-based FTEGs represent a transformative class of energy harvesters with the potential to power wearable devices and autonomous sensors in dynamic environments. Recent progress in material design, particularly the integration of self-healing, biodegradable, and stretchable polymers, has expanded the functional landscape of FTEGs. Advanced filler alignment, interface engineering, and scalable fabrication methods have collectively improved thermoelectric efficiency without compromising mechanical flexibility. However, persistent challenges such as achieving stable filler dispersion, minimizing interfacial resistance, and ensuring long-term durability under repeated deformation must be addressed. Moreover, the incorporation of sustainable practices, ranging from green synthesis to lifecycle assessment, is crucial for real-world deployment. Moving forward, the convergence of hierarchical geometry design, multifunctional interphases, and AI-driven optimization is expected to enable highly adaptive, resilient, and eco-compatible FTEGs suitable for a broad spectrum of practical applications.

Funding: The authors gratefully acknowledge the financial support from the National Science and Technology Council, Taiwan, R.O.C., under the contracts NSTC 112-2221-E-006-111-MY3 and NSTC 113-2221-E-006-195-MY3 for this study. This research is also supported in part by Higher Education Sprout Project, Ministry of Education to the Headquarters of University Advancement at National Cheng Kung University (NCKU).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kim, S.J.; We, J.H.; Cho, B.J. A wearable thermoelectric generator fabricated on a glass fabric. *Energy Environ. Sci.* **2014**, *7*, 1959–1965.
2. Yang, T.; Pan, H.; Tian, G.; et al. Hierarchically structured PVDF/ZnO core-shell nanofibers for self-powered physiological monitoring electronics. *Nano Energy* **2020**, *72*, 104706.
3. Park, S.H.; Jo, S.; Kwon, B.; et al. High-performance shape-engineerable thermoelectric painting. *Nat. Commun.* **2016**, *7*, 13403.
4. Khatib, M.; Zohar, O.; Saliba, W.; et al. Highly Efficient and Water-Insensitive Self-Healing Elastomer for Wet and Underwater Electronics. *Adv. Funct. Mater.* **2020**, *30*, 1910196.
5. Liu, C.; Yin, X.; Chen, Z.; et al. Improving the thermoelectric performance of solution-processed polymer nanocomposites by introducing platinum acetylides with tailored intermolecular interactions. *Chem. Eng. J.* **2021**, *419*, 129624.
6. Mamur, H.; Dilmaç, Ö.F.; Begum, J.; et al. Thermoelectric generators act as renewable energy sources. *Clean. Mater.* **2021**, *2*, 100030.
7. Liu, K.; Ouyang, B.; Guo, X.; et al. Advances in flexible organic field-effect transistors and their applications for flexible electronics. *NPJ Flex. Electron.* **2022**, *6*, 1.
8. Lee, B.; Cho, H.; Park, K.T.; et al. High-performance compliant thermoelectric generators with magnetically self-assembled soft heat conductors for self-powered wearable electronics. *Nat. Commun.* **2020**, *11*, 5948.
9. Wang, Z.; Gao, Q.; Wang, W.; et al. High performance Ag_2Se/Ag/PEDOT composite films for wearable thermoelectric power generators. *Mater. Today Phys.* **2021**, *21*, 100553.
10. Cao, T.; Shi, X.-L.; Li, M.; et al. Advances in bismuth-telluride-based thermoelectric devices: Progress and challenges. *eScience* **2023**, *3*, 100122.
11. Park, K.T.; Cho, Y.S.; Jeong, I.; et al. Highly Integrated, Wearable Carbon-Nanotube-Yarn-Based Thermoelectric

Generators Achieved by Selective Inkjet-Printed Chemical Doping. *Adv. Energy Mater.* **2022**, *12*, 2200256.
12. Li, Y.; Zhang, H.; Chang, J.; et al. Solvent-Free MXene/Poly(ionic liquid) Composite Elastomers with Simultaneously Improved Mechanical and Electrical Properties for Sensing and Photothermal Applications. *Nano Lett.* **2025**, *25*, 9976–9984.
