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Review

Promising and Potential Applications of Phase Change Materials in the Cold Chain: A Systematic Review

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Abstract: Appropriate measures have been taken to reduce energy requirements for cold chain applications. Thermal energy storage is an accepted method to reduce the need for electrical energy after harvesting fresh horticultural produce. The use of phase change materials (PCM) in postharvest storage, outside of a temperature-controlled environment, extends shelf life and keeps food at the ideal temperature. This review focuses on the various trials using PCM to improve cold chain effectiveness. It also discusses the advantages and disadvantages of each type of storage using different PCM, as well as the likely and potentially promising applications of thermal energy storage in the cold chain.

Keywords: cold chain app; thermal energy storage; phase change materials; post-harvest storage

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1. Introduction

Unexpected temperature fluctuations or disruptions in the food cold chain can affect food safety and quality, leading to a loss of consumer confidence and an increase in food waste. Reportedly, about one-third of the world's food production is wasted each year [1,2]. Much of these losses are due to poor post-harvest handling, lack of proper facilities, and inadequate cold chain training of workers. Cold chain issues have been studied and reviewed over the past decade [3–5]. Due to inefficient management, about 30% of all food is wasted worldwide. More than half of all harvested fruits and vegetables are lost due to poor thermal management during storage [6,7]. It is estimated that more than CAD 25 billion worth of food is wasted in Canada each year, or about 2% of Canada's GDP. Global food losses vary widely by region, with higher losses in countries such as China, where only 15% of fresh produce is shipped refrigerated, even though this food must be refrigerated [8]. In 2012, the total cost of food waste in the EU-28 was estimated at EUR 143 billion. A temperature rise of 10 °C increases the spoilage rate by 2–3 times in a short period of time if fruits are improperly handled after harvest [9]. To improve the quality of food, it is important to maintain the temperature during storage and transportation, as this helps to reduce waste. Food cold chain applications account for approximately 8% of global electricity, contributing to an increase in fossil fuel consumption and 2.5% of global carbon emissions [10]. Recently, several researchers have worked to improve the efficiency of cold storage by optimizing the stacking pattern, position, and ventilation of packages [11–18]. However, these studies only decrease the energy consumption during storage without considering thermal conditions throughout the cold chain. Produce quality must be maintained throughout the cold chain, i.e., during storage, transportation, and post-harvest retail display. Produce is stored at optimal temperature but must be transported from harvest to storage chambers, and after storage it must be delivered to customers, with transportation playing a critical role in maintaining optimal temperature. Food is transported from ports and airports through a network of nearly 4 million vehicles around the world, and maintaining a controlled environment is not feasible because containers are exposed to adverse environmental conditions [19]. Poor post-harvest handling results in unacceptable food quality and causes microbial rot, spoiled products, and maximum losses due to food waste [3]. Thermal energy storage is one of the most promising methods used to overcome the mismatch between supply and demand in energy distribution in cold chain logistics. The overall energy consumption decreases and efficiency are improved by using PCM for thermal energy storage in various applications such as transportation [20–23], showcases [24–26], household refrigerators [27–33], and buildings [34–36]. During the process of solidification and melting, cans store and release a large amount of energy in the form of latent heat. This phenomenon improves the energy management working during peak load conditions for optimum storage [37]. The management of thermal energy storage approaches usually are classified into deterministic (considering no uncertainty) and robust/stochastic (dealing with uncertainty) [38,39]. The aim of this review paper is to investigate the use of PCM in various applications, mainly related to cold storage.

Some of the researchers worked on PCM reviews related to cold chains [40–45]. Rostami et al. [40] carried out a review of properties of nano PCM and work mainly focused on solar energy storage. A review by Taher et al. [41] was mainly focused on the PCM in refrigerated trucks. Sarkar et al. [42] investigated packaging structures in cold stores using PCM. Nie et al. [43], Oró et al. [44] and Pielichowska et al. [45] reviewed all applications from solar building to textiles and their properties. Although many researchers have studied the use of PCM and its thermal properties, they are mainly concerned with the chemical properties of PCM and its encapsulation methods. This paper mainly focuses on the cold storage of perishable goods in cold chain logistics, specifically on low-temperature applications, such as refrigerated transportation, refrigerated display cases, and packaging. In addition, the use of CFD is widely used in research to predict thermal behavior. Therefore, this article focuses on the details of using different CFD methods to solve the PCM in various applications.

