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Review

A comprehensive review of portable cold storage: Technologies, applications, and future trends

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ABSTRACT

In recent years, there has been a substantial increase in the usage of portable cold storage technologies, as the demand for flexible and mobile solutions for storing perishable goods has expanded. The advantages of portable cold storage units include energy efficiency, portability, and use. This analysis examines portable cold storage technologies, their uses, and future prospects. We also examine the use of phase change materials (PCMs) in conjunction with portable cold storage units for the storage of perishable food items such as fruits and vegetables. Beginning with an introduction to the various types of portable cold storage units, including refrigerated shipping containers, portable refrigerators, and cold rooms, the study continues with a discussion of the advantages and disadvantages of each. The various methods employed in portable cold storage units, such as compression refrigeration, absorption refrigeration, and thermoelectric cooling, are then discussed. The analysis also addresses the uses of portable cold storage units, including those in the food & beverage, pharmaceutical, and medical industries. The usage of PCMs in conjunction with portable cold storage units is then described, along with the various types and qualities of PCMs. The report continues with a consideration of future prospects in portable cold storage technologies, such as using renewable energy sources, intelligent sensors, and the Internet of Things.

1. Introduction

By 2050, the global population is expected to surmount 10 billion, necessitating a 70% surge in food production [1,2]. However, as food production increases, it is also crucial to reduce food loss and waste [3]. Sadly, more than 820 million individuals worldwide are malnourished [4]. The United Nations established the "Sustainable Development Goals" (SDGs) for 2030 in September 2015, consisting of seventeen goals [5]. The "Zero Hunger" campaign ranks second among these aims. The Food and Agriculture Organization (FAO) [6,7] estimates that roughly one-third of all food produced annually, or approximately 1.3 billion tons, is lost or wasted. Approximately 630 million tons are lost, and 670 million tons are wasted [8] of the total quantity. However, it is essential to observe that the figures vary significantly by country's economic status. Due to their perishability and shortage of adequate post-production infrastructure [9–11], fruits and vegetables are the most susceptible to post-harvest losses. Approximately one-third of the world's harvested food production is lost [12]. It is estimated that 16–52% of the total produce in "sub-Saharan Africa" (SSA) is lost throughout the value chain [13,14]. Up to fifty percent of the fruits and vegetables produced annually in Tanzania are lost due to inadequate post-harvest management, storage, and processing [15].

India has a significant position in the global production of fruits and vegetables, ranking second with an annual yield of 313 million tonnes [16] of horticultural crops. Refrigerated storage facilities have been

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Nomenclature

Q	Thermal Energy in joules
C_p	Specific heat capacity
T_i	Initial temperature in K
T_f	Final temperature in K
H	Latent heat of fusion

identified as one of the most effective means of addressing post-harvest losses, accounting for up to forty percent of the nation's agricultural output [17]. There are currently 6227 cold storage facilities in India with a storage capacity of up to 30 million tonnes. These facilities store horticultural/agricultural products, processed foods, animal husbandry products, and pharmaceuticals. Uttar Pradesh has the greatest cold chain storage capacity, followed by states such as Gujarat and Maharashtra [16]. However, the current capacity needs to be increased to satisfy the rising demand for cold storage facilities in the country; 50 million tonnes are estimated to be required by 2022. Regardless of the production capacity, India has a lower per capita availability of these foods than is required. Moreover, India's produce is lost due to inefficient storage, handling, and transportation practices. Cold storage facilities have played a crucial role in connecting farmers with final consumers and combating malnutrition in India and throughout the globe. Despite 96% of cold storage facilities being privately owned [17, 18], their expansion has been hampered by government restrictions and other supply chain obstacles.

Ensuring the integrity of the cold chain is crucial in safeguarding the safety and longevity of perishable goods across the entirety of the supply chain, spanning from the initial harvesting phase to the eventual consumption by end-consumers. The demand for energy required for space cooling has increased by over three times since 1990, as per reference [19]. The consumption of electricity is significantly influenced by space conditioning, particularly in industrialized and tropical nations. The proportion of total electricity consumption attributed to space conditioning varies across different regions. In the United States (2019), it constitutes approximately 10%, while in the European Union (2017), it accounts for 5%. In Singapore (2013), however, the figure is notably higher, at 30%. These statistics are supported by sources [20], [21], and [22], respectively. In addition, the escalating need for space cooling on a global scale is anticipated to be the main driving force behind the growth of worldwide electricity demand in buildings. This demand is projected to surge from 10% in 2018 to 37% in 2050, as per recent estimates [23].

The Scopus database was utilized to assess bibliometric data for this investigation. The aforementioned database is a comprehensive repository of peer-reviewed literature, encompassing scientific journals, literary works, and conference proceedings. Scopus is a highly useful instrument for monitoring, evaluating, and graphically representing scholarly work, given its extensive coverage of various fields and capacity to offer a worldwide perspective on research productivity. The data was obtained in Microsoft Excel format, comprising of publication title, author name, keywords, publication year, source, country, citation, and other relevant information. The investigation was carried out by utilizing pertinent keywords, as enumerated in Table 1, which yielded an initial outcome of 32108 findings. Upon applying keyword filters for "cold storage" and "PCM," the search yielded a total of 307 publications, with a solitary publication pertaining to Smart Cold Storage. The categories of sources, CiteScore and CiteScore Rank, were extracted from the Scopus website, whereas the impact factors were acquired from the homepage of the corresponding source journals. The utilization of Scopus as a research tool enables us to guarantee the comprehensiveness of our analysis, as it encompasses pertinent research from various regions across the globe.

Table 1
Significant keywords (source: https://www.scopus.com/ (Accessed on 18 February 2023)).

	QUERY	Search Results	Number of Review Papers
Query 1	TITLE-ABS-KEY (Cold storage)	32108	1319
Query 2	TITLE-ABS-KEY ("Cold Storage" AND "PCM")	307	13
Query 3	TITLE-ABS-KEY ("Cold Storage" AND "Food Products")	326	14
Query 4	TITLE-ABS-KEY (Onion storage)	1371	50
Query 5	TITLE-ABS-KEY ("Smart Cold Storage")	344	18
Query 6	TITLE-ABS-KEY (solar AND cold AND storage)	1879	68
Query 7	TITLE-ABS-KEY ("cold storage" AND "food storage")	1577	33
Query 8	TITLE-ABS-KEY ("cold storage" AND "food preservation")	451	21
Query 9	TITLE-ABS-KEY (Portable AND Cold AND Storage)	201	4
Query 10	TITLE-ABS-KEY ("cold storage" AND "food storage" AND "PCM")	15	1
Query 11	TITLE-ABS-KEY ("cold storage" AND "PCM" AND "food preservation")	5	2
Query 12	TITLE-ABS-KEY ("cold storage" AND "food logistics" AND "PCM")	1	0

Cold storage solutions for food preservation have traditionally been implemented through large, stationary facilities that require permanent infrastructure. However, with the rise in demand for flexible and mobile storage solutions, portable cold storage and phase change materials (PCMs) have become increasingly popular. Research on these technologies has been relatively limited in the literature, but they offer great potential for a range of applications. Portable cold storage solutions are particularly advantageous for smaller-scale operations or in situations where mobility is required. In the Indian climate, where ambient temperatures can often reach high levels, the need for portable and efficient cold storage solutions becomes even more pressing.

