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A Conceptual Framework for a Wearable Cooling System Using PCM and TEC Integration

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Abstract – *Urban heat stress is an escalating challenge in Sri Lanka, where conventional air conditioning remains the dominant means of thermal relief. Although effective, space cooling systems are energy intensive and environmentally unsustainable. Wearable cooling devices have emerged as a potential alternative, offering localized thermal comfort in outdoor and mobile contexts. Human thermal regulation relies primarily on sweating, which dissipates heat through evaporation. However, sweat distribution is uneven across the body, and in Sri Lanka's hot, humid climate, where evaporation is often limited, devices that remove heat directly from high-sweat regions present a more effective strategy. This paper introduces a conceptual framework for a hybrid phase change material (PCM) –thermoelectric cooling (TEC) wearable system that optimizes energy usage by integrating the heat storage capacity of PCMs with the active cooling of TECs. Unlike prior studies that employ PCM as heat sinks on the hot side, this work explores PCM integration on the cold side to extend comfort duration while minimizing power demand. The study aims to establish a conceptual foundation for future research into efficient, sustainable, and context-appropriate wearable cooling solutions, particularly for users such as motor-bike riders exposed to high heat and direct sunlight.*

Keywords: *Body Cooling System; Sri Lankan Hot Climate; Phase Change Materials; Thermoelectric Cooling; Wearables; Energy Consumption; Human Thermal Regulation*

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I. Introduction

According to the Department of Meteorology, 2024 was recorded as the warmest year globally, with a daily maximum temperature reaching 36°C. A recent World Bank report identified Sri Lanka among a few South Asian countries experiencing heat levels that are considered unsafe for outdoor work for an average of six hours per day. Sri Lanka's hot and humid climate significantly affects the performance of conventional cooling devices compared to dry climates. High humidity (~70–90%) reduces the effectiveness of sweat evaporation, limiting the body's natural cooling mechanism. Devices that remove heat directly from the skin remain effective. Thus, wearable cooling solutions capable of sustaining comfort in high-humidity tropical contexts have become increasingly significant. Given Sri Lanka's consistently hot and sunny climate, such devices would provide year-round environmental relevance and usability.

Wearable cooling solutions remain uncommon in Sri Lanka, where people primarily rely on fans or air conditioning. However, in global context growing energy-saving demands, diverse personal thermoregulation needs, and the emergence of wearable electronics and smart textiles have renewed interest in personal thermal management (PTM) technologies. Most current wearable cooling technologies rely on either PCM or TEC systems. PCM based devices require pre-cooling before each use and provide only limited-duration cooling, whereas TEC based devices demand a constant power supply and additional components such as heat sinks, which increase bulk and reduce efficiency. Previous research has explored the use of PCM as a heat sink for TECs, typically to improve TEC efficiency. However, the reverse concept, using TECs to actively maintain or recharge PCM for prolonged cooling has not been addressed in the literature.

Addressing this gap, the present study aims to develop an innovative, wearable body cooling system utilizing Phase Change Materials (PCMs) and thermoelectric cooling (TEC) technology. The proposed system intends to reduce reliance on conventional air conditioning and offer a sustainable approach to personal thermal management. The concept has the potential to deliver extended, on-demand cooling without frequent dependence on external refrigeration.

II. Scope of the study, Aim, and Objectives

This study focuses on *conceptualizing a hybrid system that integrates PCM and TEC technologies, combining the advantages of both.* The present paper introduces only the conceptual framework of the proposed system, experimental validation and performance evaluations will be undertaken in subsequent stages of the research. The specific objectives of this conceptual study are to:

- Discuss capabilities and limitations of PCM and TEC.
- Address key challenges associated with existing wearable cooling devices such as bulkiness, short cooling duration, and high-power dependency.
- Identify a suitable user group for the proposed system, as certain design parameters (e.g., inclusion of a stationary power unit or battery backup) must be defined based on user needs and application context.
- Outline the conceptual system configuration and operational principles of the proposed hybrid PCM–TEC wearable cooling device.

