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Insulated Box and Refrigerated Equipment with PCM for Food Preservation: State of the Art

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Abstract

The use of Phase Change Material (PCM) as a cold accumulator in refrigeration contexts leads to better food safety, food security and energy management. However, applying PCM in real usage still depends on the user's experience or a trial-and-error basis. Studies carried out on insulated boxes and in refrigerated equipment (refrigerated trucks, cold storage facilities, display cabinets and domestic refrigerators) were reported. The influence of the studied conditions such as PCM melting point, position, mass of PCM and load, insulation material, external temperature on air/product temperatures and energy consumption was analyzed. Important parameters enabling the application of PCM in boxes and refrigerated equipment are the wall insulation and PCM configuration cited previously. Because of the complex interactions between these parameters, they need to be considered together with the usage conditions. The relationships between heat exchange and airflow inside the equipment should be further studied notably in function to the PCM position.

Keywords: Phase change material, Food cold chain, Insulated box, Energy management

1. Introduction

The main concern during food transportation is the microbial safety of the food that could be compromised by high temperature and may result in food poisoning or foodborne infection (Mercier et al., 2017). However, products with unacceptable organoleptic quality (firmness, color), although still edible, may also be regarded as not sellable by retailers or inedible by consumers, thus leading to food waste (Ndraha et al., 2018). A temperature that is too low can also lead to undesirable quality in some foods, for example, chilling injury in tropical fruit (J. Liu et al., 2019). FAO (2019) reported that 1.3 billion tons per year or one-third of edible food consumed by humans is wasted worldwide. Each food product has a specific optimal storage temperature, since a storage temperature that is too high or too low can adversely affect the quality and/or safety of the food (East et al., 2009).

Regarding frozen food, although products are kept within a suitable temperature range, temperature fluctuations can still impact their quality. Indeed, during frozen storage, ice recrystallization caused by temperature variations yields bigger ice crystals and lowers the quality of the food product (Oró, de Gracia, et al., 2012; Phimolsiripol et al., 2008; Vicent et al., 2019, 2020).

Transportation using insulated boxes plays an important role in the cold chain, particularly when passive cooling devices such as Phase Change Material (PCM) are used, e.g. during shipment from the producer to the retailer, then to the consumer (Robertson et al., 2017). Transport may involve a short distance (a few kilometers for locally produced food) or long distances, e.g. from Glasgow to London (Elliott & Halbert, 2008), from Sydney to Melbourne (East et al., 2009), or from New Zealand to Singapore (Navaranjan et al., 2013). The ambient temperature during delivery can vary according to the season, e.g. -10°C in winter and 35°C in summer (East et al., 2009). Among the different links in the cold chain, the final transport to the consumer has been found to be one of the weakest. Laguerre et al., (2013) and Mercier et al., (2017) reviewed temperature abuse in the cold chain and reported that this last step had the highest average temperature and the highest temperature variation. Accordingly, a cold storage system such as a PCM could provide a solution that maintains the product temperature, especially during delivery of temperature-sensitive products (Nie et al., 2020; Y. Zhao, Zhang, Xu, et al., 2020).

This review article investigates studies on the transport of food in insulated boxes with PCM knowing that such transport can also be used for pharmaceutical products (L. Yang et al., 2021). Despite the ease of use of this technology and its relatively low cost, temperature abuse can be observed, particularly due to insufficient PCM mass and inappropriate PCM position causing temperature heterogeneity inside the box. In fact, controlling the product temperature in a closed cavity is complex because of several simultaneous heat transfer modes: conduction, natural convection and radiation (Laguerre & Flick, 2010; Rincón-Casado et al., 2017; Shinoda et al., 2019). These transfer modes are of the same order of magnitude; thus, it is necessary to take all of them into account (Laguerre & Flick, 2010).

PCM is also used in other cold equipment such as refrigerated trucks, cold rooms, display cabinets and domestic refrigerators. Here, PCM plays an important role, not only in temperature control, but also in energy management (Schalbart et al., 2013; Sonnenrein, Elsner, et al., 2015; Yilmaz et al., 2020). However, determining the optimal PCM position and mass is still the challenge in these applications (Azzouz et al., 2009; Pirdavari & Hossainpour, 2020; Schalbart et al., 2013; Yilmaz et al., 2020).

There are several review articles on PCM classification, properties and improvement (Oró, Miró, et al., 2012; Rostami et al., 2020; Y. Zhao, Zhang, Xu, et al., 2020). Many studies on PCM application in buildings, solar systems, or even in the food industry have been performed (Nie et al., 2020; L. Yang et al., 2021; Y. Zhao, Zhang, & Xu, 2020). However, we have not found any review articles dedicated to the use of PCM to maintain the desired food temperature throughout the entire cold chain equipment including insulated boxes. For instance, Zhao et al. (2020) reviewed PCM application in refrigerated trucks, refrigerated containers and insulated boxes. Bista et al. (2018) alone reported the use of PCM in a refrigerator. It is important to investigate this subject throughout the entire cold chain in order to identify any research gaps and enhance the efficiency of the cold chain (Costa, 2020) since chilled and frozen products transport has expanded rapidly in all parts of the world in recent years. A comprehensive review devoted to all cold chain equipment would be useful for food manufacturers and logistics companies. Consequently, the objectives of this review article are firstly to present the state of the art in the field of food transportation of various product types in insulated boxes equipped with PCM (study approaches, techniques and main observations). The influence of the insulating material, box design, PCM properties and the external ambient temperature was analyzed. Secondly, the aim is to report on studies on the application of PCM in other refrigerated equipment: refrigerated trucks, cold rooms, display cabinets and domestic refrigerators where energy management is the main concern. Finally, a discussion highlights the potential and the limitations associated with the development of the use of PCM in the cold chain. Data gaps regarding the complex phenomena involving heat and mass transfer, the phase-change process and food engineering are also discussed.

2. Insulated box with PCM

There are various complex phenomena involved in an insulated box with PCM: heat conduction inside the product, PCM and the walls of the box, heat convection between the air and the product/PCM inside the box and between the external air and the box, radiation between walls, the phase change process and food quality evolution. Standard solutions cannot be widely applied as all these phenomena are impacted by the type of product itself, the operating conditions (external temperature and duration), the box dimensions, the type of PCM (latent heat, heat capacity and melting temperature), its quantity and its position in the box. The objectives of this section are to describe the existing studies in terms of the product quality (Section 2.1), type of product transported (Section 2.2), box design (Section 2.3), PCM characteristics (Section 2.4), operating conditions (Section 2.5) and influence of each factor in application and modeling (section 2.6) to identify the overall findings as well as the knowledge gaps.

2.1. Effect of PCM in insulated box on food quality

The interest of PCM application is to maintain low temperature and reduce temperature fluctuations during food transport, which leads to better food quality particularly for high perishable products. In the case of fresh fruit and vegetable, the product respires continuously during storage, which leads to heat generation. High respiration rate, a major factor contributing to the product loss, depends on product (e.g. strawberry respiration rate is 4 times higher than that of apple) and on storage temperature (e.g. strawberry respiration rate at 15°C is 5 times higher than that at 0°C) (Chakraverty & Singh, 2001). Numerous studies have shown the interest of Modified Atmosphere Packaging (MAP) for the product shelf life extension because the gas composition in the headspace (O_2, CO_2) decreases the respiration rate. X. Zhao et al. (2019) studied fresh strawberry quality change using MAP in an expanded polystyrene box exposed to ambient temperature at 10°C and 20°C. Three PCM packs, previously froze at -18°C for 24 h, were placed at the top of the box. The results were compared with the current package (air in headspace) and a control configuration where the product was directly in contact with ambient air (Fig. 1). It was observed that MAP allowed product weight loss 30% lower than that in current package and about 160% lower than that of control after 4 days at 10°C, this effect was more significant at storage temperature at 20°C (Fig. 1a). These authors also reported that the combination of MAP, PCM and the insulated box allows the strawberry quality preservation in terms of firmness, color, total soluble solids and global appearance (results not shown). The better quality preservation under this combination can be explained by first, MAP allows a reduction of product respiration rate (Fig. 1b) and second, PCM allows low product temperature fluctuation. These results confirm the interest of the combination of MAP, PCM and the insulated box for delivery when the ambient temperatures are not well controlled. Gin and Farid, (2010) stored frozen meat and ice cream in a domestic freezer without and with PCM (melting temperature -15.4°C). For meat, these authors reported the reduction of drip loss from 17% (without PCM) to 10% (with PCM) after 2-week storage and for ice cream, the average crystal size decreased from 70 µm - 80 µm (without PCM) to 40 µm -50 µm (with PCM). It is to be emphasized that the higher temperature fluctuation during frozen storage, the bigger ice crystals and lowers the food quality (Oró, de Gracia, et al., 2012; Phimolsiripol et al., 2008; Vicent et al., 2019, 2020).

2.2 Type of food product transported

Studies dealing with the transportation of different types of food products in insulated boxes with PCM are summarized in Table 1. Out of 16 studies, six of them focused on meat and fishery products since these products are extremely sensitive to temperature changes during transportation and storage. As PCM, ice packs were placed on top of the products in several experimental and numerical studies: haddock fillets (Margeirsson et al., 2011), cod fillets, (Margeirsson et al., 2012), New Zealand terakihi (Navaranjan et al., 2013), horse mackerel (Laguerre et al., 2018), and sardine (Laguerre et al., 2019). X. Zhao et al. (2019) investigated strawberry fruit transportation using an insulated box with PCM. There were fewer studies dealing with fruit and vegetable transportation by means of insulated boxes equipped with PCM. This may be due to the fact that fruit and vegetable are not as perishable as meat products, thus, they are less sensitivity to temperature abuse (Committee, 2014). However, it could be valuable to investigate such applications as higher demand for fresh tropical produce from cold climate countries has emerged recently (ICI Business on behalf of Centre for the Promotion of Imports from developing countries, 2020; Loria, 2021).