2. Materials and Methods

The research mainly focuses on the use of PCM in cold chain applications. The result of the research gives a comprehensive overview of the different PCM used in cold chain in different applications, and these data help to give a clear idea of the improvement in cooling temperature stabilization inside the cold chamber and also outside the cooled environment. Since the work is mainly concerned with PCM, a large number of research articles from Science Direct, Scopus, and Web of Science from 2012 to 2022 have been considered and are shown in Figure 1 to give an accurate overview. The paper aims to give an impression of the use of PCM in cold chain logistics.

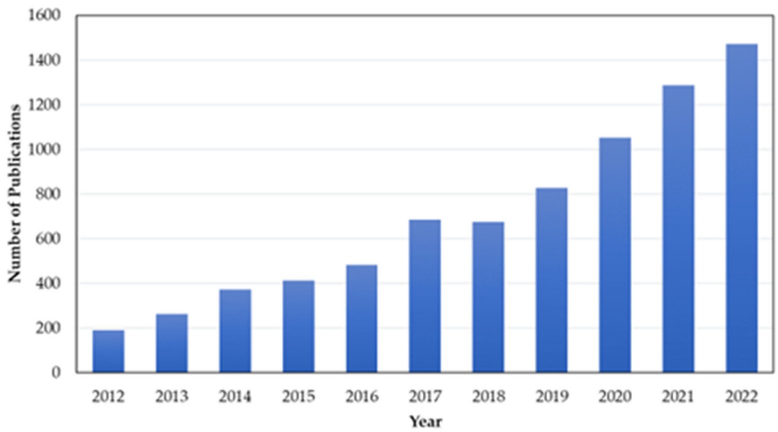


Figure 1. Published papers from past 10 years using key words "PCM, Cold Storage, PCM Refrigeration".

2.1. Thermal Energy Storage System

Thermal energy storage is divided into sensible heat storage, latent heat storage, and thermochemical storage. Sensible heat storage (SHS) is the simplest form of energy storage and depends on the specific heat capacity and density of the material during charging and discharging. Heat losses are inevitable, and only a small amount of energy is stored [46]. Latent heat storage (LHS) is more effective than SHS because heat transfer is associated with phase transition from solid to liquid, liquid to gas, and solid to solid. The materials used for this phenomenon are called phase change materials. These LHS have higher storage density at narrow temperatures during phase transition. Thermochemical storages have the highest storage capacity compared to all others, as they can store 5 to 10 times more energy than SHS and LHS [47]. Although they have the highest capacity, they lag behind in long-term stability issues in a controlled environment, and the development approaches are difficult and expensive [42].

2.2. Classification of PCM

PCM are materials that are thermally stable during the phase transition at constant temperature, and can be classified according to the phase transition they undergo. Most practical applications of solid–solid PCM are not considered due to their low latent heat of fusion. Solid–liquid PCM are commonly used. PCM are generally classified into organic, inorganic, and eutectic PCM [48], as shown in Figure 2.