The sizes of portable cold storage solutions utilized in previous research differ depending on the application. Gin et al. (2010) [24] utilized a vertical freezer with a storage volume of 153 L, whereas Nie et al. (2021) [25] utilized a cold chain portable box with external dimensions of "460 (length) × 300 (width) × 340 (height) mm" and internal dimensions of "350 × 220 × 250 mm". The portable box's capacity and weight were 17 liters and 3.2 kg, respectively. In the study conducted by Ray et al. (2021) [26], a cuboidal box was constructed with external dimensions "394 mm × 290 mm × 350 mm", while its internal dimensions were "324 mm × 220 mm × 270 mm". The total volume of PCM utilized was 6.4 liters. The box's dimensions were chosen so that it could be transported by hand or on a two-wheeled vehicle. A similar cylindrical box with an outer diameter of "371.1 mm" and an interior diameter of "285.8 mm" was also created. The volume of PCM and insulation utilized was identical to the volume of the cube box. In the study by Burgess et al. (2022) [27], a Polar Thermal insulative container was used, with water distributed evenly into 12 small Esky ice chiller bricks as the reference PCM. Ten thermowell-equipped refrigeration test M-Packs were acquired in order to house temperature sensors in various locations within the container. Polyester sponges were used to produce filler packages to fill the remainder of the container. Du et al. (2020) [28] created a portable box. Internal surfaces of the box were in intimate contact with PCM plates/modules, whose walls were composed of insulating materials.

This review paper will provide a comprehensive overview of portable cold storage technologies, including the different types of units and cooling technologies used and the application of PCMs in combination with portable cold storage for food preservation. We will also address the research gaps in the literature, including the need for further research on the effectiveness of portable cold storage in preserving fruits and vegetables, the economic feasibility of using PCMs in combination with portable cold storage, and the lack of studies on the use of PCMs in combination with portable cold storage for food preservation. Addressing these research gaps can lead to the development of more effective and cost-efficient methods for food preservation, which can benefit the food industry and consumers alike.

2. Cold thermal energy storage

The utilization of cold thermal energy storage is a viable and efficient approach to improve the energy efficacy, operational adaptability, and overall resilience of refrigeration procedures [29]. Since refrigeration is a highly energy-intensive technology, there is a significant need for the provision of thermal comfort and environmental control. As per statistical data, refrigeration constitutes over 15% of the overall energy consumption in China [30]. The Cold Thermal Energy Storage process involves the injection of cold thermal energy into a medium, which can be retrieved as required. Throughout the process of charging, storing the existing thermal energy at low temperatures within the storage medium is possible. Upon necessity, the low-temperature thermal energy that has been accumulated is extracted and distributed to the ultimate consumer. The storage of frigid thermal energy can occur through either a modification in the internal energy of the storage medium or a transformation in its phase. The aforementioned technology has been developed with the purpose of energy conservation through the accumulation of cold during periods of low demand [31,32], as well as for seasonal storage purposes [33].

The storage of thermal energy at low temperatures is frequently accomplished by employing both sensible and latent storage techniques. The determination of appropriate storage capacity is reliant on the disparity in temperature and specific heat capacity. However, latent heat energy storage has gained significant attention owing to its superior energy storage density [34,35]. The phenomenon of phase transition takes place in the course of the storage and retrieval of energy, wherein the utilization of phase change materials (PCMs) serves to augment the energy storage capability of the system [36,37]. The latent heat of fusion is the determining factor for the amount of energy contained within a substance. Expressions for the quantity of energy contained within a sensible and latent heat storage system are provided by Eqs. (1) and (2), respectively.

Eq. 1 denotes the amount of energy present in a sensible heat storage system. In the given equation, Q represents the quantity of thermal energy measured in Joules, while m denotes the mass of the substance in kilograms. Additionally, c_p is the specific heat capacity of the material measured in J/(kg K), Ti represents the initial temperature in Kelvin, and T_f represents the final temperature in Kelvin. The definite integral evaluates the amount of thermal energy necessary to increase the temperature of the substance from an initial temperature T_i to a final temperature T_f.

Eq. 2 denotes the amount of energy present in a storage system for both latent and sensible heat. In this context, the symbol Q represents the quantity of thermal energy measured in Joules. The variable m pertains to the mass of the substance measured in kilograms, while c_p denotes the specific heat capacity of the material measured in J/(kg K). T_i and T_f represent the initial and final temperatures, respectively, both measured in Kelvin. Tm stands for the melting temperature of the phase change material (PCM), while a_m represents the mass fraction of the PCM. The initial integral computes the amount of sensible heat energy necessary to increase the temperature of the substance from T_i to T_f. The second term denotes the latent heat of fusion (H) that is essential for the phase change of the PCM. Lastly, the third integral determines the quantity of sensible heat energy required to raise the temperature of the melted PCM from T_m to T_f. The amount of energy present in a storage system of latent and sensible heat. In the given equation, the symbol Q represents the quantity of thermal energy measured in Joules, while the variable m denotes the mass of the substance in kilograms. The symbol c_p pertains to the specific heat capacity of the material, measured in J/(kg K). T_i and T_f represent the initial and final temperatures of the substance, respectively, both measured in Kelvin. Additionally, T_m denotes the melting temperature of the phase change material, while a_m represents the mass fraction of the PCM. The initial integral computes the amount of sensible heat energy necessary to increase the temperature of the substance from an initial temperature T_i to a final temperature T_f. The second term denotes the latent heat of fusion (H) that is necessary to transform the phase of the material from solid to liquid. Lastly, the third integral calculates the sensible heat energy required to elevate the temperature of the melted PCM from Tm to T_f.

$$Q = \int_{T_i}^{T_f} mc_p \Delta T \tag{1}$$

$$Q = \int_{T_i}^{T_f} mc_p \Delta T + \int_{T_m}^{T_f} [ma_m H + mc_p \Delta T] \tag{2}$$

The latent heat of fusion, denoted as H, represents the quantity of energy necessary to transform a unit of mass of a substance from a solid to a liquid state. Phase Change Materials (PCMs) are utilized in cold storage applications to facilitate energy storage and release during the transition between solid and liquid states. The latent heat of the fusion of various PCMs is a crucial factor to contemplate when selecting the suitable PCM for cold storage applications. The latent heat of fusion for water is 334 kJ/kg, whereas for paraffin wax, it is 214 kJ/kg. The aforementioned equations offer a fundamental comprehension of the energy storage mechanisms in cold storage systems that utilize both sensible and latent heat. The incorporation of the latent heat component in Eq. 2 signifies the supplementary energy necessitated for the alteration of phase of the PCM. This is a crucial aspect to contemplate while devising efficient cold storage mechanisms. The determination of H for various phase change materials (PCMs) offers valuable information regarding the quantity of energy that can be either stored or released during the phase transition of the PCM.