Delivery in an insulated box offers flexibility as it is possible to transport different types of products simultaneously (Ndraha et al., 2019). Paquette et al. (2017) studied a system with a mixed load containing food cans, vegetable packs and meat packs using gel packs, but the focus of this work was the temperature of meat and vegetables, as these products are more sensitive to temperature abuse than food cans. However, greater care is needed during transport of several types of perishable products in the same box since they require different optimal temperatures. Temperature abuse may affect the final quality of sensitive products (Paquette et al., 2017).

Kozak et al. (2017) and Paquette et al. (2017) investigated liquid foods such as bottles of water and beakers containing water, respectively. East & Smale (2008) and East et al. (2009) studied beverage cans because they could be considered as lump objects without internal heat transfer resistance via numerical modelling. These authors used numerical models for the box design optimization: the material and thickness of the box and dividers between the product and the PCM below, PCM type and thickness and initial product and PCM temperatures.

The two remaining studies were conducted on an empty box to clearly determine the impact of system design: insulating material, PCM position, melting point and compartment volume (Du et al., 2020; Xiaofeng & Xuelai, 2021). As shown in Fig. 2, the more box surface covered by PCM, the longer warming time of air at the box center to increase from 0°C to 8°C (Du et al., 2020). This was due to greater heat exchange area between the PCM and internal air, thus, greater cooling capacity. It was observed that the PCM placed at the top and the bottom of the box gives almost the same warming time.

Some authors investigated the effect of product quantity on the thermal behavior of the box equipped with a PCM. Elliott & Halbert (2008) reported that a higher load quantity increases the thermal inertia, and thus generates a different temperature profile. It is to be emphasized that the load quantity and the arrangement were varied simultaneously in the experiments. Thus, it was difficult to highlight the influence of these parameters separately. Paquette et al. (2017) compared the temperature profile when one beaker of water and 4 beakers of water were placed in a box. They found that the rate of temperature increase was 20% lower in the box with 4 beakers, can be explained by the higher product inertia in comparison with 1 beaker. However, a higher load quantity may lead to a lower cooling rate if the load is not previously chilled before packing, and this causes deterioration in quality. Laguerre et al. (2018) indicated that the greater the thickness of a stack of fish in the box, the longer the cooling duration.

The load type also impacts the temperature profile because of different thermal properties. Kacimi & Labranque (2019) studied the effect of the load using an empty bag (lower thermal inertia) and a bag of water (higher thermal inertia). They noted that by using bags of water, the temperature could be maintained for a longer period of 131 h compared with 115 h for empty bags.

2.3 Insulating material and box design

Reducing heat flux by using an insulating material is essential (Singh et al., 2008). Not only the temperature inside the box should be maintained within a desired range for the longest duration, but temperature fluctuations should also be reduced, especially when the external ambient temperature varies, as is often observed in the supply chain (Fioretti et al., 2016). Low thermal conductivity rigid materials have been used above all, for example, expanded polystyrene and polyurethane (East & Smale, 2008; Kacimi & Labranque, 2019; Margeirsson et al., 2011). Many studies have shown that a change in the insulating material significantly impacted the temperature profile and product quality (Du et al., 2020; East et al., 2009; East & Smale, 2008; Kozak et al., 2017; Margeirsson et al., 2011). For instance, Margeirsson et al. (2011) reported that the average rates of fish temperature rise were 0.51°C/h and 1.41°C/h using expanded polystyrene and corrugated plastic, respectively. Kozak et al. (2017) showed that an optimal configuration can be reached, which allows maximizing the melting time of the PCM. The ratios of insulation and PCM thicknesses and their thermal conductivities are the determining factor of this optimal condition (allowing longest period at low temperature).

The insulation is reinforced when vacuum panels are used (Kacimi & Labranque, 2019). This can be explained by the fact that the thermal conductivity of vacuum panels is very low, and these panels thus provide greater insulation capacity (Du et al., 2020). These authors compared the effects of polyurethane (PU) and Vacuum Insulated Panels (VIPs) used as insulating materials. The authors found that VIPs prolonged the warming duration (defined as the duration during which the temperature at the center of the box rises from 0°C to 8°C) 3.8-fold in comparison with PU. Another solution to reduce the overall heat transfer coefficient consists of covering the surfaces with a low-emissivity material which can decrease radiation. Paquette et al. (2017) showed that by covering the internal surface of the box with aluminum foil to decrease the emissivity from 0.8 (without foil) to 0.2 (with foil) reduced the product temperature by about 2°C. The combined effects of wall emissivity and wall thickness on box insulation was studied by Navaranjan et al. (2013). These authors pointed out that replacing perpendicular spacers (with a 15 mm air gap) with double fluted spacers (with a 21 mm air gap) and metallizing the surface led to 102% greater thermal resistance.

In addition to the thermal conductivity of the material, box insulation also depends on its design. Margeirsson et al. (2012) reported that using an expanded polystyrene box with rounded corners helped to decrease the temperature difference of 2.0°C between fish at the center and at the corners, while this difference was 4.4°C for sharp corners and it also led to extending the product shelf life for an additional 2 days. This may be due to a lower exchange area at the round corner in comparison with the sharp corner, so less heat exchange with the environment occurs. However, the box design should be optimized taking into account the usable volume in comparison with the total box volume and cost (East & Smale, 2008).

Heat flow resistance (R value – m^2 K/W) is a factor determining the insulation effectiveness of a box. Singh et al. (2008) and Navaranjan et al. (2013) placed a known quantity of ice in a box, left it in a constant temperature chamber for a certain period to allow the ice to partially melt, then determined the amount of liquid water and calculated the R value. Navaranjan et al. (2013) pointed out that there was a good correlation between the R value and the quality of New Zealand terakihi fish stored in insulated packaging. Another method used to estimate heat flow resistance of a box is the use of an internal cooling or internal heating method (United Nations, 2020). For the internal heating method, a heat resistance (with a known heating power) and temperature sensors are placed in an empty box at locations suggested in the guidelines and the temperature profile is recorded continuously. When steady state is reached, the difference between the internal/external air temperatures and the heating power allow the R value to be calculated.

The box can be composed of multiple partitions to allow delivery of various types of products with different recommended storage temperatures in the same box. Xiaofeng & Xuelai (2021) developed an insulated box with partitions making it possible to transport three different product categories: no PCM for ambient storage, with PCM with a melting point of 7.1°C (87% n-caprylic acid and 13% myristic acid) for chilled storage and with a PCM with a melting point of -2.1°C (potassium sorbate solution) for storage at temperatures below 0°C. They reported that this box could maintain the internal temperature within the expected range for each partition for up to 16 h.

2.4 PCM properties, position and usage

Apart from the insulating material, thermal energy storage using PCM is another key factor that maintains the temperature in a shipment (L. Yang et al., 2021). During transportation, a difference between recommended and real product temperatures may occur because of heat diffusion from the external ambient into the box, resulting in temperature abuse. PCM plays a significant role in cold storage as it allows cold diffusion into the system to offset heat diffusion, particularly during its melting thanks to high PCM latent heat (East & Smale, 2008; Kacimi & Labranque, 2019; Laguerre et al., 2008). Oró, Miró, et al. (2012), Rostami et al. (2020), and Y. Zhao, Zhang, Xu, et al. (2020) have classified the PCM and fully described its properties.

There are numerous thermal energy storage materials e.g. water, salt solution, paraffin (Oró et al., 2012). Various compounds were applied as PCMs in an insulated box, e.g. ice or an ice pack with a melting point ranging from -0.5°C to 0.5°C (East et al., 2009; East & Smale, 2008; Laguerre et al., 2018, 2019; Margeirsson et al., 2011, 2012; Navaranjan et al., 2013). To achieve a temperature range below 0°C, Kozak et al. (2017) used salt solutions with melting points of -10°C and -33°C while Elliott & Halbert (2008) studied the system with dry ice (CO_2: phase change temperature = -78.5°C). Elliott & Halbert (2005) used Icebrix® frozen gel packs which froze at -20°C. Commercially available PCMs with various melting points between -2°C and 21°C were also investigated (East et al., 2009; East & Smale, 2008; Kacimi & Labranque, 2019; X. Zhao et al., 2019).

Today, there is greater demand for produce from different regions in the world, hence, long transport duration and fluctuating ambient conditions are unavoidable (Loria, 2021). It is challenging to establish a common guideline for various types of products and transportation conditions, e.g. transportation ranged from 3 h to 96 h under extremely cold (-10°C) or hot (35°C) conditions (East et al., 2009; Laguerre et al., 2019; X. Zhao et al., 2019).

In some studies, a PCM was placed on the internal face of the box or in the layer between the internal and external walls to compensate for heat exchange with the ambient. East et al. (2009) and East & Smale (2008) placed PCM only at the bottom of the box. Kacimi & Labranque (2019) put PCM at top, bottom and side walls while Laguerre et al. (2008) applied ice pack at top, middle and bottom layer of the box. Du et al. (2020) and Elliott & Halbert (2005) compared the effect of PCM position on temperature profile. Some studies recommended the position of the PCM on the top or side walls because this allows internal airflow by natural convection, thus generating a more uniform temperature. The PCM placed on the bottom leads to conduction alone along with greater temperature heterogeneity (Du et al., 2020; Laguerre et al., 2008). In an insulated box with PCM at the top, middle and bottom, Laguerre et al. (2008) indicated that PCMs on the top of the container completely melted within 32 h during an experiment on transport, while those at the bottom remained partially frozen for more than 72 h, while the product temperature reached 21.5°C at the level of the top layer.

A composite box wall with PCM was studied (Melone et al., 2012). Mixtures of paraffin (melting point 0°C to 10°C) and cellulose solutions with different concentrations (0%, 25% and 50% w/w) were prepared to obtain cellulose sheets with PCM. It was observed that the maximum cooling period of 87 minutes was achieved for the sample with a paraffin concentration of 50% w/w.

