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Review Article

TEC-Driven Mini Refrigerators: Recent Applications With Performance Characteristics

Tamer Guclu[1], Pinar Mert Cuce[2,3,4], Erdem Cuce[5,6,7], Emre Alvur[5] and Harun Sen[8]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Bayburt University, Dede Korkut Campus, 69000 Bayburt, Turkey*
[2]*Department of Architecture and Built Environment, School of Architecture, Built Environment, Computing and Engineering, Birmingham City University, Birmingham, B4 7XG, UK*
[3]*Department of Architecture, Faculty of Engineering and Architecture, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100, Rize, Turkey*
[4]*Center for Research Impact & Outcome, Chitkara University, Rajpura, Punjab, 140401, India*
[5]*Department of Mechanical Engineering, Faculty of Engineering and Architecture, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100, Rize, Turkey*
[6]*University Centre for Research and Development, Chandigarh University, Mohali, Punjab, 140413, India*
[7]*Center for Research Impact & Outcome, Chitkara University, Rajpura 140401, Punjab, India*
[8]*Dokuz Eylul University, Bergama Vocational School, Department of Motor Vehicles and Transportation Technologies Bergama, Izmir, Turkey*

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Corresponding Author:
Tamer Guclu
Department of Mechanical Engineering, Faculty of Engineering, Bayburt University, Dede Korkut Campus, 69000 Bayburt, Turkey
Email: tamerguclu@bayburt.edu.tr

Abstract: Thermoelectric Cooling (TEC) technology has become a remarkable alternative in mini refrigerator applications in recent years, thanks to its lack of moving parts, silent operation, compact structure and environmentally friendly features. This study aims to examine the current usage areas, performance characteristics, and engineering challenges of TEC systems in mini refrigerator applications with a holistic approach. Experimental and theoretical studies in the literature were evaluated, and the solutions provided by TEC technology in different application scenarios were comparatively evaluated. Within the scope of the study, examples for different areas such as food transportation, individual use, medical cooling, and solar energy-supported systems were examined. Performance parameters such as COP (Coefficient of Performance), temperature difference, energy consumption, and system stability were comparatively addressed. In addition, the contributions of phase change materials (PCM), nanofluid-supported coolers, and smart systems integrated with microcontrollers to TEC performance were also evaluated. The results show that TEC-based mini refrigerators offer significant advantages in terms of sustainability, portability, and low energy consumption (typically 30–90 W, about 40–60% of that of comparable compressor-based systems); however, some aspects need to be improved in terms of thermal efficiency and sensitivity to environmental conditions. This review reveals that TEC-based mini-refrigerators offer significant advantages in terms of sustainability, portability, and low energy consumption, but still have room for improvement in thermal efficiency and sensitivity to environmental conditions. In this context, the study guides both academic research and industrial applications.

Keywords: Thermoelectric Coolers, Mini Refrigerators, Portable Cooling Systems, Energy Efficiency, Sustainable Refrigeration

Introduction

Nowadays, interest in compact, energy-efficient, and environmentally friendly cooling technologies is increasing. In particular, the need for mobility, the expectation of personal comfort, and the need to keep sensitive products at low temperatures have led to the search for solutions that go beyond traditional refrigerator technologies (Pambudi *et al.*, 2022). In this context, Thermoelectric Cooling (TEC) technology stands out as an alternative solution, especially in applications requiring limited volume and power consumption, such as mini refrigerators (Guclu and Cuce, 2019).

TEC systems work with the Peltier effect, which occurs when an electric current is passed through semiconductor materials. Thanks to this effect, cooling occurs on one surface and heating occurs on the other, and this temperature difference becomes usable by heat exchange with the external environment (Zhao and Tan, 2014a). This technology offers various advantages such as silent operation, no vibration, compact design, low maintenance, and environmental sensitivity compared to gas compressor systems (Gao *et al.*, 2017). Thermoelectric modules are generally made of semiconductors based on Bi_2Te_3 (Bismuth Telluride), and when these modules are supplied with Direct Current (DC), they provide cooling by pumping heat from one surface to another (Huang *et al.*, 2010). Thanks to this structure, TEC systems are classified as solid-state devices with no moving parts. This feature makes TEC attractive, especially in applications where noise is not desired or the risk of failure of moving parts is to be minimised (Salah and Abuhelwa, 2020). For example, in-car mini coolers to increase driver comfort in the automotive industry, portable medicine and vaccine coolers in the medical sector, battery cooling and desktop mini refrigerators, and cosmetic product storage solutions for personal use are being developed using this technology (Sun *et al.*, 2022).

Although compressor systems used in traditional refrigerators offer high cooling capacity, they are not preferred in limited volume and special applications due to reasons such as their large size, high number of moving parts, noisy operation, and the necessity of using fluorinated refrigerant gas (Liang *et al.*, 2019). Environmental regulations, particularly those aimed at reducing carbon footprints and banning gases with high Global Warming Potential (GWP), have been one of the factors that have paved the way for TEC technology. TEC modules do not use gas, and there is no risk of environmental leakage (Kim *et al.*, 2025). In addition, the instant start-up of the cooling system and the fast response time are considered additional advantages in applications where time sensitivity is critical (Chen *et al.*, 2022). In the literature, typical COP values for commercial single-stage TEC modules are reported to be in the range of 0.4–0.7, with a temperature difference (ΔT) between the cold and hot surfaces of 40–70°C. Power consumption typically ranges from 30–90 W, and while ΔT can reach up to 100°C in multi-stage modules, COPs decrease accordingly. This data highlights the potential of TEC systems to provide compact cooling at low power, but also demonstrates the need for efficiency improvements. Compared to traditional compressor-powered mini-refrigerators, TEC-based systems generally have lower production costs. Furthermore, due to their simple design and ease of installation, TECs also require lower overall production time and maintenance costs. However, their relatively low energy efficiency can increase long-term operating costs. Their portability, quietness, and environmental friendliness give TEC technology a competitive advantage, particularly in low-volume and special-purpose refrigeration markets (Guclu and Cuce, 2019).