2.1. *Importance of cooling agricultural products*

Minimizing the losses incurred during the postharvest stage of fruits and vegetables is of utmost importance in enhancing worldwide food and nutrition security. The perishability of fruits and vegetables, which are agricultural commodities, is largely determined by factors such as crop water content, tissue softness, and metabolic activity, as noted in the source [38–41]. Freshly harvested crops possess a higher degree of field heat and vitality, rendering them more vulnerable to biological degradation caused by respiration, ethylene emission, mechanical harm,

Table 2
Shelf life of fresh fruits and vegetables and their relative perishability [46,47].

Vegetables	Fruits	Average Shelf Life (Weeks)	Perishability
Green Onion Sweet Corn Tomato Cauliflower	Blueberry Strawberry Cherry	< 2	Very High
Cabbage Eggplant Lettuce Potato Carrot Radish	Banana Guava Mango Papaya Apple Grapefruit Kiwifruit	2 – 8	Moderate
Dry Onion Garlic Lemon Potato Pumpkin		8 – 16	Low

water scarcity, physiological abnormalities, and pathological decay [31]. The process of deterioration results in the degradation of nutritional content, and changes in color, texture, and flavor. Efficient and accurate dissipation of field heat is imperative to maintain the freshness and quality of newly harvested produce [42,43]. As per Elansari's research findings [44], the postponement of precooling highly perishable produce by one hour can reduce its shelf life by one day. According to research findings [44], exposure to high temperatures, even for a short duration of one hour, can result in a reduction of the product's shelf life by one day. Table 3 [45] demonstrates that a rise in temperature by 10°C can potentially result in a doubling or tripling of food spoilage, whereas a decrease in storage temperatures by 10°C can potentially double the shelf life of horticultural commodities.

The preservation of fresh produce quality in refrigerated storage is contingent upon the maintenance of an optimal temperature range. Variations beyond this range may result in degradation caused by freezing or chilling damage, as indicated by previous studies [49,50]. Due to the high water content present in the tissues of fresh crops, their freezing point is relatively elevated, ranging from "-3°C to −0.5°C". As a result, the process of freezing can cause tissue collapse and a decline in cellular integrity. In contrast, it is noteworthy that chilling injury transpires when the temperature surpasses the freezing point yet remains below a specific temperature threshold, commonly referred to as the chilling threshold temperature or the lowest safe temperature, as depicted in Table 4. Chilling injury symptoms encompass surface and internal discoloration, water uptake, the emergence of undesirable flavors, irregular maturation, and heightened vulnerability to pathogens, as cited in reference [49].

In addition to the details of various fruits and vegetables stored at their lowest safe temperature in cold storage, it is essential to consider the cooling technologies used to maintain those temperatures and their limitations. Researchers have explored a range of cooling technologies, such as forced-air cooling, hydro cooling, vacuum cooling, and more. Forced-air cooling is widely used for cooling fruits and vegetables due to its simplicity and effectiveness, while vacuum cooling is suitable for heat-sensitive products. Despite their advantages, these cooling technologies also have some limitations. For example, forced-air cooling can lead to water loss in some fruits, while hydrocooling requires a large amount of water. In Table 4 below, we have classified chilling-sensitive food products based on their lowest safe temperatures for storage. It provides an overview of the critical storage temperatures for various food products, which can be helpful for designing appropriate cooling technologies.

2.2. *Types of energy storage system used in cold energy storage*

"Thermal Energy Storage (TES)" is utilized in cold energy storage to temporarily store heat or frigid energy. This stored energy can be employed for various applications, including but not limited to building heating and cooling, industrial processes, and electricity generation. In the context of cold energy storage, two primary forms of storage systems are utilized, specifically sensible and latent heat storage. The process of sensible heat storage pertains to the retention of thermal energy through the elevation of material temperature. The accumulated energy can subsequently be retrieved by releasing the heat as the material undergoes cooling. Conversely, latent heat storage pertains to retaining thermal energy within a material through a phase transition, such as converting from a solid to a liquid or from a liquid to a gas. The potential energy that has been accumulated can be retrieved through the reversal of the phase transition mechanism. These storage systems are viable options for deployment in diverse contexts, encompassing residential, commercial, and industrial domains, contingent upon particular requirements such as temperature span, energy intensity, and financial feasibility. The categorization of thermal energy storage can be observed in Fig. 1.

Table 3
Details of shelf lives of fresh fruits and vegetables at different temperature conditions [48].

Food Products	Optimal Temperature (Max. Shelf Life)	Shelf Life at		
		35°C	25°C	15°C
Spinach	0°C – (14 days)	1 day	2 days	5 days
Cabbage	0°C – (6 months)	15 days	30 days	60 days
Tomato	15°C – (14 days)	3 days	6 days	14 days
Carrot	0°C – (6 months)	15 days	30 days	60 days
Pepper	12°C – (20 days)	3 days	7 days	15 days

Table 4
Classification of chilling-sensitive food products with respect to their lowest safe temperatures for storage [49].

Food Products	Lowest Safe Temperature (°C)
Cranberry, asparagus	3
Orange, durian, cowpeas, cactus pear, guava	5
Pepper, pomegranate, okra, pineapple, olive	7
Papaya, lime, cucumber, passion fruit, eggplant, watermelon, tomato (ripe), grapefruit, plantain, mango (ripe),	10

2.2.1. *Vapor-compression cooling system*

The vapor-compression cooling system has been widely utilized for the cooling of fruits and vegetables in cold storage rooms due to its ability to maintain an extensive range of temperature values and relative humidity levels between 80% and 90%, as mentioned in sources [50] and [51]. The system operates by utilizing phase changes in the refrigerant fluid, which undergoes multiple alterations in pressure to facilitate the cooling process. The refrigerant fluid, which can be either halogenated or natural, absorbs heat from its surrounding environment during evaporation under low-pressure conditions, generating a cooling effect. The gaseous refrigerant is then compressed and condensed, releasing the absorbed heat into the surrounding environment, and transitioning back to a liquid state. Despite its efficiency and flexibility, the Vapor-Compression Cooling System has certain limitations that make it unsuitable for portable cold storage applications of fruits and vegetables. One of the primary limitations is its dependency on electricity, making it unsuitable for areas with limited or unreliable power supply. Moreover, the initial investment cost for a vapour-compression cooling system is comparatively lower than other systems, but the operating and maintenance costs are subject to variation based on the type of cold room. The use of halogenated refrigerants, which are easily accessible and cost-effective, has posed a drawback to this methodology due to their lack of ecological sustainability [52]. In terms of cold storage specifications, the size and design of the cold room play a critical role in the system's effectiveness. The dimensions of the cold room should be carefully considered to ensure that the required amount of space is available for the storage of fruits and vegetables. Additionally, the room's insulation and ventilation must be considered to maintain the desired temperature and humidity levels [53,54]. However, the use of vapour-compression cooling systems in portable cold storage applications is limited due to the need for a constant supply of electricity and the high initial investment and operating costs.