Some studies focused on maintaining the temperature of the load inside the box by placing the PCM close to the most sensitive product such as fish and meat (Elliott & Halbert, 2008; Laguerre et al., 2018, 2019; Margeirsson et al., 2011, 2012; Navaranjan et al., 2013; Paquette et al., 2017). Paquette et al. (2017) showed that placing PCM at the center of the box provided better efficiency by comparing the duration required for the temperature of meat to increase from 3.5°C to 10.0°C. It was found that this temperature rise took 32.1 h with PCM at the center and 8.6 h with PCM on the side of the box. They also pointed out the decrease in the temperature of meat during the initial period when 1 kg of PCM was placed on top of the meat and another kg of PCM was placed on the bottom, whereas this phenomenon was not noticed when both parts of PCM was combined and added either at the top or at the bottom due to lower surface area for heat exchange. However, once the temperature went up, it rose faster and reached 18°C after a 48-h interval when the PCM was split into two layers compared with only 15°C when all the PCM was placed at the same position.

However, placing PCM in an inappropriate position may still lower the internal temperature, but causes significant temperature heterogeneity (Elliott & Halbert, 2008; Navaranjan et al., 2013; Paquette et al., 2017). For instance, Navaranjan et al. (2013) indicated that the temperature difference in a box with an ice pack on top of the product compared with a box with no ice pack was over 5°C. The load type and amount, the operating conditions and the transport constraints e.g. acceptable limit of product temperature, are the determining factors when designing the system.

The weight of the PCM influences the product temperature profile and should be optimized with respect to the size of the box. Kacimi & Labranque (2019) recommended that a moderate amount of PCM should be applied, since too little or too much PCM decreases the efficiency and causes undesirable outcomes i.e. temperature abuse and chilling injury. Xiaofeng & Xuelai (2021) increased the volume of the compartment by 25% while maintaining the same amount of PCM and found that the temperature rose faster in the compartment with a higher volume of PCM (the temperature increased from 0.24°C/h to 0.41°C/h). East et al. (2009) also reported that an inappropriate amount of PCM led to temperature abuse during delivery because the products were either too warm or frozen.

2.5 Effect of the external temperature

The influence of the ambient temperature was also investigated as an important factor e.g. greater numbers of PCM packs were required during delivery in summer (East et al., 2009; Elliott & Halbert, 2005; Kacimi & Labranque, 2019; X. Zhao et al., 2019). Although the difference in heat flux caused by different ambient temperatures is well-known, investigation of the influence of this factor on product quality is still necessary. East et al. (2009) optimized box design using different ambient temperature profiles from different seasons and were able to choose the box material, the wall thickness and the amount of PCM. Kacimi & Labranque (2019) studied two PCMs with different melting points under different ambient conditions and recommended that the PCM melting point should be matched with the ambient conditions. It is to be emphasized that the PCM was placed only on the side wall of the box in this study.

Many studies have investigated the influence of ambient temperature, either by temperature monitoring during real shipping or by temperature recording in a controlled-temperature test chamber. The latter case is easier to implement and requires fewer resources. Elliott & Halbert (2005) and Elliott & Halbert (2008) performed a shipping test using long-distance delivery in different seasons generating data from real situations. Margeirsson et al. (2012) recorded the ambient temperature during cod fillet transport from Dalvík to Reykjavík and further utilized this data for numerical model validation. Navaranjan et al. (2013) reproduced, in a test chamber, the ambient temperature obtained during airfreight from New Zealand to Singapore. The delivery between these two countries was considered as the route during which highest product spoilage rate was observed for international fish exports from New Zealand, and the fish shelf life was 4.76 days lower than that stored at 0°C.

Some ambient temperature profile databases are available for member at International Station Meteorological Climate Summary (ISMCS, https://ui.adsabs.harvard.edu/abs/1992BAMS...731578J/abstract) or International Safe Transit Association (ISTA, https://ista.org/test_procedures.php) and could be useful for those with no available data (East et al., 2009; Kacimi & Labranque, 2019).

2.6 Influence of each factor in application and modeling

As mentioned above, there are numerous parameters influencing the temperature profiles in an insulated box with PCM such as the characteristics of box (dimensions, shape of the corners and type of insulating material), PCM (type, quantity and position), product (thermophysical properties, mass and arrangement) and operating conditions (ambient temperature and transport duration). In such complex situations, physical-based modeling tools can be useful to identify the most sensitive factor. Paquette et al. (2017) performed sensitivity analysis to determine the most significant factor (external convective heat transfer, emissivity of food, box and gel packs, the thermal conductivity and the heat capacity of the insulating material). They reported that the thermal conductivity of the insulating material affected the product temperature profile to the greatest extent. Consequently, this is the main criterion to take into account when designing the system. Different types of models can be developed. A 1D analytical model was utilized to gain a general perspective of the system and roughly predict useful responses, e.g. maximum temperature, PCM melting time (Laguerre et al., 2018, 2019). A zonal model which assumed that each zone has uniform and lumped properties is also used to acquire a thorough understanding with an acceptable calculation time for design optimization and temperature prediction (East et al., 2009; East & Smale, 2008). 2D and 3D heat transfer of a CFD model (in some cases, convection and/or radiation were neglected) are described in articles with extensive results such as temperature distribution and profile, PCM liquid fraction and air velocity, but this approach requires more computational time and resources (Du et al., 2020; Laguerre et al., 2018, 2019; Margeirsson et al., 2011, 2012; Paquette et al., 2017). A data-based model, which needs less background in physics, is simpler to use. This model represents a simple relationship between the input parameters and the intended responses, for example, using the thermal resistance of the insulated box to predict food quality (Navaranjan et al., 2013).

This complexity also impacts system design. To find the best compromise between these constraints, the objectives must be clearly identified depending on the application. For example, one might consider that the criterion is the maximum temperature that can be attained inside the box after a defined duration or the temperature heterogeneity within the box. The choice of this objective might impact the design of the box and the PCM. For instance, if the box is designed to transport fruit and vegetables with an optimal temperature range (e.g. from 4°C to 10°C), the temperature heterogeneity might not be crucial. Hence, there will be more flexibility in the choice of the box material and the PCM position in the box. A specific design is required during transportation of highly temperature sensitive products e.g. superchilled food products (Kaale et al., 2011). These authors reported that temperature fluctuations lead to ice recrystallization and drip loss leading to product quality degradation. East & Smale (2008) and East et al. (2009) optimized insulated box design using a hybrid genetic algorithm to obtain the box with the lowest cost regarding material, transportation and penalty due to temperature abuse. They suggested that the boxes used in summer should have a thicker insulating material and a larger quantity of PCM to withstand the heat flux from ambient than that in winter while the other factors remained almost identical.

Among the studies examined in our review, several focused on how to improve the insulation of a classic box, i.e. a box made of expanded polystyrene, polyurethane, or a corrugated box by increasing the air gap, adding spacers, vacuum panels and metallizing the surface. The rounded corner box design was also suggested to deal with temperature heterogeneity. The methods used to determine insulation efficiency was developed by measuring the heat flow resistance (R) value and was tested in real application. The external temperature and load type and mass inside the box were also investigated. The effect of each factor was described and predicted by basic heat transfer equations. There was substantial evidence proving that the application of PCM could lower the temperature of the system and possibly improve thermal homogeneity. However, the PCM melting point, the amount of PCM and optimization of its position are still necessary to achieve the most efficient conditions for each system.

For food transport, there is a lack of field data on what happen to insulated boxes when they arrive the destination. For pharmaceutical transport, a survey revealed that 79% of customer consider that using reusable containers for delivery is more attractive than single use ones in spite of higher price (Biopharma cold chain logistic survey, 2019). This statistical data is in agreement with an increase of plastic waste recycling by 92% in Europe in 2020 due to the sake of cold chain sustainability, (European Association of Plastic Recycling and Recovery Organisations, 2020).

Concerning the box with PCM, it could be possible to apply a similar principle for reusable packaging by improving the logistic organization of return boxes and PCM from the end-user (retailer, final consumer) to the supplier (food distribution center). For example, the development of deposit locations and the collection by a transporter in order to minimize the logistic costs and environmental impact.

3. Cold chain equipment with PCM

Unlike in an insulated box, PCM in refrigerated equipment often enables energy management, temperature stabilization, etc. Many articles pointed out the capacity of PCM to reduce the compressor operating time, thus lowering energy consumption (Alzuwaid et al., 2015; Azzouz et al., 2008, 2009; Berdja et al., 2019; Ezan et al., 2017; Maiorino et al., 2019; Sonnenrein, Baumhögger, et al., 2015; Sonnenrein, Elsner, et al., 2015; Yilmaz et al., 2020). Several studies showed that PCM allows the extension of the cooling period following power failure (Ben-Abdallah et al., 2019; Oró, Miró, et al., 2012; Yilmaz et al., 2020). Use of PCM can also decrease the temperature of the system with greater homogeneity (Alzuwaid et al., 2015, 2016; Azzouz et al., 2009; Ben-Abdallah et al., 2019; Maiorino et al., 2019; Sonnenrein, Baumhögger, et al., 2015).

3.1 PCM in refrigerated trucks

PCMs with various melting points were applied in the cooling unit or on truck walls, and the studies are summarized in Table 2. To obtain a very low melting point, different types of salts with different concentrations were used: an in-house inorganic salt solution with a melting point of -26.7°C (M. Liu et al., 2012), a NaCl solution with a melting point of -21.2°C, (Xiaofeng et al., 2017) and commercial blends of salts with melting points of -26°C, -29°C and -32°C, (Mousazade et al., 2020). For PCMs with higher melting points (7°C to 45°C) which are inserted between the external and internal walls, paraffin and salt hydrate were used (Ahmed et al., 2010; Copertaro et al., 2016; Fioretti et al., 2016).