13. Zadan, M.; Malakooti, M.H.; Majidi, C. Soft and Stretchable Thermoelectric Generators Enabled by Liquid Metal Elastomer Composites. *ACS Appl. Mater. Interfaces* **2020**, *12*, 17921–17928.
14. Sun, X.; Hou, Y.; Zhu, Z.; et al. Modular assembly of self-healing flexible thermoelectric devices with integrated cooling and heating capabilities. *Nat. Commun.* **2025**, *16*, 4220.
15. Padmanabhan Ramesh, V.; Sargolzaeiaval, Y.; Neumann, T.; et al. Flexible thermoelectric generator with liquid metal interconnects and low thermal conductivity silicone filler. *NPJ Flex. Electron.* **2021**, *5*, 5.
16. Gobpant, J.; Klongratog, B.; Rudradawong, C.; et al. High-performance flexible thermoelectric generator based on silicone rubber and cover with graphite sheet. *Appl. Therm. Eng.* **2024**, *236*, 121656.
17. Panbude, A.; Veluswamy, P. Silicone Elastomer: Encapsulating Materials for Flexible Thermoelectric Generator. *IEEE Sens. J.* **2023**, *23*, 16608–16615.
18. Ding, W.; Shen, X.; Jin, M.; et al. Robust bendable thermoelectric generators enabled by elasticity strengthening. *Nat. Commun.* **2024**, *15*, 9767.
19. Li, Y.; Zeng, J.; Zhao, Y.; et al. Fabric-based flexible thermoelectric generators: Design methods and prospects. *Front. Mater.* **2022**, *9*, 1046883.
20. Zhu, S.; Fan, Z.; Feng, B.; et al. Review on Wearable Thermoelectric Generators: From Devices to Applications. *Energies* **2022**, *15*, 3375.
21. Du, Y.; Xu, J.; Paul, B.; et al. Flexible thermoelectric materials and devices. *Appl. Mater. Today* **2018**, *12*, 366–388.
22. Zhang, L.; Shi, X.-L.; Yang, Y.-L.; et al. Flexible thermoelectric materials and devices: From materials to applications. *Mater. Today* **2021**, *46*, 62–108.
23. Xia, T.; Wemyss, A.M.; Salehiyan, R.; et al. Effective and Fast-Screening Route to Evaluate Dynamic Elastomer-Filler Network Reversibility for Sustainable Rubber Composite Design. *ACS Sustain. Chem. Eng.* **2023**, *11*, 17857–17869.
24. Masoumi, S.; O'Shaughnessy, S.; Pakdel, A. Organic-based flexible thermoelectric generators: From materials to devices. *Nano Energy* **2022**, *92*, 106774.
25. Gokhale, P.; Loganathan, B.; Crowe, J.; et al. Development of Flexible Thermoelectric Cells and Performance Investigation of Thermoelectric Materials for Power Generation. *Energy Procedia* **2017**, *110*, 281–285.
26. Gong, S.; Schwalb, W.; Wang, Y.; et al. A wearable and highly sensitive pressure sensor with ultrathin gold nanowires. *Nat. Commun.* **2014**, *5*, 3132.
27. Kang, Y.H.; Bae, E.J.; Lee, M.H.; et al. Highly Flexible and Durable Thermoelectric Power Generator Using CNT/PDMS Foam by Rapid Solvent Evaporation. *Small* **2022**, *18*, e2106108.
28. Liu, Z.; Chen, G. Advancing Flexible Thermoelectric Devices with Polymer Composites. *Adv. Mater. Technol.* **2020**, *5*, 2000049.
29. Choi, J.; Jung, Y.; Dun, C.; et al. High-Performance, Wearable Thermoelectric Generator Based on a Highly Aligned Carbon Nanotube Sheet. *ACS Appl. Energy Mater.* **2020**, *3*, 1199–1206.