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The subsequent stage of the research will focus on the experimental validation and practical development of the proposed system. This next phase aims to translate the conceptual framework into a functional prototype and evaluate its real-world applicability. Through these future investigations, the research ultimately seeks to contribute to the development of sustainable, energy-efficient, and context-appropriate cooling solutions tailored for hot and humid regions such as Sri Lanka.

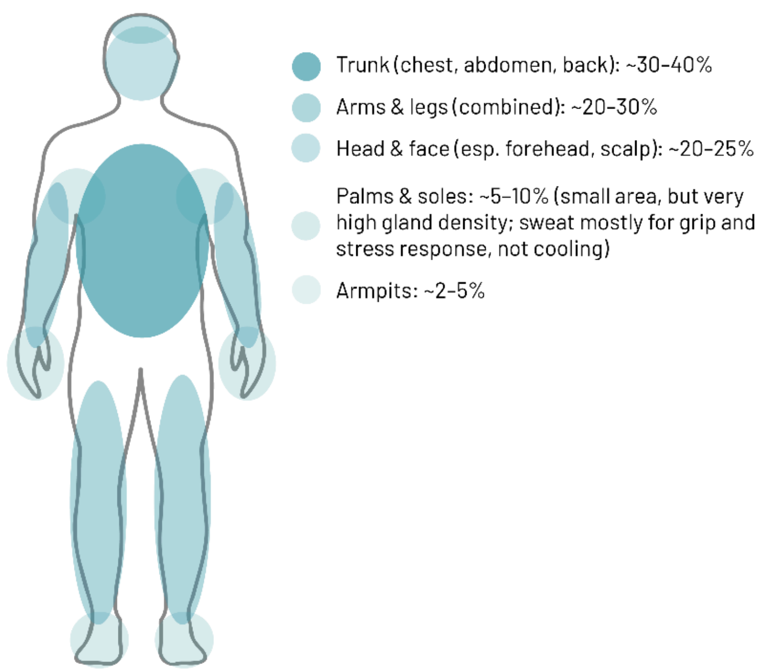
III. Literature Review

A. Personal Thermal Management (PTM)

Thermal comfort, the objective of PTM, is inherently subjective and influenced by both physiological and psychological factors. Skin temperature serves as a key indicator due to its direct contact with the environment and abundance of thermal receptors. Journal article '*Emerging Materials and Strategies for Personal Thermal Management*' suggests that comfort is generally achieved when skin temperature is maintained between 32–34°C, with discomfort arising above 35°C. The body regulates heat balance through metabolic activity and exchanges with the environment via radiation, convection, conduction, and evaporation (sweating). (Hu et al., 2020) However, sweat distribution across the body is not uniform (Figure 1). These variations indicate that localized cooling strategies should prioritize the trunk and head regions, where sweat activity and thermal sensitivity are greatest, in order to maximize heat removal and user comfort in wearable systems. (Weiner, 1945)

Figure 1

Sweat output (percentage of total body sweating)



Note. These values vary with temperature, activity, stress, and individual physiology, these are approximate ranges from physiology studies. Source: Data adopted from 'the regional distribution of sweating' by J.S. Weiner (1945), Figure created by author.

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A wide range of PTM technologies are currently available, including wearable cooling garments, vests, towels, neck wraps, and portable fans (Figure 2). While effective to some extent, most solutions present practical challenges. i.e., refrigerated products lose effectiveness after a single use unless recharged, portable fans and neck AC units can be noisy or cumbersome, and bulkier devices are often unsuitable for professional or long-duration use. (*Wearable Cooling Devices*, 2025)

While existing PTM technologies provide localized relief, most are designed for laboratory or short-term applications rather than continuous outdoor use. Developed for specific contexts, these technologies are not adopted in Sri Lanka. This gap indicates a need for compact, long-lasting, and context-responsive PTM systems suitable for field users such as delivery riders or outdoor workers.