2.2.2. *Sorption cooling system*

Sorption cooling systems function through the chemical and physical attraction between refrigerants and absorbents or adsorbents. Unlike vapor-compression cooling systems, sorption cooling systems are not reliant on mechanical components and work based on the principles of thermodynamics. Commonly employed working pairs in sorption

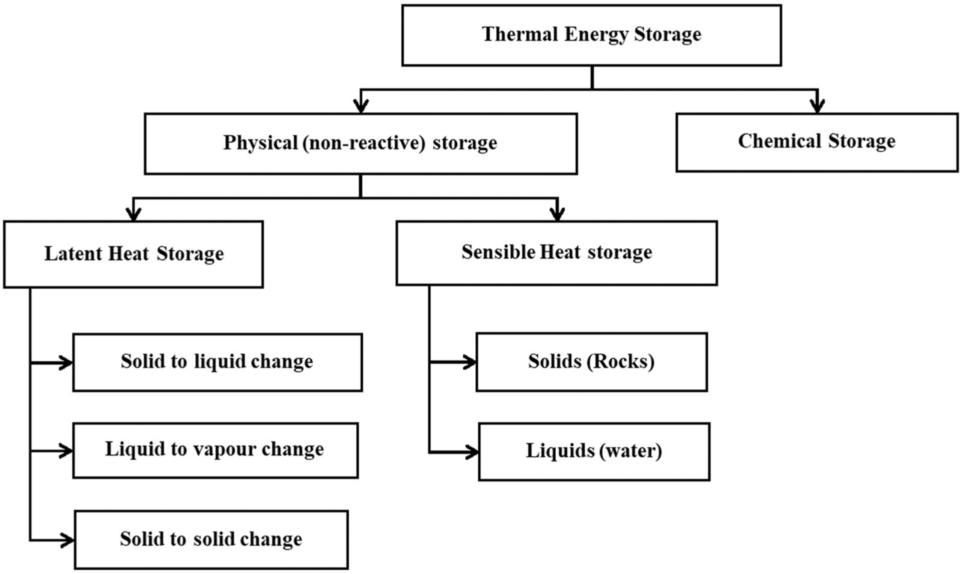

Fig. 1. Types of thermal energy storage.

cooling systems include ammonia-water and lithium bromide-water in absorption systems and "silica gel-water" and "zeolite-water" in adsorption systems. In sorption cooling systems, the refrigerant undergoes a process of exposure to low-pressure surroundings, generating a cooling effect while absorbing heat from the environment [52]. Afterwards, the absorbent or adsorbent takes the refrigerant to its gaseous state. The decrease in pressure within the evaporator leads to a rise in the amount of refrigerant that undergoes evaporation. Subsequently, thermal energy facilitates the evaporation process of the refrigerant from the absorbent, leading to the restoration of the initial conditions. The sorption refrigeration method is well-suited for the cold storage of fruits and vegetables since it is capable of sustaining a diverse spectrum of temperatures and low to moderate levels of relative humidity [54,55]. It is a viable option for preserving delicate and high-value agricultural commodities. Sorption-based cooling systems entail a larger initial capital investment but considerably lower operational expenses. Sorption cooling systems' limitations include their lower coefficient of performance (COP) compared to vapour-compression systems, as reported in the reference [50]. In addition, sorption cooling systems have a slower cooling rate and require a longer time to reach the desired temperature. This limitation makes sorption cooling systems less favourable for portable cold storage applications of fruits and vegetables, where a quick cooling rate is essential to preserve the products' quality [56]. The larger size and weight of sorption cooling systems further limit their portability.

2.2.3. Evaporative cooling system

Evaporative cooling systems have been found to be a feasible alternative to traditional refrigeration methods for the cold storage of fruits and vegetables [53]. The process of water evaporation is utilized to generate a cooling effect, which is particularly effective for tropical and sub-tropical crops that do not require chilling [51]. The system involves the application of water onto a permeable surface, such as sand or charcoal, which is then cooled by the process of evaporation. According to reference [44], this method is reliant solely on ambient heat and does not necessitate any supplementary energy input. The implementation of fan-assisted air flow systems has the potential to expedite the cooling process, as opposed to exclusively depending on natural airflow. The design of an evaporative cooling system for cold storage depends on several factors, including the size of the storage area, the desired temperature and humidity levels, and the prevailing weather conditions [57]. The system can be constructed using locally available materials, such as bricks, charcoal, and sand, resulting in a relatively low cost due to their low energy input and use of water as a coolant [44,51]. However, it should be noted that the effectiveness of evaporative cooling is heavily dependent on regional weather patterns, as the temperature regulation of this approach is restricted by the availability of ambient heat [58]. Therefore, this approach is best suited for tropical and sub-tropical crops that do not require chilling [38]. One of the major limitations of evaporative cooling systems for cold storage is the requirement for a consistent supply of sanitized and softened water. In addition, appropriate water pumping and storage facilities are essential for the operation of the system. Moreover, the system is unsuitable for portable cold storage applications of fruits and vegetables, as it relies on a continuous water supply and is not easily transportable [50].

2.2.4. Technoeconomic performance of different cold storage solutions for food preservation

When evaluating the technoeconomic performance of different cold storage options and their appropriateness for diverse food preservation needs, it is important to take into account many crucial criteria. Compression refrigeration is a cost-effective and efficient method that is ideal for a variety of food products that need precise temperature control. Contrarily, absorption refrigeration relies on the heat source and can be economically advantageous when sustainable or waste heat sources are present, rendering it appropriate for situations with reliable access to such resources. Thermoelectric cooling exhibits lower energy efficiency and cost-effectiveness compared to other cooling methods. However, it provides the advantage of portability, making it well-suited for temporary or portable applications. Phase Change Materials (PCMs) have greater upfront expenses but provide long-term cost benefits by decreasing energy usage, rendering them appropriate for situations that require energy efficiency and accurate temperature regulation. The technoeconomic performance of solar-powered solutions is contingent upon the geographical location and the availability of sunlight. In contrast, hybrid systems have the capability to enhance energy efficiency. Utilizing advanced insulating materials improves energy efficiency and is applicable for enhancing the cost-effectiveness of all cold storage solutions. In the end, the decision should be in accordance with unique preservation needs, financial limitations, and the availability of energy sources. The techno-economic performance of different cold storage solutions for food preservation with their suitability is shown in Fig. 2, given below.