To facilitate experimental implementation, several studies investigated stationary refrigerated trucks in a test chamber in which the ambient temperature alone was controlled. M. Liu et al. (2012) determined the period during which the internal temperature was below -15°C by using 136.8 kg of PCM salts in a tank connected to the truck evaporator when the ambient temperature was about 30°C. The authors predicted that 163% more PCM would be necessary for 10 h transportation during summer (maximum temperature = 41°C) in Adelaide, Australia. The same authors also pointed out that a phase change thermal storage unit could replace the cooling engine. This storage unit, charged at the distribution center before transportation, allows 51.0% - 86.4% cost savings depending on the COP of the system and the electricity tariff.

Fioretti et al. (2016) studied insulating walls with and without PCM exposed to solar radiation in a test room to simulate real conditions. They observed that the wall fitted with PCM resulted in an internal wall surface temperature that was 1.8°C lower.

Other studies dealt with stationary refrigerated trucks under real climate conditions i.e. ambient temperature, solar radiation. Ahmed et al. (2010) and Fioretti et al. (2016) investigated the efficiency of their systems with PCM under real conditions and reported that the truck equipped with PCM could decrease the total heat flux through the wall by 1.7% to 26.4%. This heat flux varied according to the angle between the wall and the radiation source.

Copertaro et al. (2016) developed a model in order to choose the PCM with the most suitable melting point to be inserted between the external and internal walls of refrigerated trucks. They recommended that with a melting point of 35°C for the truck operating under ambient temperatures varying from 20°C to 33°C as observed in various cities in Italy in summer.

Mousazade et al. (2020) conducted an experiment in a moving truck and pointed out that the speed needed optimization. In fact, a higher speed led to a greater distance covered and lowered the PCM cooling time due to higher heat exchange. This was probably due to a higher external convective heat transfer coefficient and more vibration. They reported that the longest PCM cooling period was 4.78 h in a truck moving at a speed of 81 km/h (distance covered: 387

km), but the longest distance covered was 491 km in the case of a truck moving at a speed of 110 km/h (4.46 h cooling period).

3.2 PCM in cold rooms

According to the authors' knowledge, only a few studies have been conducted on PCM application in cold storage facilities or warehouses, although it has been shown that higher product quality can be achieved using PCM (Pirdavari & Hossainpour, 2020; Schalbart et al., 2013). The difficulty in PCM charging and temperature control in a cold room may be one of the main obstacles to implementation. The application of PCM in cold storage facilities is summarized in Table 3.

PCM can be placed on the wall of the cold storage facility (T. Yang et al., 2017), in some locations inside the building (Schalbart et al. 2013), or near the product (Pirdavari & Hossainpour 2020). For potatoes cold storage at temperatures above 0°C, Pirdavari & Hossainpour (2020) considered PCM with a melting point between 8.5°C and 9.5°C. They optimized the melting point of the PCM, the ratio of the weight of PCM to the one of the potatoes and the insulation type. They indicated that a greater amount of PCM, a lower PCM melting point and a higher thermal resistance of the insulation triggered, a longer melting time and a lower product temperature. For ice cream, Schalbart et al. (2013) optimized the melting point of the PCM between -23.3°C and -17.5°C. They showed that the use of PCM reduced ice crystal growth by 2.7% to 9.0% thanks to fewer temperature fluctuations.

T. Yang et al. (2017) and Pirdavari & Hossainpour (2020) reported that installing PCM fulfilled the gap in energy supply in the case of solar energy or a more economical electrical source, which are not available all day.

3.3 PCM in display cabinets

The application of PCM in display cabinets is summarized in Table 4. Pure ice placed near the evaporator was generally used (Alzuwaid et al., 2016; Ben-Abdallah et al., 2019; Ezan et al., 2017). Ice with an additive (melting point -6°C to -2°C) was placed either near the evaporator or below the cabinet shelves (Alzuwaid et al., 2015; Yilmaz et al., 2020). Oró, Miró, et al. (2012) applied commercial PCM (Climsel C-18 and Cristopia E-21), with melting point of -18 °C and -21.3 °C respectively, over evaporator tubes located at different shelves of a closed display cabinet. The authors reported that for empty closed display cabinet, the air temperature rose from -22 °C to 0 °C within 1.5 h (without PCM), 6.5 h (-18°C PCM) and 8 h (-21°C PCM). This period extended when display cabinet was loaded by test product: 11.5 h (without PCM), 15.6 h (-18°C PCM) and 21.5 h (-21°C PCM), as illustrated in Fig. 3. These results demonstrated the interest of PCM to slow down the product temperature when the display cabinet was turn off, due to machine failure for example.

PCM decreased the compressor operating time by 4% to 10% and reduced energy consumption by 5.0% to 6.4% (Alzuwaid et al., 2015, 2016; Ezan et al., 2017). In fact, for a given average air temperature in a cold enclosure with and without PCM; the same quantity of heat has to be removed. However, the presence of PCM makes the temperature in the enclosure more stable, so, a slightly higher evaporator temperature can be used. Thus, the COP is increased and the electrical energy consumption is reduced. In this manner, the heat transfer efficiency of the cold enclosure can be improved. The amount of PCM or the thickness of the PCM slab had to be optimized (Ben-Abdallah et al., 2019). Ezan et al. (2017) compared the efficiency of PCMs with a thickness varying from 2 mm to 10 mm and reported that the compressor operating duration was the lowest with the 6-mm PCM thickness due to appropriate cooling capacity without significantly obstructing the airflow inside the equipment. The position of the PCM is another challenge in the application because PCM in an inappropriate place led to a worse outcome than in a context where no PCM was used. Yilmaz et al. (2020) reported that when a PCM was used at the back of a closed display cabinet, the system consumed 8% more energy than a system without a PCM due to the delay in cabinet temperature change detection of temperature sensor.

PCM was able to stabilize the display cabinet for 5 h to 14 h longer during a power outage (Oró, Miró, et al., 2012; Yilmaz et al., 2020). Ben-Abdallah et al. (2019) mentioned that the internal temperature increased by 1°C in the open display cabinet with PCM during the 2 h period during which the compressor was not operating compared with 2°C in the system without PCM. Adding load into the test system could prolong this period by 8 h to 12 h compared with the empty system as it increased thermal inertia (Oró, Miró, et al., 2012).

3.4 PCM in domestic refrigerators

Several studies have investigated PCM application in domestic refrigerators as summarized in Table 5. In most studies, the PCM was placed at the evaporator by using ice (Azzouz et al., 2009; Maiorino et al., 2019), a copolymer with a melting point of -4°C (Sonnenrein, Baumhögger, et al., 2015), or an eutectic solution with a melting point between -9°C and -1°C (Azzouz et al., 2008, 2009). Sonnenrein, Baumhögger, et al. (2015) and Sonnenrein, Elsner, et al. (2015) applied ice, paraffin (melting point = 34°C) and a copolymer (melting point = 34°C to 35°C) at the condenser. Sonnenrein et al. (2020) studied the application of a copolymer PCM (melting point = 9°C) in the load compartment.

PCM decreased the temperature of the system and resulted in 17.6% to 32.5% less operating time, 10% to 17% less energy consumption and 5% to 15% greater COP (Azzouz et al., 2008; Berdja et al., 2019; Sonnenrein, Baumhögger, et al., 2015). The selection of a PCM with an appropriate melting point was necessary to ensure the efficiency of the cooling system

(Azzouz et al., 2008). Azzouz et al. (2009) reported that placing a eutectic plate (melting point = -3°C) at the evaporator lowered the internal temperature by up to 1.5°C. However, the compressor operating period was 0.4 h longer. Thus the COP was lower in comparison with the system using ice. Sonnenrein, Baumhögger, et al. (2015) and Sonnenrein, Elsner, et al. (2015) reported that paraffin and copolymer PCM (melting point = 34°C to 35°C) were more efficient than ice at the condenser since they allowed a temperature that was 5°C to 6°C lower to be achieved at the condenser, leading to 2% to 17% lower energy consumption. The thickness of the PCM slab should also be optimized to achieve the highest efficiency (Azzouz et al., 2008; Berdja et al., 2019).

PCM (melting point = 9°C) in the load compartment has proved to be useful in several commercialized domestic refrigerators by decreasing the cooling time (the time required to reduce the product temperature from 25°C to 10°C) by 16% to 33%. It also makes it possible to increase the temperature rise period (the time required to raise the package temperature from 8°C to 11°C after turning off the cooling system) by 75% to 145% (Sonnenrein et al., 2020).

Frost formation on evaporator was still a challenge since it exerted a greater effect on airflow than the PCM due to higher thermal resistance (Berdja et al., 2019). Azzouz et al. (2008) pointed out that greater numbers of door openings led to lower PCM efficiency as the PCM did not completely melt by the time the compressor restarted and could not provide full cooling capacity. Maiorino et al. (2019) indicated that an ambient temperature that was 7°C higher raised energy consumption by 38.4% to 63.6% although PCM was applied in both conditions.

4. General discussion

The application of PCMs in the cold chain has been widely studied with a wide variety of types of equipment. PCMs can be used in complement with cold production in refrigerated equipment or as alternative cooling systems. For example, when refrigeration equipment is not available or the ambient temperature during transportation is not appropriate, an insulated box with a PCM can be an alternative. It ensures a low, stable temperature, and thus preserves food quality.

The incorporation of PCM in refrigerated equipment is mostly performed for energy-management-related purposes. Many studies have been conducted on PCM in domestic refrigerators and display cabinets, but fewer studies have been performed on cold rooms. This may be due to difficulties related to the controlling and recharging of PCMs.

What clearly appears from the existing studies is the absence of an ideal general solution to apply PCM in equipment and boxes as it involves complex interactions between the parameters of the studied system such as the insulating material, the external temperature, the product load, the melting point and the quantity of the PCM.

To design such a system, experimentally validated numerical studies (CFD or zonal models) can be used to simulate other configurations. These models often consider heat transfer by conduction alone, although radiation and free convection can exert significant impacts in insulated boxes, especially in terms of temperature heterogeneity. Consequently, it is important to quantify heat flux by conduction, convection, and radiation since none of them can be neglected. Therefore, further studies are essential to better understand the relationship between heat transfer and airflow by natural convection. Studies on the effect of the load porosity on heat transfer by convection and conduction and on the impact of the emissivity of walls or product packages on heat transfer by radiation should be undertaken.