Figure 2
PTM technologies available in the market

Note. (Left to right) PCM Vest: PCM vests absorb body heat and maintain a stable cooling temperature for a limited duration. Cooling Towel: Cooling towels are made from moisture-activated fabrics that use evaporation to lower surface temperature and provide instant, short-term cooling. PCM Cooling Neck Ring: encapsulated PCM that solidify at low temperatures and gradually absorb heat from the neck area, offering localized and reusable cooling. Portable Neck Fan: Portable neck fans are lightweight, battery-powered devices that circulate air around the head and neck. (Images from www.amazon.com)

B. Phase Change Materials (PCM)

Phase Change Materials are capable of storing and releasing significant amounts of heat during a phase transition, most commonly between solid and liquid states. This property enables them to provide high energy storage density with minimal temperature variation, making them highly suitable for applications in thermal energy storage and passive temperature stabilization. The principle of PCMs is their capacity to absorb heat at their melting temperature, remaining isothermal while undergoing the solid-to-liquid transition. When cooled, the material solidifies and releases the stored latent heat. (Mehling et al., 2022)

Historically, water is the most widely used PCM, its fixed phase transition temperature of 0 °C limits broader applications. To overcome this, alternative PCMs such as eutectic salt-water mixtures, salt hydrates, fatty acids, paraffins, and sugar alcohols have been developed, offering phase transition temperatures ranging from –70 °C to several hundred Celsius. These broaden the applicability of

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PCMs to contexts such as building energy storage, solar power plants, electronics, and wearable systems.

Commercially available PCMs today span a wide temperature range and are supplied either in bulk form, encapsulated, or integrated into composites. PCMs face several limitations:

- Supercooling, which delays solidification
- Leakage during the liquid phase if not properly encapsulated
- Low thermal conductivity, which leads to slow heat transfer
- Finding PCMs that match human comfort temperatures with high latent heat

Recent innovations addressing these limitations include the development of composite materials, encapsulation techniques etc. To address the inherently low thermal conductivity of most PCMs, composites incorporating conductive additives such as graphite have been developed. Adding nucleators to reduce supercooling is also a common practice. PCMs have also been embedded into fibreboards, fabrics, and coatings, expanding their usability across industries. These modifications not only improve heat transfer efficiency but also facilitate integration into consumer products, including clothing and wearable devices. (Rubitherm Technologies GmbH, 2023)

Several PCM-based wearable cooling products are available in the market, including cooling vests, neck wraps, and clothing integrated with microencapsulated PCMs. These devices are designed to absorb or release heat during phase changes, providing temporary cooling and enhancing personal thermal comfort in hot environments.

C. Thermoelectric cooling (TEC) technology

Thermoelectric cooling is a technology that offers several advantages over conventional cooling methods. TECs are highly reliable, compact, lightweight, and have no moving parts or working fluids, making them suitable for a range of applications, including wearable thermal management. They can be powered by direct current (DC) sources such as photovoltaic cells, fuel cells, or vehicle batteries, offering flexibility in off-grid or mobile scenarios. (Zhao & Tan, 2014)

The principle of TECs is the Peltier effect. Modern thermoelectric modules are typically composed of multiple n-type and p-type semiconductor elements, connected electrically in series and thermally in parallel, sandwiched between ceramic plates. The direction of the electric current determines whether the device heats or cools, allowing precise control over localized temperature. (Atta, 2018)

They are commonly used in electronics cooling, portable refrigeration, automotive seat temperature control, and even thermoelectric air-conditioning systems. Although the coefficient of performance (COP) of TECs is generally lower than that of conventional refrigeration, their ability to provide localized cooling with precise control, low-voltage operation, and compatibility with renewable energy sources like PV panels makes them attractive for wearable and energy-conscious applications. However, TECs also face limitations, notably high cost and low energy efficiency,

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which restrict their use to situations where system reliability and localized cooling are prioritized over overall efficiency.