30. Cui, X.; Ruan, Q.; Zhuo, X.; et al. Photothermal Nanomaterials: A Powerful Light-to-Heat Converter. *Chem. Rev.* **2023**, *123*, 6891–6952.
31. Xu, Y.; Wu, B.; Hou, C.; et al. Reconfigurable flexible thermoelectric generators based on all-inorganic MXene/Bi_2Te_3 composite films. *FlexMat* **2024**, *1*, 248–257.
32. Dong, X.; Xiong, S.; Luo, B.; et al. Flexible and Transparent Organic-Inorganic Hybrid Thermoelectric Modules. *ACS Appl. Mater. Interfaces* **2018**, *10*, 26687–26693.
33. Ren, W.; Sun, Y.; Zhao, D.; et al. High-performance wearable thermoelectric generator with self-healing, recycling, and Lego-like reconfiguring capabilities. *Sci. Adv.* **2021**, *7*, eabe0586.
34. Huo, B.; Guo, C.-Y. Advances in Thermoelectric Composites Consisting of Conductive Polymers and Fillers with Different Architectures. *Molecules* **2022**, *27*, 6932.
35. Wang, Y.; Yang, L.; Shi, X.L.; et al. Flexible Thermoelectric Materials and Generators: Challenges and Innovations. *Adv. Mater.* **2019**, *31*, e1807916.
36. Nathan, A.; Ahnood, A.; Cole, M.T.; et al. Flexible Electronics: The Next Ubiquitous Platform. *Proc. IEEE* **2012**, *100*, 1486–1517.
37. Chen, J.; Zheng, J.; Gao, Q.; et al. Polydimethylsiloxane (PDMS)-Based Flexible Resistive Strain Sensors for Wearable Applications. *Appl. Sci.* **2018**, *8*, 345.
38. He, X.; Shi, J.; Yunna, H.; et al. Highly stretchable, durable, and breathable thermoelectric fabrics for human body energy harvesting and sensing. *Carbon Energy* **2022**, *4*, 621–632.
39. Liu, J.; Liu, Q.; Shuping, L.; et al. Wearable Thermoelectric Generators: Materials, Structures, Fabrications, and Applications. *Rapid Res. Lett.* **2023**, *17*, 2200502.

40. Won, D.; Bang, J.; Choi, S.H.; et al. Transparent Electronics for Wearable Electronics Application. *Chem. Rev.* **2023**, *123*, 9982–10078.
41. Wu, Q.; Hu, J. Waterborne polyurethane based thermoelectric composites and their application potential in wearable thermoelectric textiles. *Compos. Part B Eng.* **2016**, *107*, 59–66.
42. Cao, Z.; Koukharenko, E.; Tudor, M.J.; et al. Flexible screen printed thermoelectric generator with enhanced processes and materials. *Sens. Actuators A Phys.* **2016**, *238*, 196–206.
43. Jian, Z.; Wang, H.; Liu, M.; et al. Polyurethane-modified graphene oxide composite bilayer wound dressing with long-lasting antibacterial effect. *Mater. Sci. Eng. C* **2020**, *111*, 110833.
44. Lavazza, J.; Contino, M.; Marano, C. Strain rate, temperature and deformation state effect on Ecoflex 00-50 silicone mechanical behaviour. *Mech. Mater.* **2023**, *178*, 104560.
45. Patil, N.A.; Joshi, K.; Lee, J.; et al. Additive manufacturing of thermoplastic elastomer structures using dual material core-shell filaments. *Addit. Manuf.* **2024**, *82*, 104044.
46. He, H.; Ouyang, J. Enhancements in the mechanical stretchability and thermoelectric properties of PEDOT: PSS for flexible electronics applications. *Acc. Mater. Res.* **2020**, *1*, 146–157.
