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# THERMOELECTRIC ACTUATORS BASED ON TEXTILE MATERIALS

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***Abstract:*** *Thermoelectric (TE) actuators integrated into textile materials have emerged as a transformative technology at the intersection of smart materials science, textile engineering, and flexible electronics. These systems exploit the Peltier effect, the ability of thermoelectric junctions to generate or absorb heat under an applied electric current, as a mechanism for thermal actuation.*

*When incorporated into fibrous architectures such as knits, woven fabrics, or printed textiles, TE actuators enable precise, bidirectional, and solid-state thermal control, which can be coupled with thermoresponsive materials (e.g., shape memory alloys, liquid crystal elastomers, phase-change materials) to produce mechanical motion.*

*This review examines the fundamental principles governing thermoelectric actuation, the main classes of materials, including inorganic semiconductors, conducting polymers, and nanocomposites, and the fabrication strategies used to develop textile-integrated devices. Applications in wearable thermoregulation, soft robotics, haptic interfaces, and rehabilitation exoskeletons are explored. Key challenges, such as low conversion efficiency, mechanical durability under repeated deformation, and washability, are discussed, and future research directions are outlined.*

***Key words:*** *Thermoelectric actuator, Textile, Peltier effect, wearable electronics, flexible thermoelectrics*

## 1. INTRODUCTION

The convergence of smart materials science, textile engineering, and microelectronics has given rise to a new paradigm of functional textiles that actively respond to environmental or physiological stimuli. Thermoelectrically driven actuators integrated into textile substrates have attracted increasing interest due to their solid-state operation, silent performance, compact form, and bidirectional thermal controllability [1, 2].

Thermoelectric (TE) devices exploit the Peltier effect: when an electric current passes through a junction of two different semiconductors (a p-type and an n-type leg, electrically connected in series and thermally in parallel), one junction absorbs heat while the other releases it. By reversing the current direction, the heating and cooling sides are interchanged. This reversibility represents a fundamental advantage for actuation, allowing the same device to both heat and cool a thermoresponsive material, thereby generating bidirectional mechanical motion without moving parts [3, 4].

Conventional TE devices are rigid, typically using bulk bismuth telluride ($Bi_2Te_3$) legs soldered between ceramic plates. Although efficient, such assemblies are incompatible with the flexibility, conformability, and breathability requirements of wearable textiles. Over the past decade, significant research efforts have focused on developing flexible and stretchable TE architectures that can be woven, knitted, printed, or coated onto fibrous substrates while maintaining adequate thermoelectric performance [5, 6].

At the same time, thermoresponsive materials such as nickel–titanium (NiTi) shape memory alloys (SMA), liquid crystal elastomers (LCE), phase-change materials (PCM), and hydrogels have been increasingly adopted due to their ability to undergo large and reversible mechanical changes in response to thermal stimuli. The integration of flexible TE devices with these materials enables electrically controlled, autonomous actuators that do not require pneumatic or hydraulic systems [7, 8].

## 2. PRINCIPLES OF THERMOELECTRIC ACTUATION

### 2.1 Seebeck and Peltier Effects

The thermoelectric effect encompasses three interrelated phenomena: the Seebeck effect (generation of voltage under a temperature gradient), the Peltier effect (heat pumping under an applied current), and the Thomson effect (heat exchange in a conductor carrying current under a temperature gradient). For actuation, the Peltier effect is of primary relevance, although in multifunctional textile systems the Seebeck effect is often simultaneously exploited for energy generation [9]. The performance of a thermoelectric material is described by the dimensionless figure of merit ZT [10]:

$$ZT = \frac{S^2\sigma T}{T} \qquad \textbf{(1)}$$

where S is the Seebeck coefficient (V/K), σ is the electrical conductivity (S/m), κ is the thermal conductivity (W/m·K), and T is the absolute temperature. A high ZT requires simultaneously large S and σ, and low κ. In practice, these parameters are interdependent, making the simultaneous optimization of all three challenging [1, 6].

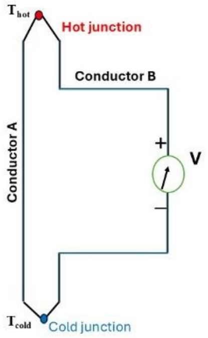

*Fig.1 Illustration of Seebeck effect in a thermoelectric junction*

The Peltier effect, discovered in 1834, describes how an electrical current forced through a junction of two different conductors causes one side to absorb heat and the other to release it. Reverse the current, and the hot and cold sides swap. In practice, a thermoelectric module pairs multiple p-type and n-type semiconductor legs electrically in series and thermally in parallel, summing the individual temperature differentials. Traditional modules use bismuth telluride ($Bi_2Te_3$) legs sandwiched between ceramic plates, a configuration that works well for benchtop cooling but is incompatible with the mechanics of a sleeve or glove.