Mini refrigerators are systems designed to store a limited group of products, usually with an internal volume ranging from 4 to 30 L, and can be portable or fixed. The most common areas of use for these systems include use in automobiles, for camping and outdoor activities, transportation of medicines and biomedical products, individual office use, and preservation of makeup/cosmetics. (Gökçek and Şahin, 2017). Users of TEC-powered refrigerators generally appreciate the system's silent operation, low power consumption (especially in battery-powered operation), light weight, and digital temperature control capabilities. Thanks to these features, TEC-powered mini refrigerators can meet today's expectations not only in terms of portability but also in terms of energy consumption policies (Astrain *et al.*, 2016).

However, despite all these advantages, thermoelectric systems have some difficulties, such as low energy efficiency (COP - Coefficient of Performance), limited ability to create high temperature differences, and dependence on the ambient temperature (Liu and Su, 2018). Especially at high outdoor temperatures, the cooling performance of TEC modules decreases significantly, and the inability to remove sufficient heat from the cold surface causes the system to reach its equilibrium temperature. This situation can be a significant disadvantage for portable coolers used outdoors, especially in the summer months. Therefore, studies in recent years have focused on the development of more advanced heat sink designs, active or passively cooled heat sinks, fan-assisted air circulation systems, and modules supported by nano-composite materials to increase the efficiency of TEC systems (Dizaji *et al.*, 2019).

In addition, the adaptation of thermoelectric coolers to energy sources is also a remarkable area of research. Apart from traditional electric operations, solar-powered TEC systems have great potential, especially in off-grid areas (Alam *et al.*, 2023). Portable mini refrigerators with solar panels, developed especially for medicine and food storage in rural areas, are directly related to the Sustainable Development Goals (Yusof *et al.*, 2022). These systems provide critical solutions for both humanitarian aid applications and primary health care in developing countries. In addition, smart TEC systems supported by microcontrollers (e.g., Arduino, Raspberry

Pi) and temperature sensors are becoming more functional with features such as maintaining target temperature range, energy optimisation, and remote monitoring (Kherkhar *et al*., 2022).

The aim of this review is to present the current literature applications, technical performances, engineering challenges, and potential improvement areas of TEC-based mini refrigerators with a holistic approach. By examining the experimental and theoretical studies published in the literature, the solutions offered by TEC systems in different application areas were evaluated comparatively. In addition, the performance characteristics of these systems, such as COP values, power consumption, temperature differences, cooling trends over time, and user-oriented criteria, were revealed with numerical data. In this context, the article aims to establish interdisciplinary connections not only in terms of engineering but also in sustainability, product design, and user behaviour. As a result, TEC-based mini refrigerators offer an important research and application area both in academic and industrial terms. They offer solutions for individual needs with their compact structures and silent and reliable operating features; however, due to their performance limitations, they are still a technology open to further development and optimization. In the following sections of this study, the technical background of TEC systems, application examples, performance comparisons, and future research directions will be discussed in detail. The study is a literature review covering relevant academic studies published in the last decade (specifically the last five). The search was conducted in the Scopus, Web of Science, and Google Scholar databases. The search was conducted using the terms "thermoelectric coolers, mini refrigerators, portable cooling systems, energy efficiency." The Inclusion criteria for the study were publication in peer-reviewed journals and a direct focus on the study's topic.

Fundamentals of Tec Technology

Thermoelectric cooling technology is an innovative system based on solid-state physics that directly converts electrical energy into heat pumping. The Peltier effect, which is the basis of this system, was first discovered by Jean Charles Athanase Peltier in 1834 and shows that when an electric current is passed through a circuit where two different semiconductor materials are connected, a temperature difference is created at these connection points (Beretta *et al*., 2019). Heat is transferred from one surface to another depending on the direction of the current, and thus, cooling is provided. Thermoelectric modules perform the cooling process without a compressor and without gas by utilising this principle (Kaiprath and VV, 2023). TECs are generally manufactured using semiconductor materials based on Bi_2Te_3 (bismuth telluride). This material is a compound with low thermal conductivity and high electrical conductivity that can perform well at low temperature differences (Mao *et al*., 2021). Each TEC module typically consists of a series of n-type and p-type semiconductor pairs. These pairs are electrically connected in series and thermally in parallel. Thanks to the applied direct current, one module's surface heats up while the other cools down, thus providing the cooling function. TEC systems have no moving parts, are silent, and require minimal maintenance. These features offer significant advantages, especially for mobile, portable or limited-volume applications (Enescu and Virjoghe, 2014). Figure 1 shows the structure of a typical TEC module. A temperature difference is created between the top and bottom surfaces of the module, cooling one side while dissipating heat from the other. Fan-assisted aluminium heatsinks are used in most applications to increase heat dissipation (Teffah *et al*., 2018).

