

# Insulated box and refrigerated equipment with PCM for food preservation: State of the art

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1	Insulated Box and Refrigerated Equipment with PCM for Food Preservation: State of
2	the Art
3	
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11	
12	Abstract
13	The use of Phase Change Material (PCM) as a cold accumulator in refrigeration contexts
14	leads to better food safety, food security and energy management. However, applying PCM in
15	real usage still depends on the user's experience or a trial-and-error basis. Studies carried out
16	on insulated boxes and in refrigerated equipment (refrigerated trucks, cold storage facilities,
17	display cabinets and domestic refrigerators) were reported. The influence of the studied
18	conditions such as PCM melting point, position, mass of PCM and load, insulation material,
19	external temperature on air/product temperatures and energy consumption was analyzed.
20	Important parameters enabling the application of PCM in boxes and refrigerated equipment are
21	the wall insulation and PCM configuration cited previously. Because of the complex
22	interactions between these parameters, they need to be considered together with the usage
23	conditions. The relationships between heat exchange and airflow inside the equipment should
24	be further studied notably in function to the PCM position.

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

27

28 1. Introduction

29 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 30 infection (Mercier et al., 2017). However, products with unacceptable organoleptic quality 31 32 (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 33 34 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-35 third of edible food consumed by humans is wasted worldwide. Each food product has a specific 36 optimal storage temperature, since a storage temperature that is too high or too low can 37 adversely affect the quality and/or safety of the food (East et al., 2009). 38

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 50 51 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 52 al., (2017) reviewed temperature abuse in the cold chain and reported that this last step had the 53 highest average temperature and the highest temperature variation. Accordingly, a cold storage 54 system such as a PCM could provide a solution that maintains the product temperature, 55 especially during delivery of temperature-sensitive products (Nie et al., 2020; Y. Zhao, Zhang, 56 Xu, et al., 2020). 57

58 This review article investigates studies on the transport of food in insulated boxes with 59 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 60 can be observed, particularly due to insufficient PCM mass and inappropriate PCM position 61 causing temperature heterogeneity inside the box. In fact, controlling the product temperature 62 in a closed cavity is complex because of several simultaneous heat transfer modes: conduction, 63 64 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 65 take all of them into account (Laguerre & Flick, 2010). 66

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).

73 There are several review articles on PCM classification, properties and improvement
74 (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 75 76 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 77 temperature throughout the entire cold chain equipment including insulated boxes. For instance, 78 Zhao et al. (2020) reviewed PCM application in refrigerated trucks, refrigerated containers and 79 insulated boxes. Bista et al. (2018) alone reported the use of PCM in a refrigerator. It is 80 81 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 82 frozen products transport has expanded rapidly in all parts of the world in recent years. A 83 84 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 85 firstly to present the state of the art in the field of food transportation of various product types 86 87 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 88 temperature was analyzed. Secondly, the aim is to report on studies on the application of PCM 89 in other refrigerated equipment: refrigerated trucks, cold rooms, display cabinets and domestic 90 refrigerators where energy management is the main concern. Finally, a discussion highlights 91 92 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-93 change process and food engineering are also discussed. 94

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## 96 2. Insulated box with PCM

97 There are various complex phenomena involved in an insulated box with PCM: heat 98 conduction inside the product, PCM and the walls of the box, heat convection between the air 99 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 100 101 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 102 103 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 104 (Section 2.1), type of product transported (Section 2.2), box design (Section 2.3), PCM 105 characteristics (Section 2.4), operating conditions (Section 2.5) and influence of each factor in 106 107 application and modeling (section 2.6) to identify the overall findings as well as the knowledge 108 gaps.

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## 110 2.1. Effect of PCM in insulated box on food quality

The interest of PCM application is to maintain low temperature and reduce temperature 111 fluctuations during food transport, which leads to better food quality particularly for high 112 perishable products. In the case of fresh fruit and vegetable, the product respires continuously 113 during storage, which leads to heat generation. High respiration rate, a major factor contributing 114 to the product loss, depends on product (e.g. strawberry respiration rate is 4 times higher than 115 that of apple) and on storage temperature (e.g. strawberry respiration rate at 15°C is 5 times 116 higher than that at 0°C) (Chakraverty & Singh, 2001). Numerous studies have shown the 117 interest of Modified Atmosphere Packaging (MAP) for the product shelf life extension because 118 119 the gas composition in the headspace  $(O_2, CO_2)$  decreases the respiration rate. X. Zhao et al. 120 (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 121 for 24 h, were placed at the top of the box. The results were compared with the current package 122 (air in headspace) and a control configuration where the product was directly in contact with 123 ambient air (Fig. 1). It was observed that MAP allowed product weight loss 30% lower than 124

that in current package and about 160% lower than that of control after 4 days at 10°C, this 125 126 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 127 preservation in terms of firmness, color, total soluble solids and global appearance (results not 128 shown). The better quality preservation under this combination can be explained by first, MAP 129 allows a reduction of product respiration rate (Fig. 1b) and second, PCM allows low product 130 temperature fluctuation. These results confirm the interest of the combination of MAP, PCM 131 and the insulated box for delivery when the ambient temperatures are not well controlled. Gin 132 and Farid, (2010) stored frozen meat and ice cream in a domestic freezer without and with PCM 133 134 (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 135 crystal size decreased from 70 µm - 80 µm (without PCM) to 40 µm -50 µm (with PCM). It is 136 137 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; 138 Vicent et al., 2019, 2020). 139