D. PCM and TEC Integration

The integration of PCMs with TEC systems has attracted attention as a potential pathway for wearable cooling solutions. While TECs are capable of both cooling and heating, their application in portable or body-worn devices is limited by rigid and heavy components, particularly the heatsink, which is essential for dissipating excess heat. (Choi et al., 2021)

Recent studies have proposed flexible heatsinks designed from composite materials to overcome these limitations. For instance, Choi et al. (2021) demonstrated a ternary composite consisting of silicone elastomer, encapsulated paraffin PCM, and graphite powder. This hybrid configuration balances mechanical flexibility with enhanced thermal conductivity and heat capacity, enabling a more portable and body-conforming cooling layer.

While this system has demonstrated significant potential for personal thermal management, each remains limited when applied independently. PCMs by their short cooling duration and TECs by their high-power demand and bulkiness. A hybrid PCM–TEC system offers a promising pathway to overcome these constraints by combining the energy storage capacity of PCMs with the active, controllable cooling of TECs. Most existing studies on PCM–TEC integration use PCM on the hot side, where it helps absorb excess heat and extend cooling duration. However, there has been little to no exploration of using PCM on the cold side as a thermal energy storage medium. The following conceptual framework introduces such a system, outlining its proposed configuration and functional principles.

IV. Conceptual Framework

The proposed concept introduces a new approach to integrating phase change materials with thermoelectric cooling systems. Unlike existing research, which primarily employs PCMs on the hot side of thermoelectric coolers to buffer excess heat, this study explores the application of PCM on the cold side of the TEC. The PCM acts as a thermal reservoir, capable of being *charged* during TEC operation and later providing cooling independently once the TEC is switched to low-power or no-power modes. This approach redefines PCM as an active cooling buffer, effectively a *thermal battery* that can extend cooling duration, reduce reliance on continuous external power, and provide greater practicality for wearable thermal management applications.

Having a motivating context makes it easier to further develop the concept. In this study, the lifestyle and environment of urban motor-bike rider are considered as a reference point. This group often experiences intense localized heat stress due to direct solar exposure, protective gear, and traffic congestion in humid city climates. Understanding such user contexts helps align the concept with real-world needs without prematurely fixing the design details. To translate this into a workable system, the concept is envisioned in two interconnected parts:

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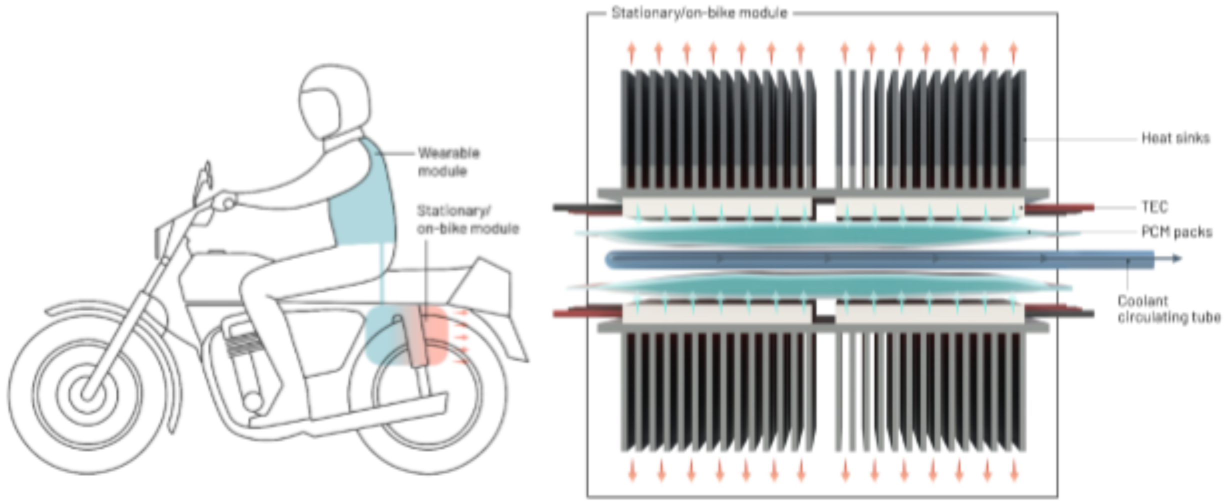
1. **Wearable module** – A lightweight cooling vest incorporating micro-tubing or flexible cold plates. Instead of circulating raw PCM, the vest carries a safe secondary coolant.
2. **Stationary/on-bike module** – A TEC-based *freezer* that combines a finned heatsink exposed to airflow, a PCM reservoir (encapsulated or plate-type), a small pump, and a controller. This unit manages two modes of operation:
   - Pre-charging PCM before a ride using mains electricity.
   - On-road charging by powering the TEC stack through the motorcycle alternator or an e-bike battery.