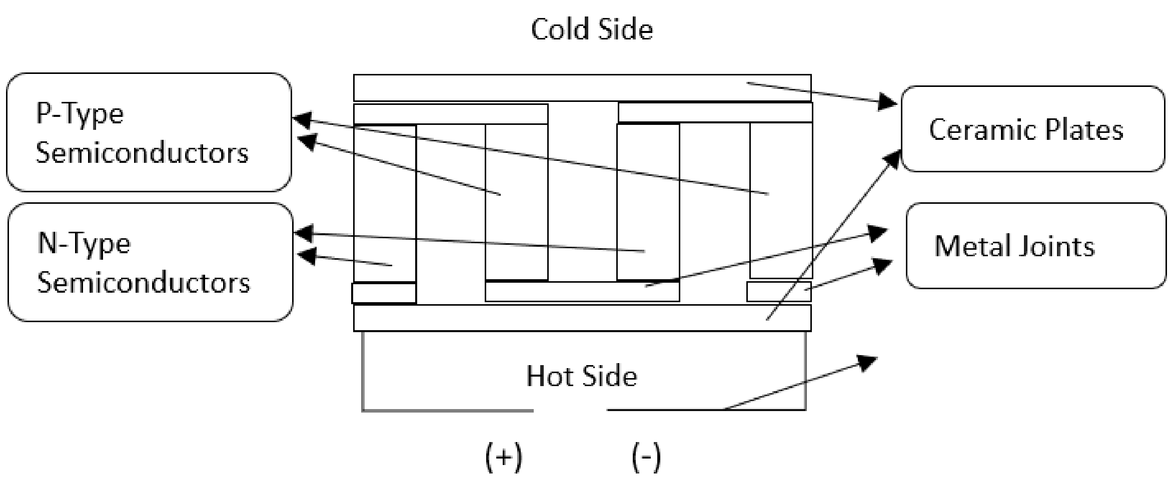

Fig. 1: The working principle of a typical TEC

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The key parameters that determine the performance of a TEC module include the Seebeck coefficient (S), electrical conductivity (σ), and thermal conductivity (κ). Together, these three parameters form a performance metric called the thermoelectric quality factor or ZT value (Venkatesan and Venkataramanan, 2020). The higher the ZT value, the higher the efficiency of the module. Today, commercially available TEC modules typically have a ZT value between 0.8 and 1.2. With some advanced materials under research, it has been possible to increase this value above 2.0, but it is not yet widespread due to cost and manufacturability limitations (Cai *et al*., 2016).

TEC modules are generally designed to operate at 12V DC and typically have a surface area of 40–60 mm square. While cooling capacity varies depending on the size, structure, and materials of the module used, a single module can typically provide cooling power between 30 and 90 W. In applications where cooling requirements are higher, multiple TEC modules can be connected in parallel or in series. In such systems, special attention must be paid to the power supply and heat dissipation design, as the use of multiple TEC modules requires both efficient heat dissipation and stable power consumption. Thermoelectric cooling systems are classified into different module types according to their structures and intended use. The most commonly used structure is a single-stage thermoelectric module. These modules contain a single Peltier layer and can generally provide a temperature difference (ΔT) of 40–70°C. They are suitable for applications requiring low and medium levels of cooling (Tan *et al*., 2017). However, in cases where a higher temperature difference is required, multi-stage TEC modules are preferred. In these modules, multiple Peltier layers are consecutively connected on top of each other, and each layer is placed on the hot side of the previous one (Ang *et al*., 2022). In this way, the ΔT value can be increased up to 100°C, but the total efficiency of the system decreases, and energy consumption increases. Multi-stage structures are used especially in applications requiring cooling at the freezer level (Karimi *et al*., 2011).

In addition, special types such as symmetric and asymmetric TEC modules have been developed. Symmetric modules can be used for both cooling and heating purposes, while asymmetric modules are optimised to provide higher performance in a specific direction. In recent years, scaled-down modules such as micro-TEC and nano-TEC systems have been developed for use in wearable devices or local electronic component cooling. This diversity allows TEC technology to be integrated into flexible designs suitable for different application areas. Finally, the control and management of TEC technology also play a critical role in system performance. The desired temperature range can be maintained more precisely by using temperature feedback control systems (e.g., PID-based). In addition, in some advanced systems, energy management is performed by microcontrollers and energy consumption is optimised. This provides significant gains in terms of system operating time, especially in battery-supported portable applications. In summary, thermoelectric cooler technology is an important alternative, especially in small-scale and special-purpose cooling applications, with its compact structure, environmental friendliness, and silent operation advantages. However, it is also clear that this technology still has room for development in terms of energy efficiency, thermal management difficulties, and material limitations. In the next section, how this basic technological infrastructure is used in mini refrigerator applications will be discussed in detail with examples from different areas.

Tec Applications in Mini Refrigerators: Literature Review

Thermoelectric cooling systems have become a preferred technology in many portable and low-volume refrigerator applications today, thanks to their compact structures and environmentally friendly features. Especially in scenarios requiring mobility, TEC-based mini refrigerators stand out as an alternative solution to replace traditional compressor systems. In this section, current literature is reviewed, and different application scenarios are technically evaluated to determine the role of thermoelectric cooling technology in mini refrigerator applications.

Portable Food and Beverage Coolers

Portable beverage and food coolers are important for users in situations that require portability, such as camping, picnics, and outdoor activities. TEC systems are generally used in such products, which have an internal volume between 4 and 20 L, operate with DC 12V, and can be connected to the vehicle cigarette lighter socket (Han *et al*., 2024).

The development of a cooling system with low energy consumption and uniform temperature distribution is a technical challenge in portable food storage applications. For this purpose, Lawal and Chang (2021) designed a multilayer thermoelectric cooler box (TE cooler box) that provides heat transfer by both conduction and convection. The system is configured with a total of six TEC1-12706 type thermoelectric modules, six heat sinks with fans on the inner and outer surfaces, a three-layer insulation wall, a dual power supply, and a thermostat unit. It was observed that the system, which operates with a power consumption of 37.7 W and a current of 3.18 A, provides a stable temperature distribution in both hot and cold regions over time. The dominant effect of heat conduction on the total heat transfer was determined; it was observed that the experimental COP value increased rapidly and stabilised over time.