Other concerns in the application of PCMs are related to chilling injury, particularly when a PCM is directly in contact with sensitive products. To avoid this problem, some studies proposed, for instance, to precondition the PCM before product loading.

The use of PCMs in insulated boxes exerts environmental impacts because of the PCM production itself, the production of the insulating material and the energy consumption required for charging the PCM before each use, along with PCM waste etc. Consequently, additional specific studies on these issues may help evaluate the feasibility and sustainability of the use of PCMs. Some progress has been achieved in the development of new insulating materials with less environmental impacts. For example, Jiang et al. (2021) and Khalaf et al. (2021) fabricated cellulose-based and chitosan-based insulating materials, respectively. Melone et al. (2012) also developed a composite cellulose and paraffin (melting point 0°C to 10°C) insulating material acting as phase change material for transporting perishable products.

5. Conclusions and suggested future research

Applying PCMs in the food cold chain provides several benefits: less temperature abuse, and thus better product quality and better energy management. To achieve these benefits, many factors should be considered: insulating material (thermal conductivity and thickness), PCM type (i.e. heat storage capacity and its melting point), its quantity and position, load characteristics (load nature, mass and arrangement), and operating conditions (i.e. ambient temperature and storage and transport duration). These factors significantly affect the efficiency of the system, especially when PCM is the only cold source (no refrigerating machine). Thus, optimization of these factors is necessary in order to design the best configuration for achieving the objective of each application.

Modeling is a complementary experimental approach but is more complicated to develop. By using modeling, the prediction of results under unexplored operating conditions is possible e.g. ambient temperature, transport/storage duration, load type and its initial temperature. Existing models could be improved by acquiring a better understanding of the instantaneous heat transfer and airflow in the cold equipment. Knowledge of airflow can be acquired by using innovative optical techniques such as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV). These techniques are already used for several types of refrigerated equipment (refrigerated trucks, display cabinets and domestic refrigerators) but are not yet applied to insulated boxes with PCM in which the air velocity is very low because natural convection is the driving phenomenon.

According to the authors' knowledge, an insulated box equipped with a fan has not yet been commercialized. This type of box would allow airflow by forced convection inside the box, and the temperature would thus be more homogeneous. A rechargeable battery should supply enough power to the fan in order to assure continuous fan running along the supply chain. After arrival at the end-user's premises, the box could be returned to the distribution center (or the departure site), then the battery could be recharged with optimal power prior to the following delivery. The rechargeable battery and fan design need future development.

Although there are many challenges in display cabinet operation such as exposure to light and door openings, few studies have investigated these effects in cold equipment with PCM, so studies focused on these aspects would be useful. Moreover, only a few studies on PCMs used in cold rooms have been published. Additional studies on this application would be valuable. Applying PCM in commercially available refrigerated equipment ranging from refrigerated trucks to domestic refrigerators could attract interest within the industry.

For the sake of cold chain sustainability, the extensive use of polystyrene and polyurethane as insulating materials should be replaced by biodegradable materials (cellulose-based and chitosan-based for example), thus exerting less impact on the environment. Also, reusable boxes and a recycling logistic chain should be developed to a greater extent taking into consideration both the economic cost and the environmental impact.

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Table 1 Summary of studies using PCM in insulated boxes

Reference / Product	**PCM (melting point) / position**	**Box material (internal dimensions)**	**Type of the study**	**Main observation(s)**
Margeirsson et al. (2011) / Haddock fillets	Ice pack (0°C) / on top of the product	- Expanded polystyrene (EPS) (35.6 cm x 22.0 cm x 8.5 cm) - Corrugated plastic (CP) (37.0 cm x 23.0 cm x 8.0 cm)	Experimental and numerical (3D CFD)	- The warmest position was at the bottom corner - The coldest position was at the top center - After 6 h, the temperature increase in EPS and CP boxes was 8°C and 14°C, respectively - Ice pack decreased the product temperature by around 4°C but increased its heterogeneity (up to 8°C compared with 3°C in the box without an ice pack).
Margeirsson et al. (2012) / Cod fillets	Ice pack (-0.5°C to 0.5°C) / on top of the product	EPS with - Sharp corners (35.6 cm x 22.0 cm x 10.9 cm)	Experimental and numerical (3D CFD)	- The warmest position was at the bottom corner - The coldest position was at the top center - Fillets in rounded box had a 2°C lower temperature difference and a shelf life that was 2 days longer.

		- Rounded corners (35.6 cm x 22.0 cm x 9.0 cm)		
Navaranjan et al. (2013) / New Zealand terakihi (*Nemadactylus macropterus*)	Ice pack (0°C) / in the center at the top of the box	6 Boxes with the same dimensions (55.0 cm x 37.5 cm x 12.0 cm) - 3 In-house EPS with 1.0 cm, 1.5 cm and 2.5 cm thickness (E10, E15 and E25) - 1 Commercial EPS box (CE) - 1 box-in-box using CP with 1.5 cm gap (B1) - 1 improved box-in-box with 2.1 cm gap	Experimental	- The warmest position was at the corner - The coldest position was at the center - Thermal resistance (R) of B2 is twice that of B1 but less than CE and it positively related to the thickness of in-house EPS box. - Fish quality estimated by time- temperature profile related to R value of the insulating material with a coefficient of determination > 0.80.

		and covered with aluminum foil (B2)		
Paquette et al. (2017) / Water beaker, food can, meat pack, vegetable pack and fresh-cut lettuce pack	Gel pack (0°C) / at different locations in the box related to the meat pack: on the side, above, below and both above and below	Multilayer box in CP box (40.4 cm x 31.9 cm x 21.5 cm)	Numerical (3D heat transfer) with experimental validation	- Use of aluminum foil led to 13% and 10% lower meat and lettuce temperatures (in °C), respectively. - More gel packs prolonged the time needed for meat to reach 10°C: 6.0 h (without a gel pack) and 36.6 h (6 kg gel pack). - The configuration with the gel pack at the center was the most efficient. - Thermal conductivity of insulation had the most influence on product temperature.
Laguerre et al. (2018) / Horse mackerel (*Trachurus*)	Flaked ice (0°C) / top of fish stack	EPS box with 3 cm thickness	Experimental and numerical (1D analytical model and 2D CFD)	- The warmest position was at the bottom - The coldest position was at the top - 2D CFD could predict the cooling front in the box. - The cooling time of the bottom stack correlated with the fish stack's thickness.

Laguerre et al. (2019) / Sardine	Ice pack (-0.1°C to 0.1°C) / top of the fish stack	2 EPS box with different dimensions. A: 21.0 cm x 21.0 cm x 17.9 cm with 1.8 cm thickness B: 17.5 cm x 23.5 cm x 15.3 cm with 2.5 cm thickness	Experimental and numerical (1D analytical model and 3D Finite Element Method or 3D FEM)	- The warmest position was at the bottom corner - The coldest position was at the top - 1D analytical model could roughly predict melting time and highest product temperature. - 3D FEM could determine temperature profile more accurately, particularly under real conditions.
X. Zhao et al. (2019) / Strawberries	Commercial PCM (-2.0°C to -1.2°C) / top wall of the box	EPS (29.0 cm x 17.5 cm x 13.0 cm)	Experimental	- The stored sample packed in the box and PCM had a higher organoleptic quality than that without PCM. - The weight loss of the product decreased 3% and 10% while the respiration rate was reduced 22% and 17% under 10°C and 20°C conditions, respectively compared with no package.

Du et al. (2020) / No load	PCM (0°C, 2°C, 3°C, 4°C, 5°C and 8°C) / 5 configuration - 100% top (A) - 20% each side and top (B) - 25% each side (C) - 20% each side and bottom (D) - 100% bottom (E)	Polyurethane (PU) or vacuum insulated panels (VIPs) (35.5 cm x 21.5 cm x 26.5 cm)	Numerical (3D heat transfer model) with experimental validation	- A PU box + PCM with melting points of 2°C and 8°C gave the highest cooling time (9.6 h) and lowest cooling time (2.1 h), respectively. - Configuration B led to highest cooling time (9.6 h) while configuration A and E had the lowest values (around 0.6 h). - VIPs allowed a longer cooling duration than PU (up to 36.9 h).
Xiaofeng & Xuelai (2021) / No load	2 PCM type: A: 87% n-caprylic acid and 13% myristic acid	PU and VIP (145 cm x 75 cm x 65 cm) divided into 3 compartments for 1) ambient storage (no PCM), 2) chilled	Numerical (3D unsteady model) with experimental validation	- The warmest position was at the top corner of first compartment - The coldest position was at the wall's surface between second and third compartment

	(7.1°C) for chilled storage B: potassium sorbate solution (-2.1°C) for sub-zero storage/ 4 side walls and a bottom of each compartment	storage at 7°C to 10°C with PCM A, and 3) storage at -3°C to -1°C with PCM B with volume ratios of 1:1:1 and 1:2:2.		- In the box with 1:1:1 volume ratio, the temperature in the second and third compartments was maintained at the desired range for 15 h and 16.5 h, respectively. - But it was only 10.8 h, and 11.5 h, respectively in the box with 1:2:2 volume ratio.
Elliott & Halbert (2005) / Small boxes containing empty packages	Ice brix® frozen gel pack: 3, 4, 8 and 16 packs (charging at -20°C) / the wall of the box	Polystyrene (32.0 cm x 32.0 cm x 24.5 cm)	Experiment and transit test to maintain the temperature between 0°C and 8°C	- 3 gel packs gave the desired temperature range. - Placing PCM before product loading (for 4 h or 24 h) or preconditioning prevented storage conditions that were too cold. - Transporting with 3 gel packs resulted in acceptable temperature profiles in all seasons except in summer, when 4 gel packs were needed.