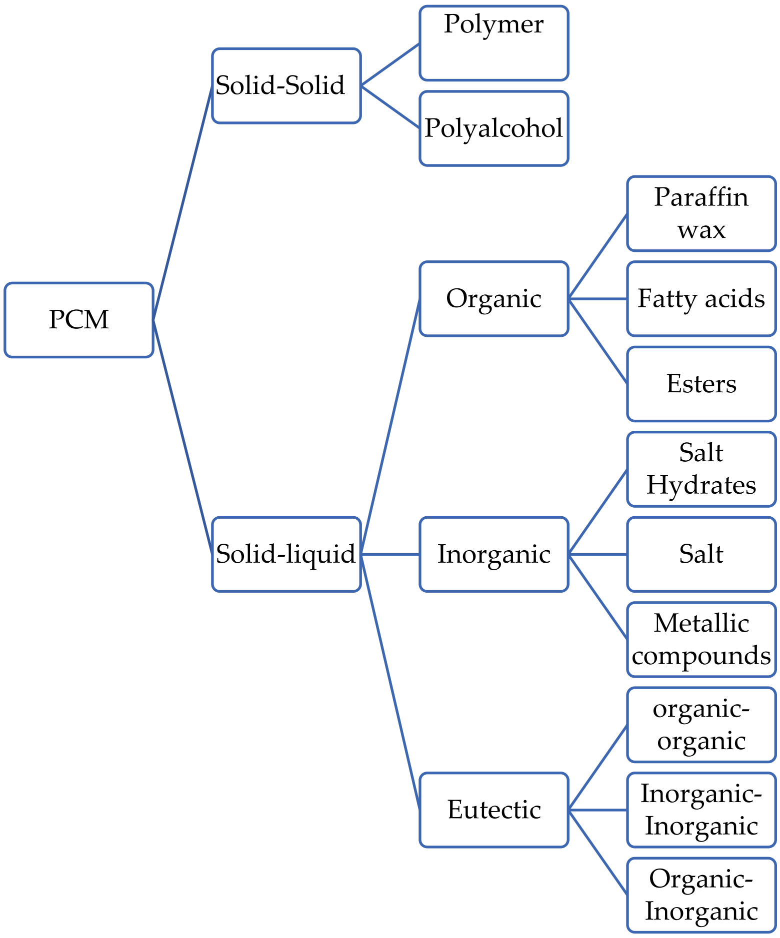


Figure 2. Classification of PCM [48].

Organic PCM are divided into paraffin, fatty acids, and esters. The properties of paraffin, with its high chemical and thermal stability, make it suitable for most applications [49]. Inorganic PCM such as salts and salt hydrates have high latent heat storage and exhibit high phase transitions due to their high enthalpy. Depending on the application, one or more PCM are combined to form eutectic salts. The combinations are organic–organic, inorganic–inorganic, or the combination of organic and inorganic. Since eutectics are tailored to the specific requirements, there is a lack of sufficient research results [50–52].

2.3. Selection and Characterization of PCM

The selection of PCM depends primarily on the cooling and heating requirements of the chosen application. Latent heat and nucleation properties must be higher than those of the selected application. The selection criteria mainly depend on the thermal, physical, kinetic, and chemical factors [53,54], as shown in Table 1.

Table 1. Selection criteria of PCM.

Category	Property
Thermal	Suitable phase transition temperature and latent heat with good heat transfer characteristics.
Physical	High density, small volume change, with favorable phase equilibrium.
Kinetic	Sufficient crystallization rate; no supercooling.
Chemical	Long lasting stability; no toxicity; nonflammable.

PCM are used in many applications, including buildings, refrigerated trucks, household refrigerators, display cases, and solar dryers. Since this work is mainly concerned with cold storage of perishable products, Table 2 shows the temperature and approximate shelf life of the products [48].

Table 2. Temperature and approximate storage life of perishable fruits refrigeration.

Products	Temperature (°C)	Approximate Storage Life
Apples	−1–4	1–12 months
Apricots	−0.5–0	1–3 weeks
Bananas	13–14	1–4 weeks
Blackberries	−0.5–0	2–3 days
Kiwi fruit	0	3–5 months
Mangoes	13	2–3 weeks
Peaches	−0.5–0	2–4 weeks
Pomegranates	5	2–3 months

The selected PCM must be able to resist the outside temperature to maintain thermal conditions outside the cooled environment. The PCM used must be able to maintain appropriate temperatures during the temperature fluctuations that occur during transportation and storage. Table 3 shows the suitable PCM for cold storage in the range of –1 °C to 13 °C [52].

Table 3. Commercially available PCM for cold storage applications within temperature range of (–1 °C to 10 °C).

Materials	Melting Temperature (°C)	Latent Heat (kJ/kg)	Type of Product	Producer
PureTemp-2	−2	277	Bio-organic	PureTemp LCC
E-2	−2	325	Inorganic	PCM products
RT0	0	175	Organic	Rubitherm GmbH
E0	0	395	Inorganic	PCM products
HS01	1	350	Inorganic	PLUSS Advanced Technologies
A2	1	230	Organic	PCM products