Figure 3

Placement and the initial configuration of the envisioned system



Note. Preliminary framework outlining the functional relationships between PCM and TEC modules, (Source: Author)

The core element of the design is the phase change material (PCM), chosen to operate within the skin comfort range. Paraffin wax blends and salt hydrates with melting points between 20–30 °C are identified as suitable candidates, as they can absorb excess body heat during melting while maintaining skin temperatures within a tolerable range. A high latent heat capacity of around 250 kJ/kg allows effective heat storage within a compact volume, while low supercooling, chemical stability, and repeatable phase transitions are essential for long-term performance. Other desirable parameters include moderate thermal conductivity (~0.2 W/m·K) and low volume expansion to ensure operational safety. Using engineered PCMs with these characteristics is the most reliable and efficient option for wearable cooling applications, as they are specifically formulated for thermal energy management. Manufacturers such as RUBITHERM and PureTemp provide a range of such PCMs optimized for different temperature ranges and design requirements.

The active cooling component is provided by thermoelectric (TE) modules based on the Peltier effect. The hot side is connected to finned aluminium heat sinks to dissipate rejected heat into the surrounding environment. The Coefficient of Performance (COP) of small-scale TECs varies with the temperature differential (ΔT) and heat dissipation quality. Under favourable conditions with ΔT between 5-10 K and adequate airflow, a COP of 0.5–0.7 is typical. Compressor-based cooling systems achieve much higher COP (2.5–4.0) compared to TECs, their reliance on bulky