Elliott & Halbert (2008) / Small boxes containing empty packages	dry ice (CO_2: -78.5°C) / bottom of the box	EPS box (32 cm x 32 cm x 29.5 cm)	Experiment and transit test to maintain temperature below -10°C	- The warmest position was at the top - The coldest position was at the bottom - The preferable configuration was when dry ice was placed closer to the product with the highest temperature at -21.9°C. - All transit tests during real transport yielded good results.
Laguerre et al. (2008) / Cartons of several product units	PCM (-0.5°C) / top, middle and bottom of the container	Corrugated cardboard insulated with polystyrene plates (108 cm x 72 cm x 137 cm)	Experimental and numerical (excitation-response model)	- The warmest position was at the middle of the side wall - The coldest position was at the bottom center - The model was validated and able to predict the product temperature inside the container exposed to a variable ambient temperature when the PCM was not completely melted.
Kacimi & Labranque	- Organic PCM (5°C) / all box faces	VIPs with 15 L, 27 L, 40 L and 64 L	Experimental	- The warmest position was at the top - The coldest position was at the bottom

(2019) / Empty packages and water bags	- Inorganic PCM (21°C) / bottom, top and two opposite sides			- Organic PCM could withstand cold better than warm conditions when the inorganic PCM could perform better. - The boxes with 27 L and 40 L volumes were more efficient than the other two box sizes.
Kozak et al. (2017) / Water bottle	Salt solution (-10°C for small box or -33°C for big box) / in bottles placed inside the box	Cardboard box (external dimensions: 32 cm x 25 cm x 25 cm – small; and 50 cm x 50 cm x 50 cm – big) with insulating material fitted with the bottle	Experimental and numerical (1D analytical model)	- The warmest position was at the top - The coldest position was at the bottom - Changing Biot number from 1 to 4 did not markedly affect the melting time. - Melting time was affected by the ratio between the thermal conductivity of the liquid PCM and insulation.
East & Smale (2008) / Beverage cans	Ice pack (0°C), or commercial PCM (2°C and 5°C) / below the product	Polyurethane or polystyrene (28.7 cm x 28.7 cm x 13.2 cm)	Box design optimization (8 parameters) regarding the cost of the	- The box thickness (about 150 mm), PCM type (ice pack) and PCM thickness (about 60 mm) were the factors that influenced optimization to the greatest extent.

			material, shipping and penalty due to temperature abuse by using zonal based heat transfer model coupled with a hybrid genetic algorithm	- The cost of the boxes is almost the same, whatever the design.
East et al. (2009) / Beverage cans	Same as East & Smale (2008)	Same as East & Smale (2008)	- Same optimization approach as East & Smale (2008) but for different climate conditions to obtain an optimal box design for summer only (22°C to 35°C, 24 h), only winter (-18°C to 10°C,	- In winter, a 10 mm polystyrene box and a 10 mm of ice pack were proposed and caused 86% heat failure. - In summer, it required a polyurethane box thickness of 90 mm and 53.9 mm ice pack but led to 26% freezing failure. - Boxes for both summer and winter had 90 mm of polyurethane wall thickness and a 30.5 mm ice pack and caused only 0.5% of freezing failure.

			24 h), and both summer-winter (-18°C to 35°C, 48 h) transport. - These boxes were numerically tested against 1095 ambient temperature profiles that varied according to climate conditions.	- The box for winter climate conditions only is about twice as cheap as those used in summer only or both in summer and winter.

Table 2 Summary of studies about using PCM in refrigerated trucks

Reference / Type of study	**PCM (melting temperature) / its location**	**Main observation(s)**
Ahmed et al. (2010) / Experimental (stationary empty truck container under real climate conditions)	Paraffin (7°C) / between the external wall and the internal wall	PCM decreased peak heat flux (11.3% to 43.8%) and total heat flux (1.7% to 26.4%) depending on the angle between the wall and the sun.
M. Liu et al. (2012) / Experimental (empty truck in laboratory) and numerical (Transient system simulation)	Inorganic salt solution (-26.7°C) / in the tank connected to the heat exchanger of the refrigerated space	- In the experiment, 136.8 kg of PCM stabilized the temperature below -15°C for 3 h. - From numerical results, 360 kg of PCM was suggested for 10 h transportation. - This system could save energy costs by 51.0% to 86.4% compared with the system using internal combustion engine cooling.
Copertaro et al. (2016) / Numerical (2D heat transfer model in empty refrigerated truck) with experimental validation	8 paraffins (27.5°C to 45°C) and 1 salt hydrate (46.5°C) / inside the refrigerated truck wall made of steel.	- Paraffin PCM was more efficient than salt hydrate: it reduced energy consumption by 4% on the average, whereas salt hydrate achieved a 2% reduction. - PCM with 35°C melting point was the most efficient.

Fioretti et al. (2016) / Experimental (stationary empty truck container in laboratory test room and real climate conditions) and numerical study (2D heat transfer model)	Paraffin wax (35°C) / inside refrigerated truck wall made of steel	- The experiment demonstrated that PCM decreased heat flux (between 15 W/m^2 and 47.5 W/m^2 to between 13 W/m^2 and 25 W/m^2), decreased the external wall surface temperature (from 93.0°C to 80.0°C), and the internal wall surface temperature (from 11.8°C to 10.0°C). - From numerical results, comparing the PCM-equipped wall and no PCM with the thicker insulated wall, the former had less temperature variation (0.3°C and 0.7°C) but a slightly higher average temperature (around 0.15°C) than the latter.
Xiaofeng et al. (2017) / Numerical (3D CFD of empty refrigerated truck)	Eutectic NaCl solution (-21.2°C) / in a plate installed on the truck wall	- Higher climate temperature led to a shorter melting time (86 h and 73 h at 20°C and 30°C, respectively), higher heat transfer rate (1.9 W/h and 2.75 W/h at 20°C and 30°C, respectively) and a higher internal air temperature (0°C and 10°C at 20°C and 30°C ambient temperature, respectively). - The highest air velocity (0.035 m/s) was located near the lowest part of the PCM plate.

Mousazade et al. (2020) / Experimental (stationary and moving empty truck)	Commercial PCM containing various blends of salts (-26°C, -29°C and -32°C) / in a plate placed on the truck wall.	- PCM melting at -26°C showed the best cooling efficiency with the longest melting time (5.11 h and 4.78 h in stationary and 81 km/h truck, respectively). - Higher truck speed caused lower melting time but longer travelling distance where the maximum distance was 491 km in a truck with a speed of 110 km/h.

Table 3 Summary of studies using PCM in cold storage facilities

Reference / Type of study	**PCM (melting point) / its location**	**Main observation(s)**
Schalbart et al. (2013) / Numerical (1D finite difference equation system) of warehouse storage of ice cream for a period of 90 days with different PCM positions.	PCM with a melting point that was optimized depending on the location / post-evaporator, ceiling, wall, storage tank and product package	- From optimization, the melting point of the PCM was in the range of -23.3°C at the storage tank to -17.5°C at the walls. - Without PCM, the predicted final ice crystal size was 58 µm and there was ±1.0°C temperature fluctuation with 13.6 GJ energy consumption. - Predicted final ice crystal size was 53 µm with PCM at storage tank to 57 µm with PCM at the ceiling and the temperature fluctuation was only ±0.01°C with PCM at product package to ±0.76°C with the PCM at the ceiling. - PCM at post-evaporator and storage tank increased the energy consumption by 2.2 GJ and 0.7 GJ, respectively, while at other locations, energy consumption was almost the same as that without PCM.

T. Yang et al. (2017) / Numerical (3D CFD) of cold storage facility with a container of potatoes	Ice plate (0°C) / on each side of the wall, the floor and the roof	The upper part was 4°C warmer than the lower part due to external heat convection via the roof which had a heat transfer coefficient of 5 W/m^2 K.
Pirdavari & Hossainpour (2020) / Optimization via numerical study (1D simplified dynamic model which is validated by using experimental data from Azzouz et al. (2009)).	$LiClO_3 \cdot 3H_2O$ PCM capsule (8.5°C, 9.0°C and 9.5°C) / in a cylindrical column placed in the stack of potatoes in the cold room.	The greater the quantity of PCM, the lower the melting point of the PCM and the lower the thermal conductivity of insulation led to a longer melting time and lower product temperature.

Table 4 Summary of studies using PCM in display cabinets

Reference / Type of study	**PCM (its phase change temperature) and its location**	**Main observation(s)**
Oró, Miró, et al. (2012) / Experimental (closed display cabinet freezer)	ClimSel C-18 (-18°C) or Cristopia E-21 (-21.3°C) / encapsulated in a stainless-steel thin plate placed on top of the evaporator tube	- For an empty display cabinet, the air temperature rose from -22°C to 0°C within 1.5 h (without PCM), 6.5 h (C-18) and 8 h (E-21). - The presence of load in the display cabinet enabled this period to be extended: 11.5 h (without PCM), 15.6 h (C-18) and 21.5 h (E-21).
Ezan et al. (2017) / Numerical (3D CFD) with experimental validation (closed display cabinet)	Ice (0°C) / placed behind rollbond evaporator at the rear of the empty cabinet	- The coldest area was at the bottom corner and the warmest area was located at the top with up to 7.5°C temperature difference. - Increasing PCM thickness explains the decreases of compressor run-time ratio: 36% (without PCM), 32% (2 mm PCM), 28% (4 mm), 26% (6 mm) 27% (8 mm) and 29% (10 mm). - PCM that was too thick obstructed the airflow with maximum velocity at 4.94 m/s (10 mm of PCM slab) and at 5.55 m/s (2 mm) and led to a higher ratio of compressor run-time.