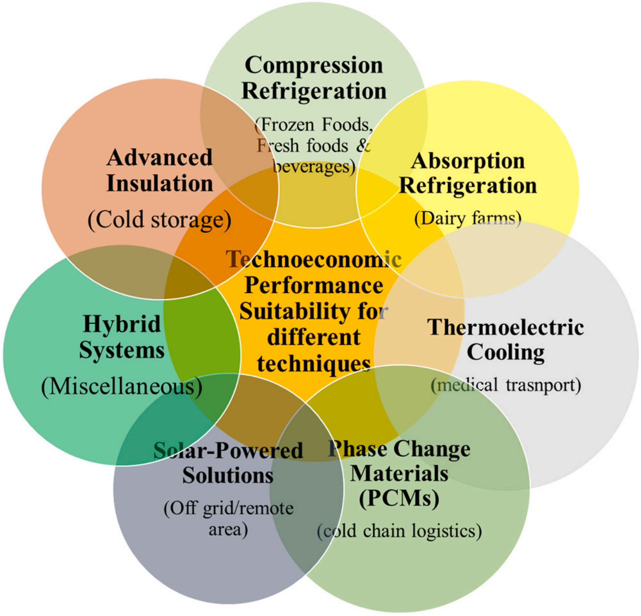

Fig. 2. Technoeconomic Performance of different cold storage solutions for food preservation.

2.2.5. *Techniques used for maintaining different temperature zones in portable cold storage*

It is crucial to establish distinct temperature zones within portable cold storage units in order to accommodate a wide range of temperature-sensitive commodities. This requires meticulous segregation, insulation, and regulation mechanisms to avoid mixing temperatures. Through the use of dual-temperature refrigeration, airflow management, temperature monitoring, and sealing mechanisms, each zone is guaranteed to retain its specified temperature range. The adaptable and energy-efficient design improves the capacity to store and handle commodities with different temperature needs, enhancing stored products' quality and safety. Successfully attaining and overseeing these zones is an intricate endeavour that necessitates meticulousness and strategic preparation to fulfil a wide range of storage requirements efficiently. (Fig.3)

2.3. *Use of phase change materials in cold energy storage*

The application of phase-change materials (PCMs) in cold energy storage has demonstrated potential in safeguarding perishable goods during transit. The authors Wang et al. (2019) [59] devised a model for refrigeration systems that integrated phase change materials (PCMs) to augment refrigeration efficiency and uphold product temperature while in transit. The study's results indicate that the utilization of phase change materials (PCMs) to decrease the temperature of sub-cooled refrigerant may lead to energy savings of up to 8% in the United Kingdom. The integration of a heat exchanger utilizing phase change materials (PCMs) as a pre-condenser within the refrigeration system has the potential to enhance the system's coefficient of performance (COP) by 6%. Oro et al. (2018) [60] conducted an experimental study utilizing phase change materials (PCM) to enhance the thermal comfort of an automobile cabin. The investigation conducted by the researchers revealed that the implementation of Phase Change Material (PCM) at a proportion of 0.22% of the internal volume resulted in a reduction of 5–10°C in the temperature of the steering wheel surface following a period of 2 hours of immobile parking. This outcome led to a decrease in both air and steering wheel surface temperatures, ultimately contributing to an improvement in passenger thermal comfort.

The TES device developed by Bourne et al. [61] utilizes cylindrical cylinders filled with phase change material (PCM) to transfer peak cooling loads to off-peak hours or periods when intermittent renewable energy sources are accessible. The authors illustrated through a two-dimensional model that the aforementioned energy storage unit has the capability to accurately anticipate its performance. Tay et al. (2019) [62] developed and fine-tuned a thermal energy storage (TES) system with a tube-in-tank configuration for the purpose of cooling. The effectiveness-NTU model was utilized in the optimization process. The placement of the PCM within the tank was accompanied by the circulation of water through copper tubes functioning as the heat transfer medium.(Fig. 4)

The study conducted by Gin et al. [24] examined the impact of door openings, defrosting cycles, and power loss on a vertical freezer. The investigators introduced 2.2 kg of phase change material (PCM), namely aqueous ammonium chloride at a temperature of −15.7°C, onto the aluminium plates affixed to the inner walls of the freezer. In a controlled environment, the research discovered that there was no discernible variance in energy usage between instances that incorporated phase

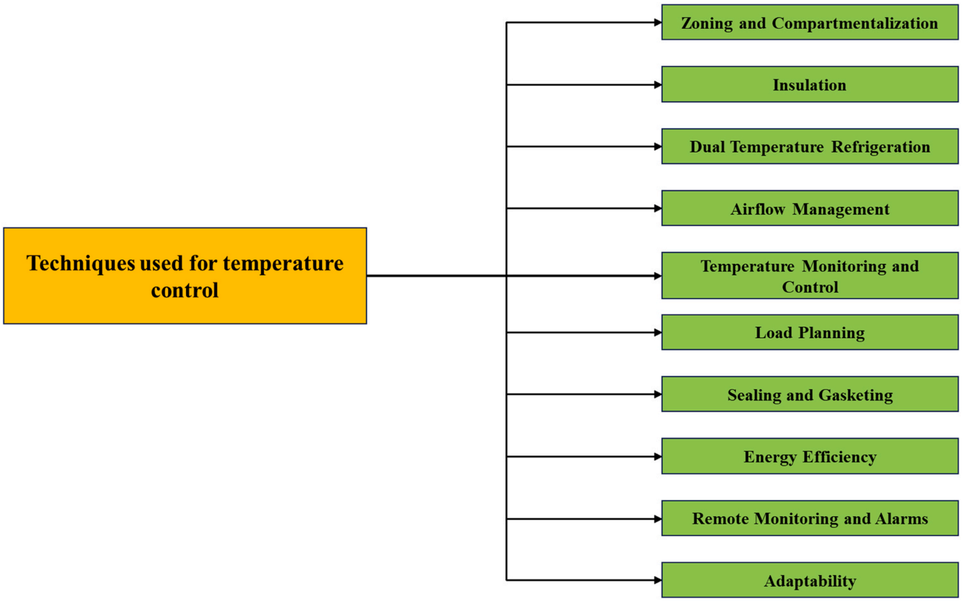

Fig. 3. Techniques used for maintaining different temperature zones in portable cold storage.

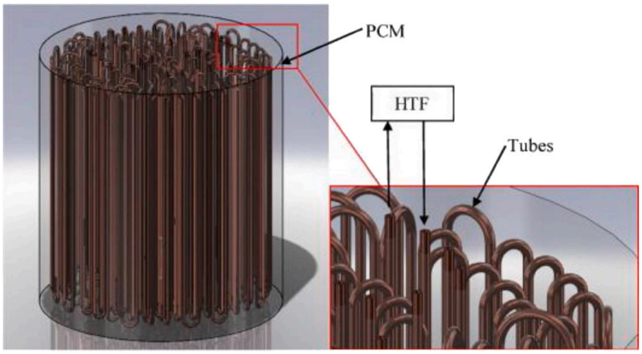

Fig. 4. Tube-in-tank PCM energy storage unit [62].

change materials (PCM) and those that did not. The employment of PCM solution resulted in a decrease of approximately 7–8% in the overall energy consumption during the process of door openings. The investigation showcased the superiority of the newly created LTES in the event of a power disruption. The novel freezer was able to sustain its operational state for 11 hours before reaching the maximum permissible temperature of −3°C, while the traditional freezer model could only operate for 4.4 hours before hitting the threshold. The study's findings suggest that using Phase Change Materials (PCM) in portable cold storage can significantly enhance its effectiveness, particularly in heat loads such as door openings and power outages. This results in extended operating times in comparison to traditional designs. To provide a comprehensive understanding of the PCM materials used in these studies and their properties have included a table below. The table includes the name of the PCM material, its properties such as temperature and latent heat, as well as the authors and year of the respective studies. This information will aid in identifying the most suitable PCM material for specific cold chain applications. (Table 5)

Table 5
PCM materials used in previous studies and their properties.