It was concluded that the system can be used successfully, especially for fruit and vegetable storage, and also in regions with low energy resources. In addition, the use of micro-scale thermoelectric coolers in portable food preservation applications presents various difficulties in terms of performance due to factors such as low air flow rate, limited internal volume, and uneven heat distribution of the system. In this context, a thermoelectric micro-refrigerator prototype with an internal volume of approximately 9 L was developed, and strategies to increase thermal efficiency under forced convection under challenging indoor conditions were investigated. The system consists of a TEC module, a cooling fan, and a finned heat sink, and parameters such as current, fan power, and fin height were optimised by means of single-factor analyses and response surface experiments. According to the results, under fixed conditions where the ambient temperature is 25°C, the cold side temperature of the system could be reduced to −11.3°C, while the hot side remained at the level of 38.2°C when 0.82W fan power, 59.15 mm high finned heat sink, and 5.09A TEC current were used. In addition, the vertical arrangement of the cooling fan and heat sink allowed the hot side to be kept below 40°C and the cold side to reach −12.9°C. This study is important in terms of revealing the effect of not only individual parameters but also component placements on system performance (Han *et al*., 2024). As a result, the developed micro-cooler model shows that optimum placement and operating conditions are critical for cooling performance in thermoelectric portable systems with limited internal volume.

In recent years, the use of thermoelectric coolers in portable food preservation systems has been increasing, while hybridisation studies carried out to increase system efficiency have also attracted attention. For example, Phase Change Material (PCM) integration with thermoelectric refrigeration systems stands out as an effective method to improve the thermal stability of the system and increase energy efficiency (Omer *et al.*, 2001). A schematic description of a thermoelectric refrigeration system integrated with PCM is shown in Figure 2.

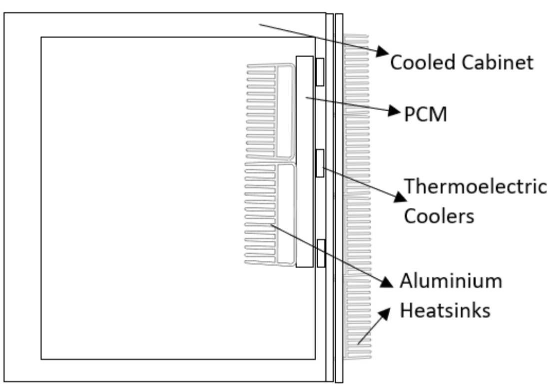

Fig. 2: Schematic description of a thermoelectric refrigeration system integrated with PCM

A recent innovative study integrated a solar-powered thermoelectric refrigerator with Phase Change Material (PCM). The main purpose of the study is to ensure that fruits and vegetables with different moisture content are preserved in the 0–5°C temperature range while minimising energy needs. In the system design, a solar panel-powered energy unit, thermoelectric modules, a copper-tube heat removal system containing a water circuit, and a PCM tank were used together. According to experimental findings, the average COP value of the system was determined as 0.69. In addition, the copper tube heat exchanger with water circulation applied to remove heat from the hot side of the TEC module reduced the freezing time of PCM by approximately one hour, thus providing a significant improvement in system performance. In this respect, the system offers an environmentally friendly alternative in terms of not containing a refrigerant and offers a feasible solution to increase food safety in regions with limited energy access. Therefore, this study constitutes an important example for the development of thermoelectric technologies in portable food cooling systems (Fenton *et al*., 2024). In another study conducted in this direction, a PCM-supported portable cooler prototype working with a Peltier-type TEC module was developed. The PCM used is an organic material with a melting point of 2°C and aims to protect perishable food products by keeping the internal temperature of the system below 4°C. The energy storage process that occurs with the melting of PCM during cooling provides passive cooling when the system needs it. The production process of the prototype was detailed with mathematical PCM mass calculations and thermal balance analyses; temperature-time curves of different food products were recorded in experimental tests. In the energy analysis performed, it was determined that the system could keep the temperature below 4°C indefinitely with 11.4W power input and maintain this temperature for 26 hours with a minimum of 4W energy. In addition, it was observed that the system could stay below 4°C for 7 hours without any energy input. This situation shows that the PCM contribution not only provides energy efficiency but also provides temperature continuity against energy interruption during portability. The system, which has a COP value of 0.75 at a temperature difference of 19°C, shows superior performance even at low energy levels compared to commercial refrigerators (Siddique *et al*., 2023).

In studies to increase the efficiency of thermoelectric cooling systems, nanotechnology-supported solutions stand out, especially for more effective heat removal from the hot surface. In this context, the effects of nanofluid-added water-cooled systems on the performance of portable thermoelectric refrigerators have been extensively investigated. In an experimental study conducted by Cuce *et al*. (2020), Al_2O_3, TiO_2, and SiO_2

particles were circulated in the water-cooling block integrated into the hot surface of the TEC module in portable TEC refrigerator applications; heat was removed from the hot surface of the TEC with a water-to-air heat exchanger. In the experiments, system performance was observed under both load and no-load conditions and at different ambient temperatures. In particular, at an ambient temperature of 30°C, a 26% improvement in indoor temperature was achieved with 1% Al_2O_3-added nanofluid, and a 55.1% improvement was recorded in terms of chilled water temperatures. In another study, the effects of the same system on energy consumption were detailed, and it was determined that the use of nanofluid made it possible to reach the target temperature in a shorter time compared to the reference cooling fluid, pure water. In this way, both the total cooling time of the system was shortened, and thermal stability was achieved faster (Cuce *et al.*, 2022a). In the third and most comprehensive study, a portable cooling cabinet with a volume of 36 L was designed, and the use of hybrid nanofluids (Al_2O_3-TiO_2-SiO_2) was evaluated. In the tests conducted in both loaded and unloaded scenarios, significant increases in cooling performance were observed as the nanoparticle ratio increased; for example, the temperature difference obtained under load at 2% concentration showed a 30.3% improvement compared to the reference case. However, small decreases in COP values were detected in all conditions (e.g., COP = 0.45 with 2% hybrid nanofluid), but this decrease was relatively limited compared to the gains in thermal performance (Cuce *et al.*, 2022b). This series of studies shows that nanofluid integration in thermoelectric cooling technologies can affect not only heat transfer performance but also energy efficiency. Researchers emphasise that the use of nanofluid provides more significant advantages, especially at high ambient temperatures and in larger volume portable coolers. In this respect, it has been demonstrated that nanofluid-supported hybrid systems offer a sustainable and more effective alternative in portable food coolers compared to classical water-cooled TEC systems. Table 1 summarises the comparative COP and lowest temperature values achieved for portable TEC systems.