Yilmaz et al. (2020) / Experimental (closed display cabinet)	Distilled water with a nucleating agent and thickening agent (-6°C) / either on the back wall or on the shelves	- PCM on the back wall generates minimum running cycles: 17 cycles (without PCM) to 11 cycles (PCM on shelves) and 9 (PCM on back wall) over 8 h running. - PCM on shelves is more efficient than that on the back wall: 888 kJ, 3.8 h "on" cycle (shelves) and 1003 kJ, 5.6 h, (backside) over 8 h running. - During power failure, the system with PCM had a longer cooling period with 6 h, 17 h, and 20 h, without PCM, with PCM at the back, and with PCM on the shelves, respectively.
Alzuwaid et al. (2015) / Experimental (open display cabinet)	Ice gel PCM (-2°C) / above evaporator	Adding PCM led to 5% energy savings, 70% longer defrost period, 2°C lower maximum cabinet temperature and more stable product temperature: Tmax-Tmin 7.33°C (without PCM) and 6.50°C (with PCM).
Alzuwaid et al. (2016) / Numerical study (2D CFD)	Pure-water ice PCM (0°C) / above the evaporator	- Installing PCM enabled 6.4% energy savings to be achieved and decreased the product temperature difference from 5.0°C (without PCM) to 4.2°C (with PCM).

with experimental validation (open display cabinet)		- The highest product temperature was at the front of the middle shelf and the lowest one was located at the back of top shelf.
Ben-Abdallah et al. (2019) / Experimental (open display cabinet)	Ice (0°C) / in a finned tube heat exchanger placed in the rear duct	- Adding PCM decreased the average air temperature from 8.4°C (without PCM) to 1.5°C (with PCM). - PCM is an airflow obstacle and lowered the airflow by 28%. - When the compressor stopped operating for 2 h, the product in the cabinet with PCM the temperature increase was only 1°C compared with a 2°C increase without PCM.

Table 5 Summary of studies using PCM in domestic refrigerators

Reference / Type of study	**PCM (melting point) / its location**	**Main observation(s)**
Azzouz et al. (2008) / Numerical study (1D simplified dynamic model) with experimental validation.	Eutectic aqueous PCM (-9°C, -7°C, -5°C, -3°C or -1°C) / on evaporator surface	- Adding PCM increased the COP by 5% - 15 %, decreased operating time by 28.5% - 32.5% and prolonged the cooling period by 4 h – 8 h when the compressor was off. - Increasing the melting temperature of the PCM led to a higher COP but also a higher cabinet temperature. - Thicker PCM caused a shorter operating time because of the higher cooling capacity.
Azzouz et al. (2009) / Experimental	Ice (0°C) or eutectic mixture (-3°C) / on evaporator surface	- Eutectic mixture PCM led to 1.0°C to 1.5°C lower air temperatures but a 0.4 h longer compressor operating period. - The COP of the refrigerator with ice or with eutectic salt solution were not significantly different. - Increasing the PCM thickness did not improve the COP since it was not completely frozen.

Sonnenrein et al. (2015b) / Experimental	Paraffin (34°C), copolymer compound with 10% (w/w) graphite (34°C), or water (0°C) / condenser	- Paraffin PCM on the condenser led to a 5°C lower condenser temperature and 2% to 7% lower energy consumption compared with water (only sensible heat variation). - Copolymer compound PCM on the condenser generated up to 10% energy savings.
Sonnenrein et al. (2015a) / Experimental	- Copolymer PCM (-4°C) / evaporator - Another copolymer PCM (35°C) / on the condensers of 2 different refrigerator models	- PCM increased the evaporator temperature between 6°C and 8°C and decreased the condenser temperature by 6°C. - 12% to 17% less energy consumption and a more constant compartment temperature were observed in refrigerators with both types of PCM.
Berdja et al. (2019) / Experimental and numerical (1D analytical model)	PCM (-11°C) / covering the evaporator surface	- From the experiment, installing PCM resulted in 10% lower energy consumption, 17.6% lower compressor operating time, 5.05% greater COP and an evaporator temperature that was 1.89°C lower. - From numerical results, higher PCM slab thickness yielded a lower overall heat transfer coefficient (H).

		- Adding PCM led to longer periods during which the compressor was off, but also generated a higher air temperature. - H was more affected by frost formation and its thickness than by PCM slab thickness due to lower thermal conductivity of frost.
Maiorino et al. (2019) / Experimental	Ice (0°C) / above and below the evaporator rack tube	- PCM reduced and stabilized the product temperature. - Higher ambient temperature caused 0.1 h to 3.6 h lower compressor off period and 0 h to 3.4 h shorter cycle time. - More product yielded a 0.5 h to 1.1 h longer compressor off period and a 0.6 h to 1.4 h longer cycle time. - These effects were more pronounced at higher hysteresis. - Generally, the products at the higher level were colder, except in the system with high hysteresis.
Sonnenrein et al. (2020) / Experimental	Polymer-bound PCM (9°C) / in each load compartment	- PCM decreased 16% - 33% cooling time and increased 75% - 145% the temperature rise period. - Energy consumption was not significantly different.

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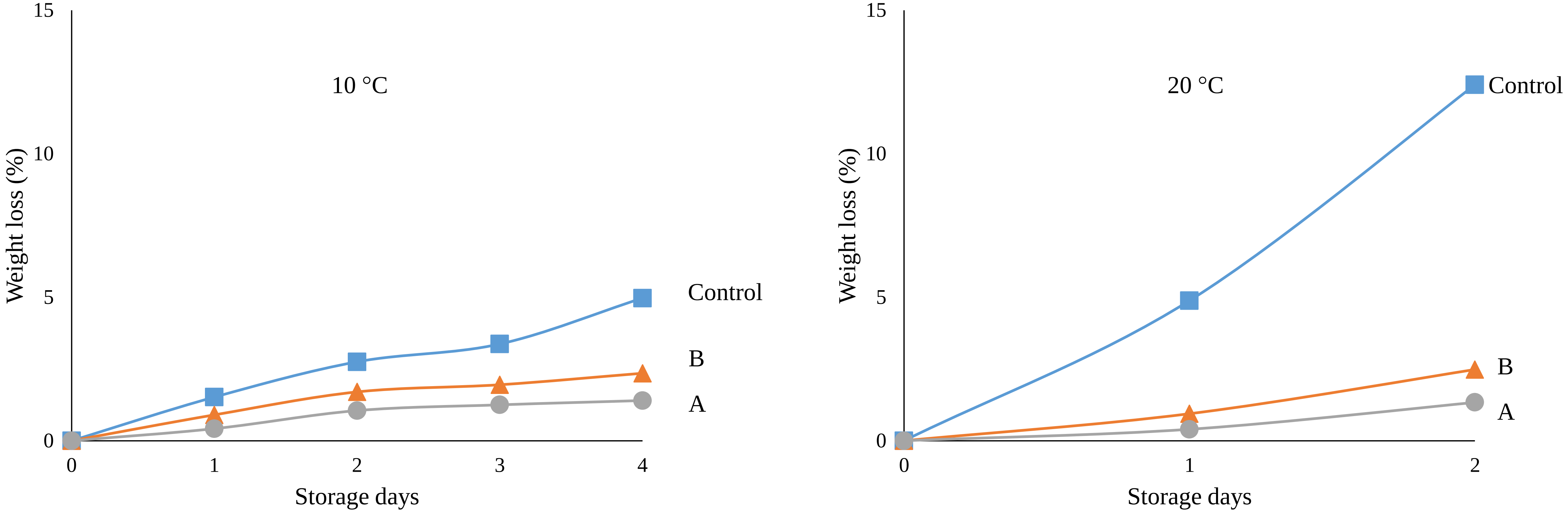
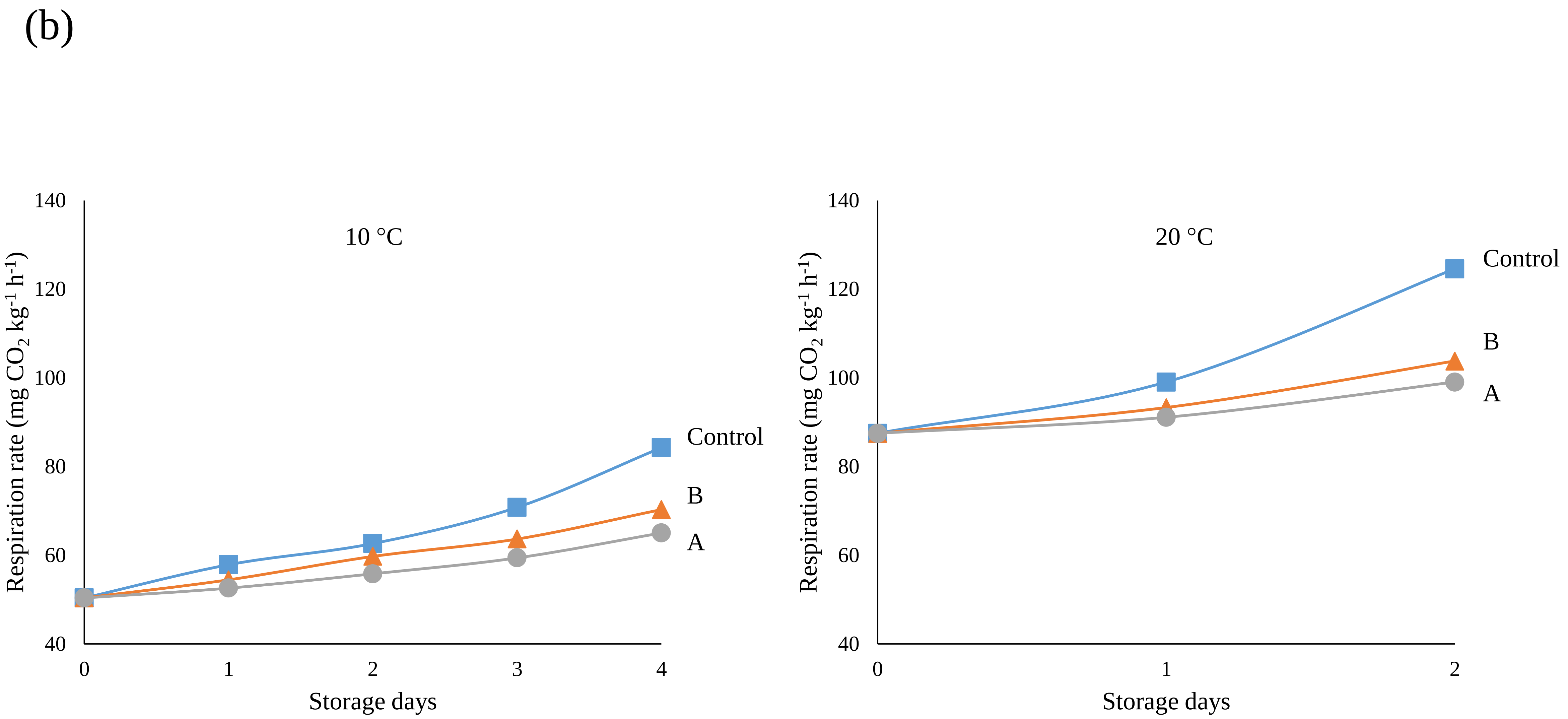
Fig 1: Evolution of (a) product weight loss and (b) product respiration rate of a strawberry packed in an expanded polystyrene box with PCM. A = MA pack (10% O_2, 0% CO_2), B = air pack and C = Control (product directly in contact with ambient air). (Adapted from X. Zhao et al. (2019)).