47. Chang, Y.; Huang, Y.-H.; Lin, P.-S.; et al. Enhanced Electrical Conductivity and Mechanical Properties of Stretchable Thermoelectric Generators Formed by Doped Semiconducting Polymer/Elastomer Blends. *ACS Appl. Mater. Interfaces* **2024**, *16*, 3764–3777.
48. Jeong, Y.J.; Jung, J.; Suh, E.H.; et al. Self-healable and stretchable organic thermoelectric materials: Electrically percolated polymer nanowires embedded in thermoplastic elastomer matrix. *Adv. Funct. Mater.* **2020**, *30*, 1905809.
49. Yang, S.; Qiu, P.; Chen, L.; et al. Recent developments in flexible thermoelectric devices. *Small Sci.* **2021**, *1*, 2100005.
50. Tzounis, L.; Petousis, M.; Grammatikos, S.; et al. 3D printed thermoelectric polyurethane/multiwalled carbon nanotube nanocomposites: A novel approach towards the fabrication of flexible and stretchable organic thermoelectrics. *Materials* **2020**, *13*, 2879.
51. Guo, R.; Shi, W.; Guo, R.; et al. A Novel PDMS-Based Flexible Thermoelectric Generator Fabricated by Ag_2Se and PEDOT:PSS/Multi-Walled Carbon Nanotubes with High Output Performance Optimized by Embedded Eutectic Gallium–Indium Electrodes. *Nanomaterials* **2024**, *14*, 542.
52. Wang, S.; Han, L.; Liu, H.; et al. Ionic Gelatin-Based Flexible Thermoelectric Generator with Scalability for Human Body Heat Harvesting. *Energies* **2022**, *15*, 3441.
53. He, M.; Lin, Y.-J.; Chiu, C.-M.; et al. A flexible photo-thermoelectric nanogenerator based on MoS2/PU photothermal layer for infrared light harvesting. *Nano Energy* **2018**, *49*, 588–595.
54. Yu, Z.-D.; Lu, Y.; Wang, Z.-Y.; et al. High n-type and p-type conductivities and power factors achieved in a single conjugated polymer. *Sci. Adv.* **2023**, *9*, eadf3495.
55. Zhang, C.; Huang, H.; Han, S.; et al. Layer-by-Layer flexible organic thermoelectric devices based on PEDOT: PSS and PBFDO Energy Material Advances **2024**, *5*, 0104.
56. Kim, J.H.; Hwang, J.-Y.; Hwang, H.R.; et al. Simple and cost-effective method of highly conductive and elastic carbon nanotube/polydimethylsiloxane composite for wearable electronics. *Sci. Rep.* **2018**, *8*, 1375.
57. Wei, Y.; Zhou, H.; Deng, H.; et al. "Toolbox" for the Processing of Functional Polymer Composites. *Nano-Micro Lett.* **2021**, *14*, 35.
58. Park, S.J.; Cho, K.S. Filler-elastomer interactions: Influence of silane coupling agent on crosslink density and thermal stability of silica/rubber composites. *J. Colloid Interface Sci.* **2003**, *267*, 86–91.
59. Kim, S.-U.; Kim, J.-Y. Dynamic Statistical Mechanics Modeling of Percolation Networks in Conductive Polymer Composites for Smart Sensor Applications. *Materials* **2025**, *18*, 3097.
60. Bai, X.; Zhang, C.; Zeng, X.; et al. Recent progress in thermally conductive polymer/boron nitride composites by constructing three-dimensional networks. *Compos. Commun.* **2021**, *24*, 100650.
61. Saglik, K.; Yahyaoglu, M.; Candolfi, C.; et al. Enhancing Thermoelectric and Mechanical Properties of p-Type $(Bi, Sb)_2Te_3$ through Rickardite Mineral ($Cu_{2.9}Te_2$) Incorporation. *Chem. Mater.* **2023**, *35*, 3603–3613.
62. Aboughaly, M.; Babaei-Ghazvini, A.; Dhar, P.; et al. Enhancing the Potential of Polymer Composites Using Biochar as a Filler: A Review. *Polymers* **2023**, *15*, 3981.