Table 1: Comparative COP and lowest temperature values achieved for portable TEC systems

Ref.	System Description	Application	COP	Cold Side Temp (°C)	Power Consumption
(Lawal and Chang, 2021)	Multilayer TEC box with 6 TEC1-12706, dual fans, thermostat; conduction & convection cooling	Fruit & vegetable cooling; low-power areas	-	Stable cooling	37.7W
(Han *et al*., 2024)	Micro TEC fridge (9L) optimised with fan power, fin height, and TEC current; cold side at −11.3°C	Micro portable refrigeration; parametric optimization	-	−11.3 / −12.9	5.09A TEC, 0.82W fan
(Fenton *et al*., 2024)	Solar-powered TEC fridge with PCM; copper tube cooling; COP=0.69; latent heat effect	Solar/PCM hybrid food cooler; moisture adaptive	0.69	0–5	Solar + PCM
(Siddique *et al*., 2023)	PCM-enhanced portable TEC cooler with RT 2HC; works with 4–11.4W; 7h no power hold	Off-grid passive food cooling; PCM backup	0.75	<4	4–11.4W
(Cuce *et al*., 2020)	Nanofluid-enhanced TEC fridge with water-air exchanger; best ΔT with 1% Al_2O_3 at 30°C	Portable cooler with nanofluid thermal booster	0.4-0.5	< -4	Low consumption
(Cuce *et al*., 2022a)	Time-to-cool optimization with 1% Al_2O_3, TiO_2, SiO_2; faster reach to target temp than water	Portable food box; nanofluid vs water	0.4-0.5	< -4	Faster cooling
(Cuce *et al*., 2022b)	36L hybrid nanofluid TEC cooler; max ΔT gain: 30.3% (2% conc.); COP drop to 0.45	Large-volume portable cooler; hybrid nanofluids	0.45–0.48	< -2	Standardized test

Medical and Pharmaceutical Applications

Portable thermoelectric cooling systems have reached significant application potential in the medical and pharmaceutical fields in recent years (Reid *et al.*, 2018). They offer silent, vibration-free, and low-energy alternatives that can replace traditional compressor systems, especially in the storage of drugs, vaccines, biological samples, and sensitive medical products that require temperature-controlled transportation. The gas-free, mechanically moving part-free structure and compact dimensions of these systems make them usable both in urban centres with developed health infrastructures and in rural areas where electricity access is limited. The accelerated cold chain requirements with widespread vaccination campaigns and pandemics in developing countries have made the use of thermoelectric coolers in this area even more critical (Kartoglu and Milstien, 2014). Thermoelectric coolers used in medical applications generally target a temperature range of 2°C to 8°C. This range is necessary for the transportation of vaccines, biologically based drugs such as insulin, and some laboratory samples. Therefore, it is vital that systems not only reach the target temperature but also maintain this temperature stably for a long time. In this context, optimising thermoelectric coolers, especially with PCMs, solar panels, and insulation technologies, makes significant contributions to the continuity of the cold chain (Vangroenweghe, 2017). Storing vaccines at 2–8°C is of vital importance in order to prevent them from losing their effectiveness. Maintaining this temperature range uninterruptedly requires significant engineering solutions, especially in portable systems. In this context, a solar-powered, nanofluid-supported thermoelectric vaccine cabinet was designed and experimentally tested in an innovative study. The system has a capacity of 200 vaccine vials and 200 ready-made syringes and is designed as an integrated unit with battery and inverter systems. The operating logic of the vaccine cabinet is based on the transfer of heat removed from the hot surface of the thermoelectric module to the environment via a water-to-air heat exchanger. The differences in the fluids used in this process and the effects of fan use on system performance were examined in detail. The experiments conducted within the scope of the study were conducted at two different outdoor temperatures and in a total of 8 different operating scenarios. According to the results obtained, the highest average COP value of 1.19 was observed in the fan-supported and nanofluid-using scenario. This value indicates a significant improvement compared to classical water-based cooling systems. It was also reported that the system reached the targeted vaccine storage temperatures under experimental conditions and was able to maintain these temperatures stably (Cuce, 2024). Vaccine storage systems must be able to maintain the target temperature range even with frequent lid openings. While most reviewed studies lack detailed data on temperature fluctuations under these conditions, the available evidence suggests that well-insulated TEC units using PCM or nanofluid-assisted cooling can maintain internal temperature increases below 1–2°C during short-term access, thus providing the temperature stability critical for vaccine efficacy. In another study conducted in this direction, a solar-powered and portable vaccine transport box based on the Peltier effect was designed and tested experimentally. The system includes four 12V DC, 3.5A capacity TEC modules, externally placed heat sink fins, a 180W PV panel, and 3.7V 4500mAh Li-Po batteries. The battery structure allows the system to operate continuously for up to 3 hours when sunlight is insufficient. The average COP value of the system was determined as 0.42 under all experimental conditions. The study reveals that systems that can go below 15°C with low energy consumption offer suitable solutions in terms of ensuring vaccine transport safety, especially in regions with no connection to the outside environment (Khan *et al.* (2024) In a comprehensive review published by Hu *et al.* (2022) the current status, potential and technical challenges of thermoelectric systems in medical applications were evaluated in detail. It is emphasised that TECs can be used in the safe transportation of drugs, vaccines, and biological samples with low energy. In addition, the study states that the development of biocompatible materials is critical for clinical integration, that low COP values limit system performance, and that these obstacles can be overcome with material engineering and design improvements. It is stated that thermoelectric technologies, which offer a wide range of applications from wearable devices to smart drug delivery systems, will play an important role in personalised medicine in the future (Hu et al., 2022). Table 2 summarises the thermoelectric cooling performance parameters of TEC systems used in medical and pharmaceutical applications.