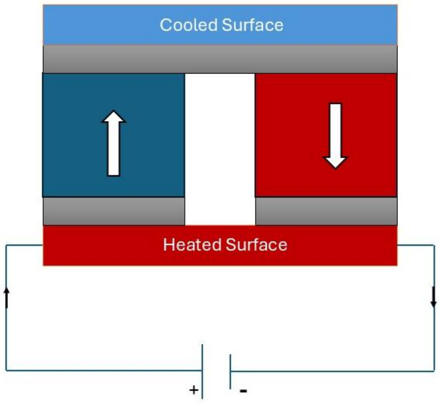

*Fig. 2 Schematic representation of the Peltier effect and directional heat flow*

## 3. THERMOELECTRIC MATERIALS FOR TEXTILE INTEGRATION

Three broad material classes are relevant to textile-integrated TE actuators, and their practical trade-offs are quite different (Fig. 3). The choice of material determines not only the achievable temperature differential but also the fabrication route, the mechanical behaviour of the finished textile, and the long-term stability under washing and repeated flexure.

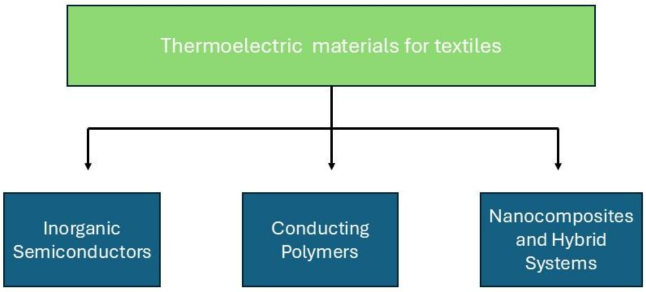

*Fig. 3 Classification of thermoelectric material classes for textile-integrated actuators*

### 3.1 Inorganic Semiconductors

Bismuth telluride alloys remain the benchmark near room temperature, with ZT values of 1–1.5 under optimal conditions. Their practical appeal for textile integration has been demonstrated by embedding small rigid TE cuboids within flexible silicone matrices, creating so-called island-bridge architectures. Hong et al. [4] presented a wearable TE device in which $Bi_2Te_3$ legs were encapsulated in a stretchable elastomer matrix and worn on the wrist; under natural convection, the device generated 17.5 mW at a body-to-air temperature difference of 15 K. More relevant to actuation, Wei et al. [5] added a pin-fin elastomeric heat spreader to a similar architecture, achieving a steady-state skin cooling of 1.5 °C via Peltier operation and a power density of 6.63 μW/cm² during energy harvesting, showing that the same module can switch between harvesting and actuating depending on current direction. Beyond island-bridge configurations, researchers have explored embedding $Bi_2Te_3$ nanoparticles directly into yarn coatings and woven structures. Nanoparticle-loaded polyester fabrics have been used to create dual-mode pressure and temperature sensing arrays, where the thermoelectric voltage provides the temperature signal and the piezoresistive response of the nanoparticle network provides the pressure signal — again within a single fabric layer [1]. The nanoparticle approach sacrifices some ZT relative to bulk single-crystal legs (typical values fall to 0.3–0.6), but gains substantially in mechanical compliance and compatibility with textile manufacturing. The reduction in ZT is primarily a consequence of increased phonon and electron scattering at the numerous grain boundaries in a nanoparticle film, alongside incomplete electrical percolation when particle loading is below the threshold needed for a continuous conductive network. Careful control of particle size distribution and sintering conditions can partially recover the ZT, and several groups have reported ZT values above 0.8 in free-standing nanoparticle films, though transferring these numbers to a rough textile substrate remains challenging. An important materials challenge shared across all $Bi_2Te_3$ textile systems is the toxicity of tellurium compounds, which becomes a non-trivial concern in skin-contact applications and must be addressed through encapsulation or surface passivation strategies before clinical deployment. Alternative inorganic compositions with lower toxicity including copper selenide ($Cu_2Se$), tin selenide (SnSe), and Bi-Sb alloys are receiving growing attention for wearable applications, though their room-temperature ZT values currently lag behind optimised $Bi_2Te_3$ [12].

### 3.2 Conducting Polymers

The appeal of polymers is their intrinsically low thermal conductivity, mechanical flexibility, and compatibility with roll-to-roll or inkjet processing. PEDOT:PSS is the most studied p-type organic TE material, while coordinated metal-organic compounds such as poly[Na(NiETT)] serve as n-type counterparts. Massetti et al. [6] demonstrated a 32-leg textile TE device printed onto commercial sports fabric using these two inks via stencil transfer; the device produced an open-circuit voltage of ~3 mV at $\Delta T = 3$ K. Scaling the design to 864 legs raised the output to ~47 mV, constituting the first fully polymer-based, through-plane body heat harvester integrated into a wearable.