Table 3. *Cont.*

Materials	Melting Temperature (°C)	Latent Heat (kJ/kg)	Type of Product	Producer
ATP2	2	215	Organic	Axiotherm GmbH
RT2 HC	2	200	Organic	Rubitherm GmbH
RT3 HC	3	190	Organic	Rubitherm GmbH
A3	3	230	Organic	PCM products
RT4	4	175	Organic	Rubitherm GmbH
A4	4	235	Organic	PCM products
PureTemp 4	5	187	Organic	Rubitherm GmbH
RT5	5	180	Organic	Rubitherm GmbH
RT5 HC	5	250	Organic	Rubitherm GmbH
OM05p	5	216	Organic	PLUSS Advanced Technologies
A5	5	170	Organic	PCM products
CrodaTherm 5	5	191	Bio-based organic	Croda
SP7 gel	5 to 8	155	Inorganic	Rubitherm GmbH
ATP 6	6	275	Organic	Axiotherm GmbH
Gaia OM PCM7	7	180	Organic	Global-E-Systems
ClimSel C7	8	123	Inorganic	Climator AB
A7	7	190	Organic	PCM products
A8	8	180	Organic	PCM products
A9	9	190	Organic	PCM products
A10	10	210	Organic	PCM products

3. Applications of PCM

Over the years, a number of researchers have looked at PCM in various applications, with most of the work related to buildings [54–59], domestic refrigeration [60–62], and solar panels [62–65]. The current work focuses on post-harvest storage of perishable products, and therefore mainly considers cooling in cold chains. Using PCM in the cold chain not only maintains the optimal thermal condition of the products, but also improves the efficiency of cold storage [36,43].

3.1. PCM in Packaging and Display Cabinets

In order to provide consumers with high-quality products after harvest, the cold chain is essential. The design of appropriate packaging ensures product quality at all stages of storage, transportation, and sale to consumers. The temperature of perishable products must be maintained within certain limits to provide high-quality products [66]. To mitigate the temperature rise, packaging can be designed with insulated containers, PCM, and modified atmosphere packaging (MAP) and stored on refrigerated shelves, as shown in Figure 3 [61]. PCM are used in freezers to protect products at optimal temperature during power outages and to reduce energy consumption by reducing the duty cycle of the compressor.

Figure 3. Commercial display cabinet [61].

PCM with thermal insulated materials provides a reduction in energy consumption in cold chain logistics [61]. Table 4 summarizes the studies reported on the use of PCM in packaging and freezers for different types of food.

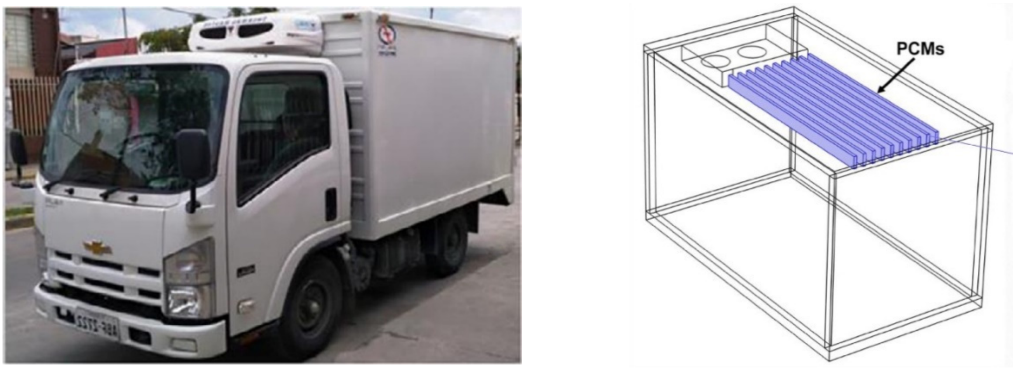
Table 4. Summary of studies reported with the use of PCM in packaging and display cabinets.