PCM Material	Properties of PCM Materials		Author	Year
	Temperature	Latent Heat		
Rubitherm RT5 (Technical grade paraffin wax)	7°C	158.3 kJ/kg	B He, F Setterwall [32]	2002
Organic paraffin-based PCM (RT 5), fumed silica, graphene	Pure PCM = 6.46°C, Composite PCM = 6.49°C	Pure PCM =143.74 kJ/kg, Composite PCM = 131.86 kJ/kg	Nie et al. [25]	2021
Eutectics	21°C	220 kJ/kg	Wang et al. [59]	2007
Rubitherm RT-27	25–28 °C	184 kJ/kg	Oro et al. [60]	2005
Tetradecane PCM	5–6°C	180 kJ/kg	S Bourne, A Novoselac [61]	2015
PCM17 (liquid)	17°C	160 kJ/kg	Tay et al. [62]	2012
RT28	-1.8 °C	192 kJ/kg	Gin et al. [24]	2010
Salt hydrate PCM	10°C	200 J/g	Liu et al. [63]	2017
S24 (make: PLUSS™)	23–32 °C	199 kJ/kg	Garg et al. [64]	2018
RT20 paraffin	20–22°C		C Arkar, S Medved [65]	2007
Energain® PCM	25°C	150 kJ/kg	Glouannec et al. [66]	2014
SP-50	223 K (-50.15°C)	190 kJ/kg	Ray et al. [26]	2021
RT28 (Paraffin wax)	28°C	181.1 kJ/kg	Fioretti et al. [67]	2016
Rubitherm RT5	4.96°C	180 kJ/kg	Tong et al. [68]	2021
PCM A	−10	244 kJ/kg	Kozak et al. [69]	2017
Water, Tetradecane, Docosane	0°C, 5.8°C, 10.8°C	334 kJ kg^{-1}, 180 kJ kg^{-1}, 235 kJ kg^{-1}	Burgess et al. [27]	2022
Sodium Polyacrylate, MWCNTs, Water	-0.037°C	335.4 J/g	Xu et al. [70]	2018
PCMs	2°C, 3°C, 4°C, 5°C, 8°C	170, 160, 145, 220, 160	Du et al. [28]	2020

2.3.1. *Experimental studies on portable cold storage*

This section of the review pertains to recent experimental studies conducted on portable cold storage systems. A study was conducted by Liu et al. [63] to evaluate the efficacy of an air-cooled household refrigerator that utilizes cold phase change materials (PCMs). The phase change materials (PCMs) exhibited melting points of 0.41°C and −18.98°C in the cold and freezing chambers, respectively. The research investigated different control modes and found that the employment of PCMs resulted in a reduction of 18.6% in energy consumption compared to the reference case. Additionally, the use of PCMs led to a decrease in the compressor on-time ratio by 13.6%. Furthermore, the research demonstrated that the created prototype for long-term energy storage (LTES) had a beneficial effect on the quality of food. The integration of cold phase change materials (PCMs) into domestic refrigeration systems holds promise for substantial reduction in energy usage and improvement in food preservation.

The thermal performance of TES devices using encapsulated Phase Change Materials (PCMs) for building thermal management was investigated by Garg et al. [60]. The study employed HDPE containers that were fitted with circulating copper tubes. The containers were filled with an inorganic chemical compound with a phase transition temperature range of 23–32°C and water. The findings indicate that the utilization of the TES apparatus, which features PCM encapsulation, resulted in a 50% decrease in the heat gain of the experimental chamber. Additionally, the mean air temperature was reduced by more than six degrees Celsius, and a consistent maximum temperature was sustained for a prolonged duration. According to the study, the TES device based on PCM demonstrated the potential to manage building thermal conditions effectively by reducing variations in the average air temperature. Arkar et al. (58) proposed the utilization of a TES system in conjunction with free cooling as a means of enhancing the performance of a mechanical ventilation system. The researchers found that using PCM for free cooling was viable for attaining the targeted thermal comfort level. Hubbard for Dakin has successfully implemented the commercial application of TES utilizing PCM in cold chain transportation. The refrigeration vehicles were equipped with eutectic plates that facilitated the charging of phase change materials (PCMs) during their stationary periods. The PCM unit and cargo compartment were interconnected with a fan regulated by a thermostat, thereby facilitating air circulation and coldness transfer from the PCM. The refrigeration vehicles have demonstrated efficacy in the transportation of deep-frozen and ice cream products, as they effectively sustain the necessary temperature during transit [71].

The heat transfer characteristics of an insulated PCM-based van panel were investigated by Glouannec et al. [66] through an experimental and computational study. The panel comprised multiple layers, including an outer layer, an air gap, a fibreglass layer, a polyurethane foam layer, and an inner layer. A comparison was made between the reference panel and panels featuring an aerogel and multi-foil layer, as well as a PCM layer. The aforementioned panels were utilized for the purpose of enclosing a diminutive compartment located within a climate chamber. The climate chamber in question was subject to active maintenance, whereby a refrigeration system was employed to maintain a constant temperature of 0°C. The heat flux densities of the panels were determined following a four-hour testing period conducted at temperatures of 10°C and 30°C. In comparison to the reference panel, the incorporation of an aerogel and multi-foil layer resulted in a reduction of energy consumption by 36%, whereas the PCM layer led to a decrease in energy consumption by 25%. The utilization of aerogel and multi-foil layer resulted in a 27% decrease in the thermal impact of solar radiation. The results of this study suggest that insulation panels utilizing phase change materials (PCMs) exhibit promise in enhancing the energy efficiency of mobile refrigeration units.

The cooling efficacy of portable cold storage cases that incorporate PCM for the transport of vaccines was examined by Ray et al. [26]. This research investigates the cooling efficacy and duration of a cuboid and cylindrical-shaped container with equivalent phase change material (PCM) and volume. Additionally, the study identifies the PCM (SP-50) that satisfies the prescribed temperature range of 55°C to 40°C. Following a 17-hour cooling period at an ambient temperature of 45°C, the cylindrical-shaped box experienced a decrease in interior temperature by 4.03 percent compared to the cuboid-shaped box. At an ambient temperature of 30°C, the cylindrical-shaped box exhibits a cooling performance of 8.7% greater than that of the cuboid-shaped box. Additionally, the cylindrical-shaped box has a duration of cooling that is 20.4% greater than that of the cuboid-shaped box. This research investigates the prevalence of convection and radiation heat transfer on various surfaces in two-box configurations. Additionally, the study analyzes the effect of the box's shape on cooling efficiency and duration. The principal objective of the investigation was to maintain the enclosure's internal temperature within the range of 218 K to 233 K (-55°C to 40°C), regardless of the surrounding temperature conditions.