63. Choi, H.; Kim, Y.J.; Kim, C.S.; et al. Enhancement of reproducibility and reliability in a high-performance flexible thermoelectric generator using screen-printed materials. *Nano Energy* **2018**, *46*, 39–44.
64. Yang, Y.; Dias, M.A.; Holmes, D.P. Multistable kirigami for tunable architected materials. *Phys. Rev. Mater.* **2018**, *2*, 110601.
65. Song, J.; Park, K.; Kim, Y.; et al. Self-Healing Stretchable Thermoelectric Polymer Composite with Bismuth Antimony Telluride and Single-Walled Carbon Nanotubes for Thermoreceptor-Inspired Modular Systems. *ACS Appl. Mater. Interfaces* **2025**, *17*, 36922–36933.
66. Claumarchirant, J.F.; Nasiri, M.A.; Cho, C.; et al. Textile-based Thermoelectric Generator Produced Via Electrochemical Polymerization. *Adv. Mater. Interfaces* **2023**, *10*, 2202105.

67. Lin, Z.; Li, T.; Yang, S.; et al. Revolutionizing flexible electronics with liquid metal innovations. *Device.* **2024**, *2*, 100331.
68. Shukla, D.; Wang, H.; Awartani, O.; et al. Surface Embedded Metal Nanowire-Liquid Metal-Elastomer Hybrid Composites for Stretchable Electronics. *ACS Appl. Mater. Interfaces* **2024**, *16*, 14183–14197.
69. Zhang, P.; Deng, B.; Sun, W.; et al. Fiber-Based Thermoelectric Materials and Devices for Wearable Electronics. *Micromachines* **2021**, *12*, 869.
70. Chen, S.; Wu, Z.; Chu, C.; et al. Biodegradable Elastomers and Gels for Elastic Electronics. *Adv. Sci.* **2022**, *9*, e2105146.
71. Song, Y.; Zeng, W.; Rong, M.; et al. Flexible thermoelectric composite materials with self-healing ability for harvesting low-grade thermal energy. *Compos. Sci. Technol.* **2023**, *242*, 110179.
72. Kim, M.J.; Hwang, M.; Kim, J.-H.; et al. Biodegradable and Elastomeric Poly(glycerol sebacate) as a Coating Material for Nitinol Bare Stent. *BioMed Res. Int.* **2014**, *2014*, 956952.
73. Ali, Z.; Yaqoob, S.; Yu, J.; et al. Unveiling the Influential Factors and Heavy Industrial Applications of Graphene Hybrid Polymer Composites. *J. Compos. Sci.* **2024**, *8*, 183.
74. Liu, Y.; Wang, X.; Hou, S.; et al. Scalable-produced 3D elastic thermoelectric network for body heat harvesting. *Nat. Commun.* **2023**, *14*, 3058.
75. Shahil, K.M.F.; Balandin, A.A. Graphene–Multilayer Graphene Nanocomposites as Highly Efficient Thermal Interface Materials. *Nano Lett.* **2012**, *12*, 861–867.
76. Wu, Y.; An, C.; Guo, Y.; et al. Highly Aligned Graphene Aerogels for Multifunctional Composites. *Nano-Micro Lett.* **2024**, *16*, 118.
77. Zadan, M.; Patel, D.; Sabelhaus, A.; et al. Liquid Crystal Elastomer with Integrated Soft Thermoelectrics for Shape Memory Actuation and Energy Harvesting. *Adv. Mater.* **2022**, *34*, 2200857.
78. Park, T.H.; Kim, B.; Yu, S.; et al. Ionoelastomer electrolytes for stretchable ionic thermoelectric supercapacitors. *Nano Energy* **2023**, *114*, 108643.
79. Feng, C.; Hemantha Rajapaksha, C.P.; Jákli, A. Ionic Elastomers for Electric Actuators and Sensors. *Engineering* **2021**, *7*, 581–602.