Application/Type of Study Experimental (E) Numerical (N)	PCM/Producer	Main Observations	Reference
Strawberries/E	Commercial PCM (−2.0 °C to −1.2 °C)	Use of PCM in the EPS box improved the quality of strawberries outside refrigerated environment. Products were maintained at 3 °C at ambient temperature of 10 °C.	[67]
Ice cream/E	PCM E21 (−21 °C)/Cristopia	Comparison made with and without PCM slab in ice-cream container. Use of 2.5 cm thickness slab maintains the temperature of ice cream with less than 1 °C at 20 °C surrounding temperature.	[68]
Fish/E	Ice pack 0 °C	Least temperature change experienced at the center under the ice packs.	[69]
Meat pack, food can, vegetable pack, lettuce./E	Gel pack 0 °C	Use of aluminum foil reduces temperature up to 13% Temperature of the meat maintained below 6 °C when gel packs are placed above the meat.	[70]
Open Display cabinet/E	Ice 0 °C	PCM are introduced in the heat exchanger in the airflow region Products temperature is maintained for 2 h when compressor stops operating.	[71]
Closed display cabinet/E	Thickening agent in distilled water −6 °C	PCM positioned on the shelves are more efficient than the PCM positioned at the back Use of PCM holds the optimum temperature for 20 h when placed on the shelves.	[29]
Closed display cabinet/E	E-21(−21.3 °C) & C-18 (−18 °C)/Cristopia, Climsel	Encapsulated PCM placed over evaporator Use of PCM Extended cooling to 15.6 h with use of (C-18) and 21.5 h for (E-21)	[72]

Marques et al. [61] studied the temperature stabilization of food display cases in the temperature range of 0 °C to 5 °C and found that the addition of nucleating agents (AgI) with water-preserved products is better during power outages and frequent opening of doors.

3.2. PCM in Refrigerated Transport

Maintaining the desired temperature inside a refrigerated trailer is challenging due to vehicle movement, frequent door openings, and inadequate tailgate insulation [73,74]. To ensure optimal thermal comfort without temperature fluctuations, innovative methods such as hybrid technology with the use of PCM in conventional refrigeration improve the quality and economy of transportation [75]. Figure 4 shows the refrigerated vehicle model used for the experimental study with a 3D cad model of the vehicle with PCM for the numerical analysis performed by [75].



(**a**) (**b**)

Figure 4. (**a**) Commercial refrigerated truck; (**b**) 3D model of the PCM incorporated truck [75].

Table 5 provides an overview of the use of PCM in refrigerated transport and storage. Although many researchers have expressed interest in the cold chain, few researchers have explicitly studied the refrigerated transporter PCM.

Table 5. Summary of studies reported with the use of PCM in refrigerated transport.

Application/Type of Study Experimental (E) Numerical (N)	PCM/Producer	Main Observations	Reference
Moving truck/E	(E-26/E-29/E-32) (−26 °C, −29 °C, −32 °C)/PCM products.	PCM studied at different truck speed (80–110 km/h) E-26 at 81 km/h gave maximum melting time of 17,200s.	[76]
On vehicle PCM unit added into refrigeration system/E	New PCM made with inorganic salts.	Energy cost was reduced by 82.6% compared to the conventional refrigeration system with use of new low-cost PCM.	[77]
Mobile refrigeration system with PCM/N	New PCM made with Inorganic salts is used.	250 kg and 360 kg PCM required without and with door opening to maintain −18 °C temperature for 10 h were identified.	[78]
Integrated rail-road refrigeration/E	RT 5 PCM/Rubitherm	PCM stored in plates are equipped within the container containing fruits and vegetables. Results are compared with the diesel-powered reefer, and the results suggest that energy consumption was reduced by 86.7%.	[79]
Mobile refrigeration unit for transport/E	Developed a Eutectic PCM	Phase change cold storage unit installed internally in thermal insulated compartment. PCSU maintains different air temperature −12.3–16.5 °C for 16.6 h and 10 h and reduces the energy cost 15.4–91.4% compared to the conventional refrigeration units.	[80]
Refrigerated truck/E	Ice cube mass	Performance of mobile cooling unit is studied using ice cube at different mass of ice cube. Average COP of an ice cube of 6.8 g was 28% higher than that for an ice cube of 10 g.	[81]

Although the installation of PCM improves cooling temperature stabilization, the location and PCM packaging must be considered to maintain both thermal and mechanical load capacity [81]. Sonnenrein et al. [82] performed an experimental analysis of refrigerators with and without PCM and found that the use of PCM (RT35HC) maintained a 2 °C lower temperature than conventional refrigerators. Alzuwaid et al. [25] added thin layers of multi-foil insulation and aerogel layers inside the standard van insulation walls, and the temperature stabilization of the addition was improved, but the addition of PCM showed inconsistent results, as the experiments were tested in an indoor chamber. To obtain a better result, the experiments need to be conducted under real-time conditions.