In their experimental research, Fioretti et al. (2018) [67] investigated the heat transfer effectiveness of a thermal insulation layer that incorporated RT35HC in two distinct campaigns, namely indoor and outdoor. A prototype was developed for the purpose of indoor analysis, which consisted of a "3 cm PCM layer" that was encapsulated in "polyethylene capsules", along with a "10 cm PU-foam insulation layer". The research findings indicate a significant reduction of 59% in overall energy usage for the prototype wall utilizing PCM. The exterior surface temperature remained constant at 63°C, while the interior surface temperature was observed to be 1 or 2°C lower than the reference case. The 2014 outdoor campaign involved an assessment of a refrigerated space that was subjected to simulated summer conditions in Ancona through the application of PCM layers on its external surfaces. The results indicate that the PCM layer exhibited a noteworthy time lag in achieving the maximum heat flux, which led to a delay of 4.5 hours and 3.5 hours on the respective days. This delay positively impacted reducing energy/fuel consumption and subsequently contributed to mitigating greenhouse gas emissions. The study's authors noted a decrease in temperature of 5.5% and 8.57% in the PCM cold rooms compared to the reference cold rooms on the first and second days, respectively. The research validates that the utilization of PCM insulation layers can notably amplify the energy efficacy of mobile refrigeration units.

Tong et al. [68] examined the passive cooling efficacy of a rail-road container equipped with PCM for refrigerated transport. The container was connected to an external charging facility containing a refrigeration unit, heat transfer fluid (25 wt percent "Ethylene glycol aqueous solution") pump and storage tank. Insulated with "0.1 m of polyurethane foam", the container contained ten cold TES plates, each containing paraffin wax RT5 as PCM. Despite varying external conditions, the passively chilled container was able to maintain a temperature between "4°C and 12°C" for the entire "94.6-hour" journey. It was determined that the system was more efficient than conventional diesel-powered refrigeration systems, with an 86.7% reduction in energy consumption and up to a 78.5% reduction in emissions. The system maintained an optimal relative humidity range between 80 and 90 percent, which is appropriate for transporting fruits and vegetables. The reduction of latent air heat transfer by the passive system contributes to the optimal RH performance of the system.

An experimental and theoretical analysis of two distinct cold storage packages was conducted by Kozak et al. (2019) [69]. The smaller package comprised a cardboard box, high-density polystyrene insulation, and a double-walled plastic container that was filled with a green aqueous salt solution PCM. On the other hand, the larger package consisted of a cube-shaped cardboard box, high-density polystyrene insulation, and four arched bottles that contained a purple aqueous salt solution PCM. The experimental procedure entailed water transportation, and the phase change material (PCM) was subjected to a cooling process reaching a temperature of −70°C to guarantee the attainment of full solidification. The investigators formulated analytical models in one dimension and numerical models in one and two dimensions using the Ansys Fluent 13 software to ascertain the most favourable insulation thickness that could prolong the duration of melting. The duration of melting was influenced by the ratio of thermal conductivity between the phase change material and the insulating material. The 2D numerical simulation exhibited a high degree of accuracy in forecasting the experimental outcomes and can be used to scrutinise various substances, sizes, and operational circumstances. The findings of this research hold significance in the development of an ideal cold storage unit.

Burgess et al. (2022) [27] conducted research on the optimization of a phase-change material (PCM) storage system for a portable cold chain delivery system for perishable foodstuffs. They evaluated three configurations, first with PCM containers placed on the top and bottom, the second one with only along the sides, and evenly distributed in the third. Experiments were conducted using layout 1 with 2 kg of PCM bricks placed on the top and bottom of a $500 \times 300 \times 180\ \mathrm{mm}^3$ box, which maintained the contents below 5°C, serving as the performance indicator. The authors created a numerical model in Ansys Fluent and discovered that uniformly distributed PCM achieved the extended time, which was significantly longer than the reference case (without PCM), which maintained the required conditions for only 5.3 hours. The authors also discovered that layout 2 provided the greatest performance in terms of content temperature uniformity. In addition, the authors analyzed the effect of four PCMs with varying melting points and latent heat values and discovered that a higher latent heat value prolonged the time under the temperature threshold, while a lower melting point increased discharging efficiency but caused temperature inhomogeneity. The study demonstrates the significance of contemplating the content type when designing a cold storage box, especially for high-value perishable goods.

An experiment was conducted by Xu et al. [39] on a refrigerated storage box that is frequently used for transporting agricultural products such as fruits and vegetables. The objective of the research was to assess the efficacy of various PCMs in preserving a temperature range of −5°C to 8°C within a cold environment. The investigators utilized three distinct substances, namely water, water containing 1% sodium polyacrylate, and water containing 1% sodium polyacrylate and 0.1% multiwalled carbon nanotubes (MWCNTs), as phase change materials (PCMs). The experimental setup involved the placement of four cold plates made of polyethylene, each containing phase change materials (PCMs), in strategic locations along the internal walls of a vacuum-insulated box. The box had external and internal dimensions of "320 mm×275 mm x 280 mm" and "200 mm×200 mm x 200 mm", respectively. The study was carried out under controlled environmental conditions with an ambient temperature of "15°C ± 3°C". The investigation focused on the cooling capacity of the cold plates until the attainment of an internal temperature averaging 10 degrees Celsius. The impact of transported goods was examined through the utilization of yogurt as a specimen for experimentation. Under the condition of a frigid ambient temperature of 6°C, the yoghurt was able to maintain its desired temperature for a duration of around 56 hours using solely water. The study revealed that the utilization of PCM2 resulted in prolonging the constant temperature phase within the refrigeration box by roughly 9 hours while sustaining a temperature below 6°C for an extra 4.5 hours compared to PCM1. PCM3 was able to sustain a temperature of less than 6°C for a duration of 87 hours. The study has determined that commodities that are susceptible to temperature can be conveyed under appropriate circumstances by integrating a high-quality insulating substance with a phase change material (PCM) that exhibits improved thermal conductivity and superior heat transfer characteristics.

3. Numerical studies on portable cold storage

Numerical simulations have emerged as a crucial instrument for evaluating and enhancing the efficiency of portable refrigeration units in contemporary times. The simulations offer significant insights into the physical behaviour of said systems under varying circumstances. This section presents a compilation of recent numerical studies. A study was conducted by Ismail and Henriquez [71–73] to assess the efficacy of water-filled spherical capsules as phase change material (PCM) for the purpose of thermal energy storage. The capsules containing phase change material (PCM) were positioned within a cylindrical vessel equipped with a functional fluid circulation mechanism for the purpose of the investigation conducted by the researchers. A hybrid approach of numerical and experimental techniques was employed to forecast the impact of diverse parameters on the solidification process. The system's governing differential equations were solved by the researchers through the utilization of the finite difference method and a moving grid. The research bears noteworthy consequences for the progression of thermal energy storage methodologies, particularly in the domain of sustainable energy. The utilization of phase change materials (PCM) as a storage medium has the potential to achieve high efficiency in the storage and discharge of thermal energy. This approach can lead to a reduction in the dependence on fossil fuels and contribute to the mitigation of climate change. The outcomes of the research can provide valuable insights for enhancing the effectiveness of thermal energy storage systems that utilize PCMs. These systems can significantly contribute to promoting the extensive utilization of sustainable energy sources. Some more studies on numerical analysis of portable cold storage are tabulated in Table 6 given below,

Table 6
Summary of numerical studies related to portable cold storage.