Solar-Driven TEC Applications

Thermoelectric cooling systems powered by solar energy have gained a remarkable position among sustainable cooling technologies in recent years, especially due to their low energy consumption and environmentally friendly structures. These systems, which operate by feeding electricity obtained through PV panels directly to thermoelectric modules, are becoming widespread in both fixed and portable applications thanks to their lack of moving parts, silent operation, and compact structure. Portable refrigerators are used in various areas such as agricultural product storage units, medicine storage boxes, and beverage coolers. Thanks to their advantages such as low energy consumption, silent operation, and environmental sustainability, they offer ideal solutions especially in off-grid regions Xi *et al.*, 2007. A schematic of the solar-driven TEC refrigerator system is shown in Figure 3.

Table 2: Thermoelectric cooling performance parameters of TEC systems used in medical and pharmaceutical applications

Ref.	System Description	Application	COP	Cold Side Temp (°C)	Power Consumption
(Cuce, 2024)	Solar-powered, nanofluid-supported thermoelectric vaccine cabinet	Vaccine storage (200 vials + syringes)	1.19	2–8	PV + Battery + Inverter
(Khan *et al*., 2024)	Portable Peltier-based vaccine transport box (4 TECs, PV panel, Li-Po battery)	Portable vaccine transportation	0.42	<15	180W PV, 3.7V battery
(Hu *et al*., 2022)	Review on TECs in medical applications	Medical devices, personalised medicine	Low (review)	N/A	Varies
(Zaferani *et al*., 2021)	Small-sized portable thermoelectric refrigerator for vaccines	Portable vaccine refrigeration	Not specified	Sub-zero	Vehicle DC system
(Ivanov *et al*., 2021)	Review of TECs for medical cooling and wearable devices	Medical coolers, wearable health tech	Not specified	N/A	Varies

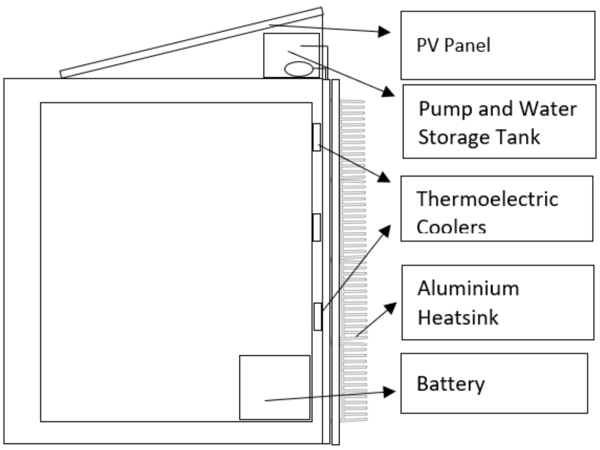

Fig. 3: Schematic of the solar-driven TEC refrigerator system

The limited energy infrastructure in developing regions, the need for uninterrupted cooling in sensitive areas such as medical equipment transportation, and the demand for portable solutions in the food sector are increasing the interest in these technologies. Among the solutions for increasing energy efficiency needs and sustainability today, optimising portable thermoelectric coolers by supporting them with solar energy is a remarkable trend. In a study conducted in this direction, a dual-stage cooling system using TEC modules with different powers was supported by a Photovoltaic (PV) energy source, and its applicability to portable food coolers was examined. In the system design, in order to meet the basic cooling need with low power consumption, the TEC1-12703 module was supported by the TEC1-12715 module, which is activated when rapid cooling is required. In this way, the system gained a more flexible structure in terms of both constant temperature control and response time. The refrigerator developed within the scope of the study was tested in two different operating modes. While an average power consumption of 94.9 W/h was observed in the "normal" mode, this value was reduced to 5.8 W/h in the "energy saving" mode. In particular, the fact that cooling from 17°C to 4°C was completed in 7 hours reveals that the system offers sufficient thermal performance. Maintaining the internal temperature despite frequent lid opening is a positive indicator for scenarios that may be encountered in practice. The study also reported the highest COP value of the system as 0.9 and the overall efficiency value as 6.4%. These values reveal that portable thermoelectric systems operating solely on PV energy can provide significant energy savings compared to traditional energy consumption patterns and maintain the temperature levels required for food safety. The developed system is considered a viable, sustainable, and efficient alternative for both food storage scenarios requiring mobility and areas where access to grid electricity is limited (Alani *et al*., 2025). Dhawan *et al*. (2023) conducted an experimental study to evaluate the performance of solar-driven TEC refrigerator systems. Instead of the compressor that causes high energy consumption in traditional refrigerators, a solar energy cooling system using a thermoelectric module based on the Peltier effect has been developed. The system is supported by an automatic sun-tracking mechanism for maximum efficiency. In the experiments conducted in a 2.6-litre volume, the indoor temperature of 22.48°C was reduced to 15.15°C in 136 seconds, and the system's COP value was measured as 0.54. It was also reported that it provided 44–63% energy savings compared to traditional systems. The integration of advanced solar tracking technologies into thermoelectric cooling systems stands out as an effective method for increasing system efficiency. In this context, a study has shown that a solar-powered thermoelectric refrigerator supported by a dual-axis solar tracking system provides significant performance gains compared to fixed panel systems. In experiments conducted at a fixed ambient temperature of