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141 2.2 Type of food product transported

Studies dealing with the transportation of different types of food products in insulated 142 boxes with PCM are summarized in Table 1. Out of 16 studies, six of them focused on meat 143 144 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 145 experimental and numerical studies: haddock fillets (Margeirsson et al., 2011), cod fillets, 146 (Margeirsson et al., 2012), New Zealand terakihi (Navaranjan et al., 2013), horse mackerel 147 (Laguerre et al., 2018), and sardine (Laguerre et al., 2019). X. Zhao et al. (2019) investigated 148 strawberry fruit transportation using an insulated box with PCM. There were fewer studies 149

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 bottomof the box gives almost the same warming time.

Some authors investigated the effect of product quantity on the thermal behavior of the 176 177 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 178 emphasized that the load quantity and the arrangement were varied simultaneously in the 179 experiments. Thus, it was difficult to highlight the influence of these parameters separately. 180 Paquette et al. (2017) compared the temperature profile when one beaker of water and 4 beakers 181 of water were placed in a box. They found that the rate of temperature increase was 20% lower 182 183 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 184 previously chilled before packing, and this causes deterioration in quality. Laguerre et al. (2018) 185 186 indicated that the greater the thickness of a stack of fish in the box, the longer the cooling duration. 187

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.

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194 2.3 Insulating material and box design

195 Reducing heat flux by using an insulating material is essential (Singh et al., 2008). Not 196 only the temperature inside the box should be maintained within a desired range for the longest 197 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 198 199 thermal conductivity rigid materials have been used above all, for example, expanded polystyrene and polyurethane (East & Smale, 2008; Kacimi & Labranque, 2019; Margeirsson 200 201 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 & 202 Smale, 2008; Kozak et al., 2017; Margeirsson et al., 2011). For instance, Margeirsson et al. 203 (2011) reported that the average rates of fish temperature rise were 0.51°C/h and 1.41°C/h using 204 205 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. 206 207 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). 208

The insulation is reinforced when vacuum panels are used (Kacimi & Labranque, 2019). 209 This can be explained by the fact that the thermal conductivity of vacuum panels is very low, 210 and these panels thus provide greater insulation capacity (Du et al., 2020). These authors 211 212 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 213 214 the duration during which the temperature at the center of the box rises from  $0^{\circ}$ C to  $8^{\circ}$ C) 3.8-215 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. 216 Paquette et al. (2017) showed that by covering the internal surface of the box with aluminum 217 218 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 219 220 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) 221 222 and metallizing the surface led to 102% greater thermal resistance.

In addition to the thermal conductivity of the material, box insulation also depends on 223 224 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 225 226 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 227 228 area at the round corner in comparison with the sharp corner, so less heat exchange with the 229 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). 230

Heat flow resistance (R value  $-m^2$  K/W) is a factor determining the insulation 231 232 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 233 partially melt, then determined the amount of liquid water and calculated the R value. 234 Navaranjan et al. (2013) pointed out that there was a good correlation between the R value and 235 236 the quality of New Zealand terakihi fish stored in insulated packaging. Another method used to 237 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 238 power) and temperature sensors are placed in an empty box at locations suggested in the 239 240 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 241 value to be calculated. 242

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.

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252 2.4 PCM properties, position and usage

Apart from the insulating material, thermal energy storage using PCM is another key 253 254 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 255 diffusion from the external ambient into the box, resulting in temperature abuse. PCM plays a 256 significant role in cold storage as it allows cold diffusion into the system to offset heat diffusion, 257 particularly during its melting thanks to high PCM latent heat (East & Smale, 2008; Kacimi & 258 Labranque, 2019; Laguerre et al., 2008). Oró, Miró, et al. (2012), Rostami et al. (2020), and Y. 259 Zhao, Zhang, Xu, et al. (2020) have classified the PCM and fully described its properties. 260

There are numerous thermal energy storage materials e.g. water, salt solution, paraffin 261 (Oró et al., 2012). Various compounds were applied as PCMs in an insulated box, e.g. ice or an 262 ice pack with a melting point ranging from -0.5°C to 0.5°C (East et al., 2009; East & Smale, 263 2008; Laguerre et al., 2018, 2019; Margeirsson et al., 2011, 2012; Navaranjan et al., 2013). To 264 achieve a temperature range below 0°C, Kozak et al. (2017) used salt solutions with melting 265 points of -10°C and -33°C while Elliott & Halbert (2008) studied the system with dry ice (CO<sub>2</sub>: 266 267 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 268 and 21°C were also investigated (East et al., 2009; East & Smale, 2008; Kacimi & Labranque, 269 270 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).