80. Li, P.; Zhao, Y.; Li, H.; et al. Facile green strategy for improving thermoelectric performance of carbon nanotube/polyaniline composites by ethanol treatment. *Compos. Sci. Technol.* **2020**, *189*, 108023.
81. Xie, F. Natural polymer starch-based materials for flexible electronic sensor development: A review of recent progress. *Carbohydr. Polym.* **2024**, *337*, 122116.
82. Jeong, M.; Bae, E.; Park, B.; et al. High-performance and flexible thermoelectric generator based on a robust carbon nanotube/BiSbTe foam. *Carbon Energy* **2024**, *7*, e650.
83. Lv, H.; Liang, L.; Zhang, Y.; et al. A flexible spring-shaped architecture with optimized thermal design for wearable thermoelectric energy harvesting. *Nano Energy* **2021**, *88*, 106260.
84. Wang, H.; Lee, J.; Kim, J.H.; et al. Revealing the origin of the thermal conductivity improvement of the silane@polydopamine modified graphene/epoxy nanocomposites: A multiscale study. *Compos. Sci. Technol.* **2025**, *261*, 111009.
85. Romero-Gilbert, S.; Castro-García, M.; Díaz-Chamorro, H.; et al. Synthesis, Characterization and Catechol-Based Bioinspired Adhesive Properties in Wet Medium of Poly(2-Hydroxyethyl Methacrylate-co-Acrylamide) Hydrogels. *Polymers* **2024**, *16*, 187.
86. Chen, X.; Sun, P.; Tian, H.; et al. Self-healing and stretchable conductor based on embedded liquid metal patterns within imprintable dynamic covalent elastomer. *J. Mater. Chem. C* **2021**, *10*, 1039–1047.
87. Sargolzaeiaval, Y.; Padmanabhan Ramesh, V.; Neumann, T.; et al. Flexible thermoelectric generators for body heat harvesting–Enhanced device performance using high thermal conductivity elastomer encapsulation on liquid metal interconnects. *Appl. Energy* **2020**, *262*, 114370.
88. Liang, L.; Liu, X.; Li, P.; et al. A wearable multimodal health monitoring bracelet powered by high-power-density flexible thermoelectric generators. *Device* **2025**, *3*, 100748.
89. Liu, T.; Xie, L.; Zeng, J.; et al. Interfacial Superassembly of Light-Responsive Mechanism-Switchable Nanomotors with Tunable Mobility and Directionality. *ACS Appl. Mater. Interfaces* **2022**, *14*, 15517–15528.
90. Tuyen, N.T.; Kim, D.M.; Lee, J.-W.; et al. Innovative Hybrid Nanocomposites in 3D Printing for Functional Applications: A Review. *Molecules* **2024**, *29*, 5159.
91. Jamil, U.; Holden, N.M. Systematic review of life cycle assessment of thermoelectric materials and devices to identify knowledge gaps and sustainability perspectives. *Environ. Impact Assess. Rev.* **2025**, *115*, 108060.
92. Tang, Q.; Jiang, B.; Wang, K.; et al. High-entropy thermoelectric materials. *Joule* **2024**, *8*, 1641–1666.
93. Liu, J.; Wu, S.; Zhang, L.; et al. Molecular dynamics simulation for insight into microscopic mechanism of polymer reinforcement. *Phys. Chem. Chem. Phys.* **2011**, *13*, 518–529.
94. Tan, P.; Wang, H.; Xiao, F.; et al. Solution-processable, soft, self-adhesive, and conductive polymer composites for soft electronics. *Nat. Commun.* **2022**, *13*, 358.

95. Min, H.; Shuai, S.; Wanyu, L.; et al. Advances in printing techniques for thermoelectric materials and devices. *Soft Sci.* **2023**, *3*, 29.
96. Lin, H.; Peng, S.; Guo, S.; et al. 2D Materials and Primary Human Dendritic Cells: A Comparative Cytotoxicity Study. *Small* **2022**, *18*, 2107652.