25°C, it was reported that the COP value of the system with the dual-axis solar tracking system reached a maximum of 2.07 and provided an improvement of 44% to 75% compared to fixed systems (Qamar *et al*., 2024). Sarbu and Dorca have examined the development, performance parameters, and application areas of solar-powered thermoelectric cooling systems in detail. The study emphasizes the advantages of thermoelectric cooling systems, such as their compact structure, lack of moving parts, and ability to operate directly with direct current. In addition, the applications of these systems in various areas such as electronic cooling, domestic cooling, air conditioning, and energy production are examined. The study also discusses the applicability of solar-powered TE cooling technologies in "nearly zero" energy buildings (Sarbu and Dorca, 2018). Table 3 presents the COP values and cooling performance of solar-powered thermoelectric cooling systems under different design configurations and operating conditions.

Performance Evaluation and Influencing Parameters

The performance of thermoelectric cooling systems varies significantly depending on system design, operating conditions, and environmental factors. The performance of these systems is mainly related to various parameters such as cooling capacity, temperature difference, power consumption, reduction of thermal resistance, heat sink performance, ambient temperature, insulation quality, and stability over time (Owoyele *et al*., 2015). Cooling capacity expresses the amount of energy that a system can cool in a certain period of time and is usually evaluated in Watts (W). This parameter is directly related to the amount of heat received from the cold surface of the TEC. The cooling capacity of TECs is basically expressed by the following equation (Twaha *et al*., 2016):

$$Q_c = \alpha \cdot I \cdot T_c - 0.5 \cdot I^2 \cdot R - K \cdot (T_h - T_c) \quad (1)$$

In this equation, Q_c represents the cooling capacity (W), α is the Seebeck coefficient (V/K), I is the electric current passing through the module (A), T_c is the cold-side temperature (K), R is the electrical resistance (Ω), and K denotes the thermal conductance of the module (W/K). The equation consists of three main terms: Cooling by the Peltier effect ($\alpha \cdot I \cdot T_c$), Joule heating loss ($0.5 \cdot I^2 \cdot R$), and Fourier heat conduction ($K \cdot (T_h - T_c)$).

An important parameter that determines the performance of these systems is the COP (Coefficient of Performance) value. COP is used to measure the efficiency of the system and is defined as the ratio of the cooling capacity to the electrical energy input (Su *et al*., 2021):

$$COP = \frac{Q_c}{W} \quad (2)$$

The higher the COP value, the better the energy efficiency of the system. However, this value can vary greatly depending on ambient conditions and system design.

Table 3: COP values and cooling performance of solar-powered thermoelectric cooling systems under different design configurations and operating conditions

Ref.	System Description	Application	COP	Cold Side Temp (°C)	Power Consumption
(Alani *et al*., 2025)	Dual-stage PV-powered TEC system (TEC1-12703 + TEC1-12715); tested in normal and energy-saving modes	Portable food cooling; hybrid TEC power design	0.9	4	5.8–94.9 W/h
(Dhawan *et al*., 2023)	PV-powered TEC refrigerator (2.6L); sun-tracking mechanism; rapid temperature drop observed	Mini solar cooler for food/medicine	0.54	15.15	44–63% less than traditional
(Qamar *et al*., 2024)	SPTR with dual-axis solar tracking system (STS) and fixed panel comparison	Solar TEC with tracking; enhanced COP	0.27–2.07	N/A	Improved by 44–75%
(Sarbu and Dorca, 2018)	Review study: Applications and development of solar-powered TEC systems in electronic and building cooling	General overview; residential & electronics	N/A	N/A	N/A

One of the most critical parameters used to define the efficiency of thermoelectric materials is the Figure of Merit (ZT). It is expressed by the equation (Shittu *et al.*, 2020):

$$ZT = \frac{(\alpha^2 \cdot \sigma \cdot T)}{k} \quad (3)$$

Here, σ is the electrical conductivity, and T is the absolute temperature (K). A higher ZT value indicates that the thermoelectric material is more efficient.

The temperature difference (ΔT) between the cold and hot surfaces directly affects the maximum capacity of the system. This difference usually occurs in the range of 30–70°C. However, increasing ΔT can also cause an increase in Joule heat and thermal conductivity losses, leading to a decrease in the COP value (Sajid *et al.*, 2017).

The role of heat sink and fan systems is critical in maintaining the balance of the system by providing effective heat removal from the hot surface. An inadequate heat sink will cause the heat accumulated on the hot surface not to be removed, which will lead to a decrease in ΔT and a decrease in COP (Han *et al.*, 2008). Therefore, heat sinks with a large surface area, made of good conductive material and supported by an active fan, should be preferred. In addition, by using nanofluid-supported cooling blocks, more effective heat removal from the hot surface is provided, and performance values can be increased (Ahammed *et al.*, 2016).

Ambient temperature is the main environmental factor that determines the starting and operating limits of the system. At high ambient temperatures, the capacity of the hot surface to transfer heat to the external environment decreases, and it becomes difficult to reach the target temperature value on the cold surface. In this case, higher input power may be required, and the COP may decrease. In studies, it has been observed that the COP value decreases by up to 20% when the ambient temperature increases from 25 to 35°C (Kishore *et al.*, 2019).

Insulation quality is an important design element to minimize temperature losses, especially in low-volume and portable systems. Multi-layer insulation materials ensure that the internal environment remains constant and reduce the load on the cooling system. This allows the desired cooling to be achieved with less energy. In addition, in PCM-supported systems, heat energy can be stored to ensure that the temperature remains constant even in power outages (Zhao and Tan, 2014b).