3.3. PCM in Domestic Refrigeration and Freezers

Energy consumption for household cooling as a function of time is significant [83]. The International Institute of Refrigeration (IIR) estimates that about 4% of the world's energy is consumed through household cooling and freezing [83]. In recent years, several researchers have expressed interest in household cooling to improve temperature stabilization (PCM) and maintain temperature during power fluctuations and idling. Figure 5 shows the experimental freezer used in the laboratory [84] and Table 6 provides a summary of studies reported with the use of PCM in domestic refrigeration and freezers.

Figure 5. Experimental freezer used in laboratory [84].

Table 6. Summary of studies using PCM in domestic refrigeration and freezers.

Application/Type of Study Experimental (E) Numerical (N)	PCM/Producer	Main Observations	Reference
Household refrigerator/E	Eutectic Solution	Evaporator cabinet is placed within the PCM box. Two different PCM are used in the experiments. Results suggest that that Eutectic solution 2 performs better with reduced compressor usage of about 5–30%.	[84]
Household miniature Refrigerator/E	PlusICE organic A4/plusICE hydrate salt S5/PCM products	Miniature domestic refrigeration unit evaluated with use of PCM with use of solar radiation is performed. Results suggest 26% decreased power consumption and PCM enhanced the temperature of cabinet.	[85]
Household refrigerator/E	Polyethylene glycol-400	Temperature inside the domestic refrigerator is studied during power fluctuations. Use of Polyethylene glycol-400 PCM reduces the temperature fluctuations around 3–5 °C and during the power failure lower temperature is maintained for 2 h.	[86]
Commercial freezer/E	Climsel C-18/Climator	PCM plates are placed over evaporator's tube. Experiments were tested for frequent door opening and power failure. Results suggest that PCM maintains the temperature of the freezer almost constant from (−12 to −14 °C) for 3 h of power loss.	[87]

Table 6. *Cont.*

Application/Type of Study Experimental (E) Numerical (N)	PCM/Producer	Main Observations	Reference
Household frost free Refrigerator/E	PCM made with (18% NaCl solution added with 5% SAP and 0.03% diatomite)	Compressor OFF time, PCM retained the temperature of 8 °C and average temperature of M-packs were maintained less than −18 °C. Frost-free refrigerator incorporated with PCM exhibit performs better with the energy and quality of food stored.	[88]
Household refrigerator/E	Eutectic PCM Polyethylene glycol-100/600. Merck Germany.	PCM pack placed behind the wire and tube condenser in domestic refrigerator. Use of PCM increases longer compressor off-time per cycle compared with normal refrigerator and consumed 13% less electrical energy than the conventional refrigerator.	[89]
Industrial refrigerator/E	RT-9HC PCM/Rubitherm	Industrial refrigerators with different temperature requirements and load characteristics can be implemented with use of PCM.	[90]

3.4. Numerical Methods in PCM Modeling

Computational fluid dynamics is a powerful numerical method used to solve complex problems in various fields. The temperature, velocity, and pressure distributions within the model can be visualized, and the results can be validated with experimental data, which improves the overall quality of the products [90]. The reliability of the numerical model used to solve the thermal behavior during phase change must be acceptable, as these models are very complex and involve nonlinear motions and phase transitions related to the change in ambient temperature [91].

In thermal engineering applications, a simplified model PCM is used in most cases to predict heat transfer, and some building models are tested without considering the convection term in the transport equations. The effective thermal conductivity approach is also used to account for the effect of natural convection based on the Rayleigh number [92]. In general, temperature-based and enthalpy-based methods are the two most commonly used methods for analyzing the phenomenon of phase change between solid and liquid PCM. In the temperature-based model, individual energy equations for the solid and the fluid must be established to explicitly predict the temperature behavior. The enthalpy-based model includes a single-phase mushy zone, and the new commercial software Fluent is widely used to validate this method against the experimental task performed [93]. Table 7 shows some of the numerical methods used in CFD with PCM in various applications.

Table 7. Summary of studies reported with the use of PCM in various applications using CFD.