Carbon nanotube (CNT) yarns offer a complementary route. Zheng et al. [7] dip-coated CNT yarns alternately in PEDOT:PSS and polyethylenimine (PEI) solutions to create p- and n-type legs, then knitted them into a weft-knitted spacer fabric. At $\Delta T = 47.5$ K, the device achieved an output power density exceeding 50 $mW/m \cdot K^2$, with a gravimetric power density of 171.7 $\mu W/g \cdot K^{-1}$, among the highest reported for an all-polymer textile TE system.

### 3.3 Nanocompozitie si sisteme Hibride

Hybrid approaches aim to combine the high ZT of inorganic fillers with the processability and flexibility of polymer matrices, addressing the key limitation of each material class when considered individually: inorganic semiconductors are too rigid and brittle for textile integration, while organic polymers alone exhibit ZT values that are too low for practical actuation [1, 11]. Nanocomposites navigate this trade-off by dispersing high-performance inorganic nanoparticles within a continuous polymeric or fibrous matrix, resulting in materials that are both mechanically compliant and thermoelectrically functional.One of the more creative demonstrations in this field involves the fabrication of thermoelectric aerogels from recycled cotton, multi-walled carbon nanotubes, and PEDOT:PSS crosslinked with methyltrimethoxysilane. The resulting structure exhibits a dual behavior that is highly relevant for integrated actuator systems. Under mechanical compression, the electrical resistance changes predictably (mechanical sensing mode), while under a thermal gradient and without any applied mechanical load, it generates a measurable thermoelectric voltage (harvesting/actuation mode) [1]. These two responses are physically decoupled, meaning that the same textile element can simultaneously sense contact forces and generate or absorb heat, a combination that is difficult to achieve with single-component materials and is particularly attractive for soft robotic skins.Two-dimensional materials, particularly MXenes (transition metal carbides and nitrides), have emerged as an attractive class of fillers for textile TE composites. $Ti_3C_2T_x$ MXene exhibits electrical conductivities exceeding 10,000 S/cm in thin-film form, along with a moderately negative Seebeck coefficient, making it a promising n-type component in hybrid TE textiles [8].

## 4. FABRICATION STRATEGIES

Dip-coating and immersion impregnation are among the simplest approaches: yarns are repeatedly passed through TE solutions to build up an ակտիվ layer, after which they are incorporated into woven or knitted structures. The main limitation is adhesion, as illustrated by the wash-resistance results reported by Massetti et al. [6] mentioned above.

Stencil printing, screen printing, or inkjet printing enable precise geometric patterning of p- and n-type legs on the textile surface, which is essential for multi-couple TE modules. The primary processing challenge lies in ink rheology: textile surfaces are inherently rough, requiring a careful balance of viscosity to prevent spreading while ensuring electrical isolation between oppositely doped legs.

A more structurally integrated approach employs TE-active fibers or yarns as primary textile elements. Shin et al. [9] wrapped NiTi shape memory alloy (SMA) wires in polyester fibers to prevent short circuits, then knitted the composite yarn into looped structures for textile actuators. Atalay et al. [11] utilized 3D digital knitting to create seamless textile actuators with integrated resistive heaters, achieving peak forces of 50 mN at voltages below 12.5 V; the authors explicitly note that replacing the resistive heater with a Peltier layer represents a logical next step [11].

## 5. CONCLUSIONS

Thermoelectric actuators integrated into textile platforms represent a promising direction for the development of next-generation smart and wearable systems. By exploiting the Peltier effect, these devices enable solid-state, bidirectional thermal actuation that can be directly coupled with thermoresponsive materials to generate controlled mechanical motion.

The material landscape reveals clear trade-offs. Inorganic semiconductors such as bismuth telluride offer high thermoelectric performance but suffer from brittleness and limited compatibility with deformable textile systems. Conducting polymers provide excellent flexibility and processability, although their thermoelectric efficiency remains comparatively low. Hybrid nanocomposites emerge as a compelling compromise, combining improved electrical performance with mechanical adaptability and multifunctionality.

Fabrication strategies play a critical role in determining device performance and durability. While coating and printing techniques enable scalable integration, challenges such as adhesion, ink rheology, and washability persist. Structurally integrated approaches based on thermoelectric fibers or yarns show significant potential for improving mechanical robustness and long-term stability in wearable applications.

Despite significant progress, several challenges remain. The inherently low temperature gradients available in wearable environments limit power output and actuation efficiency. Additionally, ensuring mechanical durability under repeated deformation and maintaining performance after washing cycles are key barriers to practical deployment.

Future research should focus on enhancing thermoelectric efficiency in flexible materials, optimizing thermal management within textile architectures, and developing robust, scalable fabrication methods.

## ACKNOWLEDGEMENTS

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