Performance change and thermal stability over time are related to the reliability of the system in long-term use. As the number of thermal cycles increases, the internal structure of the TEC modules may deteriorate; solder joints, electrical resistance, and Seebeck coefficient may change. This causes the COP of the system to decrease over time and the temperature control to deteriorate. Therefore, periodic testing of the systems and monitoring of module life are critical.

Comparing data from studies reveals significant differences in COP values across similar application types. For example, while COP values in portable food coolers range from 0.4 to 0.75, this value can reach 0.54 to 0.9 in solar-assisted hybrid systems. In medical applications, nanofluid-assisted designs can reach COP values as high as 1.19. This demonstrates that improved heat transfer surfaces and additional cooling aids (PCM, nanofluid, hybrid PV) have a direct positive impact on COP. Furthermore, a common trend across studies is a significant decrease in COP with increasing ambient temperature; COP has been reported to decrease by 15–25% from 25 to 35°C. This demonstrates the critical importance of heat removal design in portable systems, particularly those used outdoors and in hot climates. In general, the comparisons reveal that system efficiency is shaped by the joint influence of module design, additional cooling technologies, and environmental conditions, and emphasise the need to develop optimisation strategies for future studies.

As a result, the performance characteristics of thermoelectric cooling systems are affected by many interconnected parameters. In order to achieve optimum cooling performance in these systems, current, voltage, module type, heat sink design, insulation level, and environmental conditions must be evaluated together. Thanks to developing material technologies and hybrid solutions (e.g., solar panels, PCM, nanofluid integration), the efficiency and usage area of these systems are expanding day by day. In today's world, where energy efficiency is at the forefront, thermoelectric cooling systems are candidates to be at the forefront of sustainable solutions.

Conclusion

In this study, the technical infrastructure, application examples, performance characteristics, and engineering challenges of TEC-based mini refrigerator systems are discussed in detail. Analyses made on different application scenarios in the literature have revealed that TEC technology is increasingly widespread in both individual and institutional use. The main advantages offered by TEC systems include silent operation, low failure risk due to not having moving parts, compact design, instant start-up capability, and gas-free operating principle. These features have become an important preference criterion, especially in medical and food applications, where ease of transportation and safety are at the forefront. However, technical limitations such as low COP values, limited capacity to create high temperature differences, and high dependence on environmental temperature indicate that this technology is still open to development for large-scale applications. The application examples examined in the study have shown that TEC systems provide successful results, especially in low-power and portable mini refrigerators with an internal volume of 4–30 L. The integration of these systems is becoming widespread in both individual use scenarios, such as camping and travel, and in critical health services, such as drug and vaccine transportation. At this point, the integration of PCMs, nanofluid coolers, solar panels, and microcontroller-supported temperature control systems into TEC technology provides significant increases in system performance. For example, the ability of PCM-supported systems to keep the internal temperature constant even when there is no energy input has increased the capacity to provide uninterrupted cooling during transportation. Similarly, nanotechnology-supported heat transfer solutions have visibly increased system efficiency, especially in hot environments. Solar energy-supported TEC applications are remarkable in terms of providing sustainable cooling solutions, especially in regions where the electrical infrastructure is limited. Studies have shown that TEC systems fed by PV panels significantly reduce energy consumption and increase the success of maintaining a constant temperature. These systems can play a critical role in a variety of humanitarian scenarios, including emergency health responses, food preservation in rural areas, and medicine delivery in disaster areas. In addition, the integration of innovative designs such as dual-axis solar tracking systems has made these systems even more efficient, providing increases in COP values of up to 75%. However, some basic engineering elements need to be carefully considered to increase the efficiency of TEC systems. Proper heat sink design, strong insulation materials, optimum current-voltage balance, module layout, and system adaptability according to the external temperature are the factors that directly affect the performance. In addition, the long-term thermal stability of the system, module life, and maintenance requirements are also important in terms of system reliability. Future studies should focus on the development of new thermoelectric materials with high ZT values, multi-layer module designs, and integrated energy management systems. In addition, the development of systems equipped with intelligent control algorithms and operating adaptively according to user behaviour can open new horizons in terms of both energy efficiency and user satisfaction. TEC technology is expected to play a greater role in advanced applications such as zero-energy buildings, wearable cooling systems, and personal air conditioning technologies.

The following areas are considered priority areas for future research:

- Advanced Thermoelectric Materials: New semiconductor materials with high ZT values
- Multi-Stage and Hybrid Designs: Optimisation of multi-stage TEC modules and their integration with PCM, nanofluid, and PV-assisted hybrid systems to improve thermal performance
- Thermal Management Improvements: Innovative heat exchangers, cooling surface designs, and active/passive cooling techniques to increase heat removal efficiency from hot surfaces
- Smart Control and Energy Management: Implementation of microcontroller and AI-based algorithms to provide real-time data monitoring, load forecasting, and energy optimisation
- Cost and Production Optimisation: Investigating low-cost production processes to increase the industrial-scale applicability of advanced technologies
- Research focusing on these areas will significantly increase the energy efficiency, performance stability, and global adoption potential of TEC-based mini-refrigerators

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Authors Contributions

Erdem Cuce: Led the foundational and drafting aspects of the study.

Pinar Mert Cuce: Provided critical oversight, supervision, and specialized analytical expertise.

Tamer Guclu: Contributed significantly to the research design and execution of experiments.

Emre Alvur: Participated actively in the data collection, execution of the methodology, and manuscript refinement.

Harun Sen: Instrumental in carrying out the investigation, developing the methodology, and reviewing the final manuscript.

Ethics

This study is a compilation based solely on the existing literature and does not include any experimental studies on human or animal subjects. Therefore, ethics committee approval is not required.

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