Fig. 2: Influence of PCM position and surface area in an insulated box on warming duration defined as the duration during which the temperature at the center of the box rises from 0 °C to 8 °C (Adapted from Du et al. (2020) for a polyurethane box with PCM of 5°C melting point).

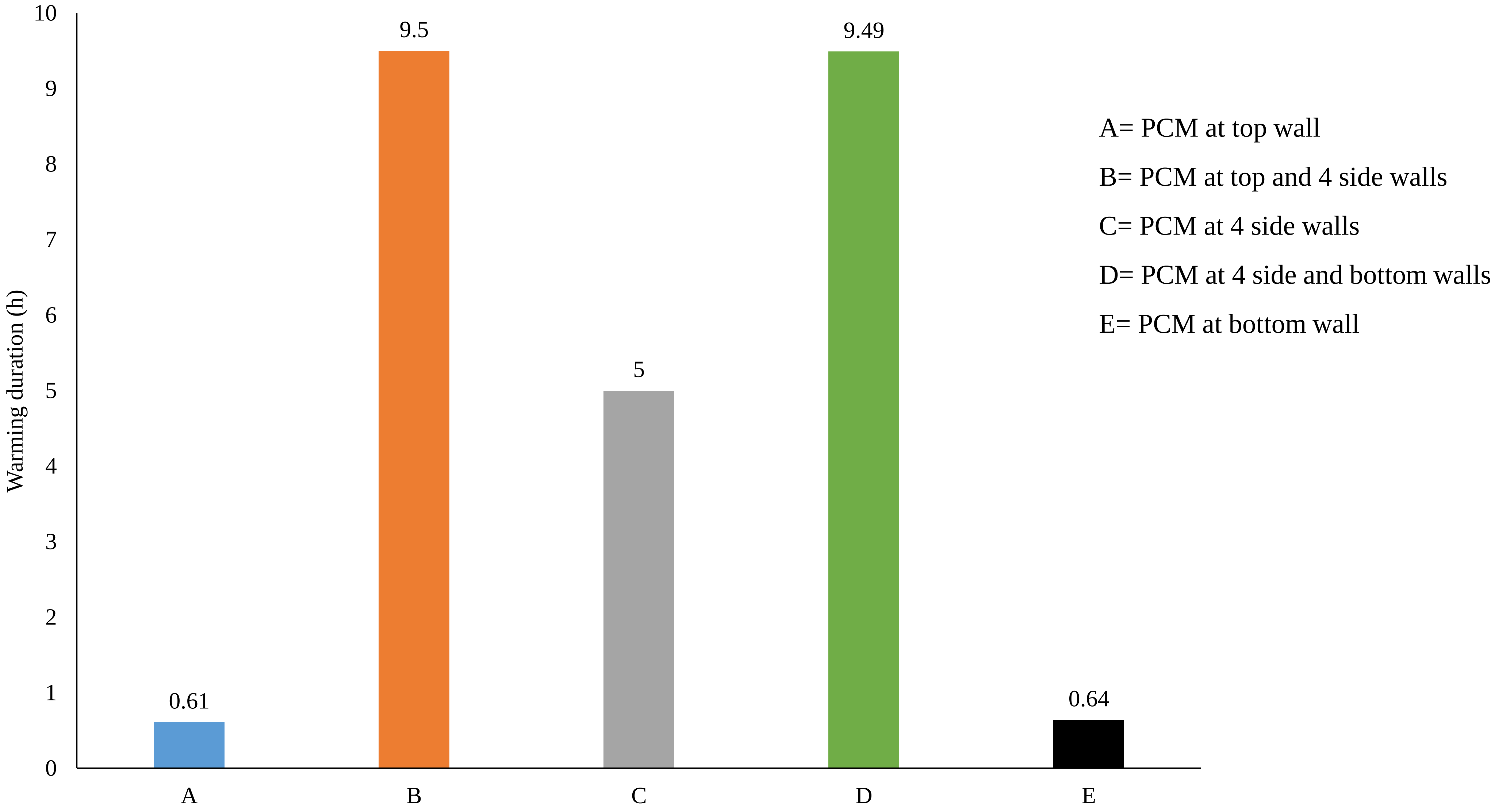
Fig. 3: Test product temperature evolution during “turn off” closed display cabinet (Adapted from Oró, Miró, et al. (2012))

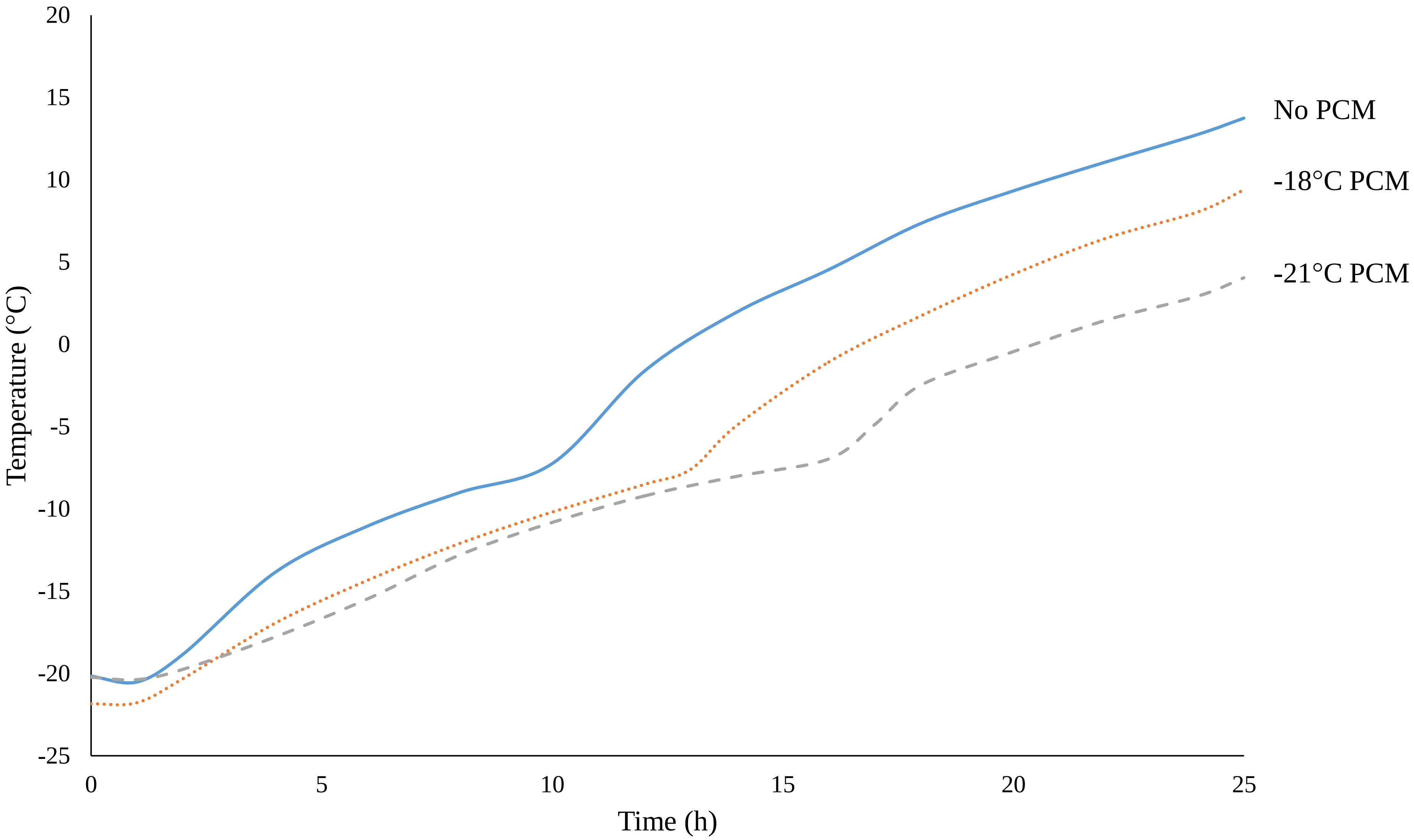
(a)


10 °C
20 °C
Weight loss (%)
15
10
5
0
Storage days
0
1
2
3
4
Control
B
A
Weight loss (%)
15
10
5
0
Storage days
0
1
2
Control
B
A



(b)
10 °C
20 °C
Respiration rate (mg CO_2 kg^{-1} h^{-1})
140
120
100
80
60
40
0
1
2
3
4
Storage days
Control
B
A


Warming duration (h)
0
1
2
3
4
5
6
7
8
9
10
0.61
9.5
5
9.49
0.64
A
B
C
D
E
A= PCM at top wall
B= PCM at top and 4 side walls
C= PCM at 4 side walls
D= PCM at 4 side and bottom walls
E= PCM at bottom wall


Temperature (°C)
20
15
10
5
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
Time (h)
No PCM
-18°C PCM
-21°C PCM