Sr. No.	Numerical Technique used	Key Findings
Lin et al. [74].	Computational Fluid Dynamics (CFD)	Analyzed the efficiency and energy release process of cold storage plates in temperature-controlled containers, providing insights into their effectiveness in maintaining optimal conditions.
Ray et al. [75].	Heat Transfer Analysis	Explored the cooling performance of portable cold storage boxes using different phase change mediums, offering comparative results to identify the most efficient medium.
Kashyap et al. [76].	Magnetic Refrigeration Performance Analysis	Investigated the transient performance of a novel portable magnetic refrigeration system, highlighting its potential for improved cooling efficiency and portability.
Fu et al. [77].	Multi-Physics Simulation	Focused on the storage duration capabilities of a cold box using a multi-physical approach combining conduction, convection, and radiation aspects, leading to enhanced storage efficiency.
Bai [78].	Flow Field Optimization	Emphasized the significance of optimizing airflow within cold storage systems to improve temperature uniformity and reduce energy consumption.
Khattari et al. [79].	Latent Heat Storage Analysis	Analyzed a latent cold storage system for industrial applications in discharge mode, providing a framework for assessing and improving its efficiency in real-world scenarios.
Soedjono et al. [80].	Thermoelectric Model Analysis	Conducted a numerical study on a thermoelectric portable cold storage unit (TEC1–12706), offering insights into its performance and potential applications.
Mun [81].	Phase Change Material (PCM) Analysis	Investigated a cold storage system using an array of solid-liquid phase change modules, focusing on their effectiveness in maintaining desired temperatures over time.

4. Present challenges

Some of the main challenges in this field include:

- Temperature Control: One of the primary challenges is maintaining a consistent and controlled temperature within the portable storage unit. Fluctuations in temperature can lead to spoilage, degradation, or loss of the stored products. Achieving precise temperature control throughout the entire storage duration, especially in varying environmental conditions, is a significant challenge.
- Energy Efficiency: Portable cold storage units often rely on power sources such as batteries or generators. It is crucial to develop energy-efficient systems that minimize power consumption while still maintaining the required low temperatures. Balancing energy efficiency with the storage unit's cooling capacity is a key challenge in this field.
- Size and Weight: Portability is a critical aspect of these storage units. They need to be compact, lightweight, and easy to transport. Designing systems that are both portable and capable of maintaining low temperatures can be a challenge due to the need for insulation, cooling mechanisms, and power sources.
- Durability and Reliability: Portable cold storage units may be exposed to various environmental conditions, including temperature extremes, humidity, and vibrations during transportation. Ensuring the durability and reliability of these units is essential to prevent failures and maintain the integrity of the stored products.
- Monitoring and Data Logging: Effective monitoring and data logging systems are necessary to track temperature conditions during transportation and storage. Developing robust sensors and data logging technologies that can provide real-time monitoring, alerting, and data recording is a challenge in the field.
- Cost-effectiveness: Achieving cost-effective solutions for portable cold storage is important, particularly for applications in resource-limited settings or for small-scale operations. Balancing the costs of insulation, cooling systems, power sources, and other components can be a significant challenge.
- Regulatory Compliance: The storage and transportation of temperature-sensitive products are subject to various regulations and guidelines, such as those set by food safety agencies and pharmaceutical regulatory bodies. Adhering to these regulations and ensuring compliance can be complex, as portable cold storage units must meet specific standards for temperature control, hygiene, and product safety.
- Cold Chain Management: Portable cold storage is often part of a larger cold chain, which involves the transportation, storage, and distribution of temperature-sensitive products from the point of origin to the end consumer. Coordinating and managing the cold chain effectively to maintain product integrity and quality throughout the entire supply chain can be challenging, particularly when dealing with multiple stakeholders and varying environmental conditions.

- Remote Access and Control: In some scenarios, portable cold storage units may be located in remote or inaccessible areas. It is crucial to develop technologies that allow remote access and control over the storage units, enabling real-time monitoring, adjustment of temperature settings, and troubleshooting from a central location.
- Scalability: Portable cold storage solutions need to accommodate different storage capacities and product volumes. Designing scalable systems that can meet the diverse needs of various industries and applications, from small-scale operations to large-scale logistics, can be challenging due to the need for flexible cooling systems, insulation, and power sources.
- Sustainability: As with any field of research, sustainability is becoming increasingly important in portable cold storage. Developing environmentally friendly solutions that minimize energy consumption, reduce greenhouse gas emissions, and utilize sustainable materials is a significant challenge in this field.
- Technological Advancements: The field of portable cold storage is continuously evolving, driven by advancements in technology. Researchers are exploring new cooling technologies, such as thermoelectric cooling, phase change materials, and cryogenic systems, to improve the efficiency and effectiveness of portable cold storage units. Incorporating these technological advancements while addressing practical challenges can be complex.

5. Conclusion

The increasing demand for flexible and portable storage solutions has led to the development of various technologies and applications to cater to these requirements. One such technology that is rapidly evolving is portable cold storage. This paper presents a thorough examination of portable cold storage technologies, their various applications, and potential future developments.

- The discourse has encompassed the various classifications of transportable cold storage apparatuses, comprising refrigerated shipping containers, portable refrigerators, and cold rooms, alongside the cooling mechanisms employed in these devices, encompassing compression refrigeration, absorption refrigeration, and thermoelectric cooling. Furthermore, the utilization of phase change materials (PCMs) in tandem with portable refrigeration units has been deliberated as a means to prolong the longevity of perishable comestibles, such as fruits and vegetables. The utilization of Phase Change Materials (PCMs) in portable refrigeration units offers numerous benefits such as effective energy storage and discharge, decreased electricity consumption, and decreased carbon footprint.
- In addition, the incorporation of the Internet of Things (IoT) and intelligent sensors in portable cold storage units facilitates instantaneous monitoring of diverse parameters, including temperature and humidity, thereby affording improved regulation and management of the storage milieu.
- The forthcoming developments in portable cold storage technology involve the assimilation of sustainable energy sources, such as solar and wind power, to operate portable cold storage units. Additionally, the integration of IoT and other sophisticated technologies is anticipated to enhance the performance and functionality of these units.

In conclusion, the utilization of portable cold storage technology is anticipated to assume a progressively significant function in fulfilling the surging need for adaptable and mobile storage alternatives across diverse sectors, including but not limited to the food and beverage, pharmaceutical, and medical industries.

Conflict of Interest

We have no conflict of interest

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