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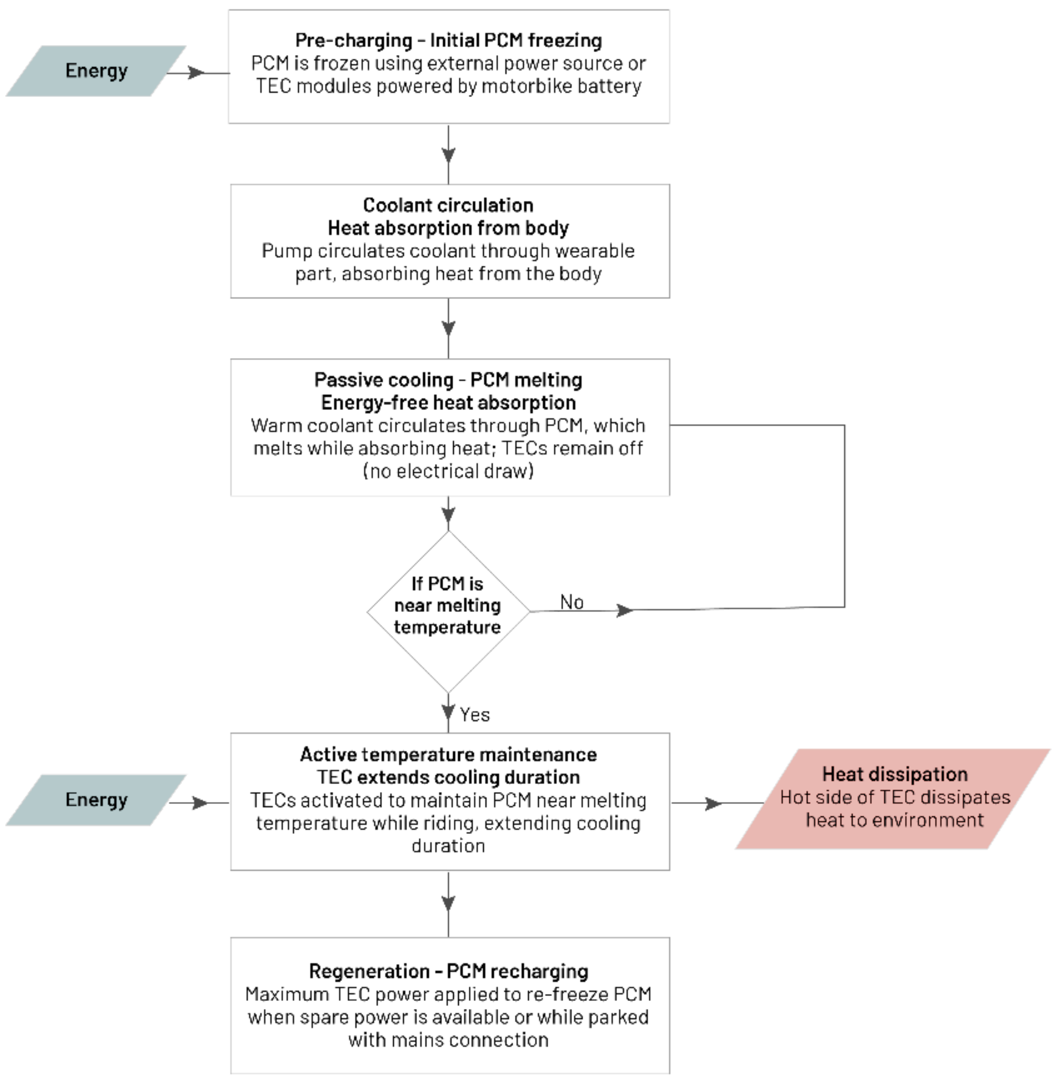
compressors, refrigerants, and moving parts makes them unsuitable for wearable or mobile applications. Consequently, the lower efficiency of TECs presents a significant challenge for this conceptual system, as it must balance cooling effectiveness with energy consumption and portability.

For heat transfer between the user and the PCM–TEC system, a coolant circulation system should be integrated. Two design pathways are considered, a liquid-based loop using water (or a water–propylene glycol mixture), driven by a miniature pump or an air-based system employing small ducts and a blower to channel cool air across the body.

Figure 4

Functional flow of the concept



Note. Functional flowchart illustrating the main framework of the proposed PCM–TEC hybrid cooling system. The process operates in a cyclic manner, repeating with each ride. (Source: Author)

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These modules are connected in a closed loop: body heat is absorbed by the circulating coolant in the vest, transferred to the PCM reservoir (where it melts and stores the heat), and periodically re-solidified by the TECs when power is available. This division between wearable and stationary components avoids the risks of pumping molten PCM through clothing, while maintaining durability, washability, and comfort.

Discussion

The integration of a PCM–TEC hybrid cooling system presents a promising sustainable solution for personal thermal management, particularly in tropical climates. Unlike compressor-based cooling units that rely on refrigerants and continuous high-power consumption, the PCM–TEC system minimizes energy demand by exploiting latent heat storage and phase equilibrium to maintain comfort within a narrow temperature range. This approach reduces operational energy use, carbon emissions, and dependence on conventional air-conditioning systems. This hybrid system introduces several technical challenges that must be addressed through further research and experimentation. The need for pre-charging to achieve better efficiency, the low COP of thermoelectric coolers, and the low thermal conductivity of PCMs are some of the major challenges of the system.

To date, no prior work has systematically investigated cold-side PCM charging for wearable thermal management. This gap positions the current study as an important first step in exploring whether such an approach can be viable. The objectives of this study are to introduce a hybrid system aimed at reducing body temperature and enhancing personal comfort and to identify the key technical challenges and research directions needed to evaluate its feasibility. Future work will focus on material selection, heat-transfer optimization, and prototype testing to assess real-world feasibility. Ultimately, determining whether this integration can deliver both energy efficiency and user practicality will shape its potential as a next-generation solution for personal thermal management.

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