Application	PCM/Producer	Software/Solver	Main Observations	Reference
Food packaging	RT 5 PCM/Rubitherm	Numerical	Heat transfer behavior of plate Sub micro encapsulated PCM was studied and the results suggest that the PCM encapsulated plate had better thermal buffering compared to standard cardboard.	[94]
Transportation box.	Gel pack	Comsol Multiphysics	Heat transfer within the multilayer box of nonrefrigerated transport using 3D model was predicted and results were compared with experimental work. Results suggest that the aluminum foil paper maintains the food reduces the radiation. Gel pack has to be positioned far away from the exterior of the walls to prevent the optimum temperature.	[70]
Household refrigerator	Novel PCM made with Paraffin.	FORTRAN	COP of the condenser is increased by 19% with the use of shape-stabilized PCM.	[95]

Table 7. *Cont.*

Application	PCM/Producer	Software/Solver	Main Observations	Reference
Heating system	RT60 paraffin/Rubitherm	Ansys Fluent 14.5/2D model	Design of heat exchanger by the position of the PCM's vertical and horizontal is studied and the vertical arrangement shows higher flow intensity for both solidification and melting.	[93]
Refrigerated container envelopes	RT35HC/Rubitherm	COMSOL/1D model	Different PCM tested in the refrigeration container results suggest that RT35HC PCM performs better during the peak load, with 4.55–4.74% energy savings.	[96]
Portable packaging box	Water/Tetradecane+ docosane	Ansys Fluent 2021/3D model	PCM layout are evaluated within the portable box. Position of PCM top, bottom, long side is the effective configuration with discharge efficiency of 80% and threshold time of 15.8 h.	[97]
Portable packaging box	RT2HC/Rubitherm	Comsol Multiphysics	Different PCM are tested at different positions inside the portable box, and the results suggest that the model with 20% of PCM on top and each side of the wall with two melting point PCM performs better with maximum cooling time up to 46.5 h with 90% discharge efficiency.	[98]

4. Discussion

In cold chain logistics, maintaining the optimal temperature is the main concern to avoid temperature heterogeneity in stored products. The review mainly focuses on the use of PCM in cold chain applications such as refrigerated transport, display cabinets, domestic refrigeration, cold rooms, and buildings. In the first part of the article, a brief overview of thermal energy storage and PCM is given, using different properties of PCM in a range from −1 °C to 10 °C.

Different PCM are used in display cases depending on the products inside. Most commonly, water/ice packs are used as the medium to maintain the temperature. It is worth noting that in the open display cases, the PCM are placed at the outlet of the heat exchanger so that the products can be maintained for 2 h during the compressor shutdown time. Some closed display cases perform better with PCM positioned on the shelves that can maintain the temperature of the products for 20 h. Encapsulation of PCM is used in display cases to prevent spoilage of the food stored inside.

The use of PCM in a refrigerated vehicle has been employed with various strategies to maintain the thermal conditions of the products to overcome the frequent opening of the doors and the different temperature levels in the environment. The most commonly used method is to integrate PCM into the walls and compartments of the truck container. The efficiency of the refrigeration unit is improved by using less diesel fuel. Instead, the PCM can maintain the optimal temperature for up to 10 h and can reduce operating energy costs by about 15%.

The use of PCM in household refrigerators improves the efficiency of the refrigerator by reducing the consumption of the compressor by 5–30% and maintaining the thermal homogeneity of the products at about 3°–5° in the event of a power failure. In commercial freezers, PCM are introduced into the evaporator tube when the door is opened frequently to maintain cooling comfort and improve the overall temperature stabilization of the refrigerator.

5. Conclusions

The cold chain is essential for preserving and improving the quality of products handled after harvest. Improving the performance of the cold chain, from transport to storage and display, saves energy and lowers environmental emissions. Several studies on energy management have been conducted in refrigeration and display cabinets; however, very few studies have been conducted in packaging boxes, cold rooms, and refrigerated trucks with PCM. This is perhaps due to the challenges in controlling external factors such as temperature, insulation, and frequent door openings. For instance, refrigerated trucks were tested with constant ambient temperature by modified reefers in the container. The model's performance must be evaluated in testing with real-time factors to provide a more reliable solution. Furthermore, the use of computational resources may provide greater flexibility in the test performed. Several authors investigated PCM in simulations, but most of them used a simplified model based on 2D analysis or a 3D model within a rectangular box. Heat transfer phenomena within models that take convection and radiation into account provide important results that can be validated with the experimental task performed. In future, considering the PCM with its thermal requirements, quantity, and position with extensive efforts considering the contemporaneous factors could provide more decisive solutions that can improve the performance of cold storage applications.

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