276 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. 277 (2009) and East & Smale (2008) placed PCM only at the bottom of the box. Kacimi & 278 279 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 280 (2005) compared the effect of PCM position on temperature profile. Some studies 281 282 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 283 on the bottom leads to conduction alone along with greater temperature heterogeneity (Du et 284 al., 2020; Laguerre et al., 2008). In an insulated box with PCM at the top, middle and bottom, 285 Laguerre et al. (2008) indicated that PCMs on the top of the container completely melted within 286 287 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. 288

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 298 increase from 3.5°C to 10.0°C. It was found that this temperature rise took 32.1 h with PCM at 299 the center and 8.6 h with PCM on the side of the box. They also pointed out the decrease in the 300 301 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 302 303 when both parts of PCM was combined and added either at the top or at the bottom due to lower 304 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 305 15°C when all the PCM was placed at the same position. 306

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 314 315 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 316 317 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 318 319 amount of PCM and found that the temperature rose faster in the compartment with a higher 320 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 321 322 the products were either too warm or frozen.

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## 324 2.5 Effect of the external temperature

The influence of the ambient temperature was also investigated as an important factor 325 e.g. greater numbers of PCM packs were required during delivery in summer (East et al., 2009; 326 Elliott & Halbert, 2005; Kacimi & Labranque, 2019; X. Zhao et al., 2019). Although the 327 difference in heat flux caused by different ambient temperatures is well-known, investigation 328 329 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 330 to choose the box material, the wall thickness and the amount of PCM. Kacimi & Labranque 331 (2019) studied two PCMs with different melting points under different ambient conditions and 332 recommended that the PCM melting point should be matched with the ambient conditions. It is 333 to be emphasized that the PCM was placed only on the side wall of the box in this study. 334

Many studies have investigated the influence of ambient temperature, either by 335 temperature monitoring during real shipping or by temperature recording in a controlled-336 temperature test chamber. The latter case is easier to implement and requires fewer resources. 337 Elliott & Halbert (2005) and Elliott & Halbert (2008) performed a shipping test using long-338 distance delivery in different seasons generating data from real situations. Margeirsson et al. 339 (2012) recorded the ambient temperature during cod fillet transport from Dalvík to Reykjavík 340 and further utilized this data for numerical model validation. Navaranjan et al. (2013) 341 342 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 343 during which highest product spoilage rate was observed for international fish exports from 344 New Zealand, and the fish shelf life was 4.76 days lower than that stored at 0°C. 345

Some ambient temperature profile databases are available for member at International
Station Meteorological Climate Summary (ISMCS, https://ui.adsabs.harvard.edu/abs/1992
BAMS...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).

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352 2.6 Influence of each factor in application and modeling

As mentioned above, there are numerous parameters influencing the temperature 353 354 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 355 (thermophysical properties, mass and arrangement) and operating conditions (ambient 356 temperature and transport duration). In such complex situations, physical-based modeling tools 357 can be useful to identify the most sensitive factor. Paquette et al. (2017) performed sensitivity 358 analysis to determine the most significant factor (external convective heat transfer, emissivity 359 of food, box and gel packs, the thermal conductivity and the heat capacity of the insulating 360 material). They reported that the thermal conductivity of the insulating material affected the 361 product temperature profile to the greatest extent. Consequently, this is the main criterion to 362 take into account when designing the system. Different types of models can be developed. A 363 1D analytical model was utilized to gain a general perspective of the system and roughly predict 364 useful responses, e.g. maximum temperature, PCM melting time (Laguerre et al., 2018, 2019). 365 A zonal model which assumed that each zone has uniform and lumped properties is also used 366 to acquire a thorough understanding with an acceptable calculation time for design optimization 367 and temperature prediction (East et al., 2009; East & Smale, 2008). 2D and 3D heat transfer of 368 a CFD model (in some cases, convection and/or radiation were neglected) are described in 369 articles with extensive results such as temperature distribution and profile, PCM liquid fraction 370

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 databased 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).

377 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, 378 379 one might consider that the criterion is the maximum temperature that can be attained inside 380 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 381 designed to transport fruit and vegetables with an optimal temperature range (e.g. from 4°C to 382 10°C), the temperature heterogeneity might not be crucial. Hence, there will be more flexibility 383 in the choice of the box material and the PCM position in the box. A specific design is required 384 385 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 386 recrystallization and drip loss leading to product quality degradation. East & Smale (2008) and 387 388 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 389 abuse. They suggested that the boxes used in summer should have a thicker insulating material 390 and a larger quantity of PCM to withstand the heat flux from ambient than that in winter while 391 the other factors remained almost identical. 392

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 396 heterogeneity. The methods used to determine insulation efficiency was developed by 397 measuring the heat flow resistance (R) value and was tested in real application. The external 398 399 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 400 evidence proving that the application of PCM could lower the temperature of the system and 401 possibly improve thermal homogeneity. However, the PCM melting point, the amount of PCM 402 and optimization of its position are still necessary to achieve the most efficient conditions for 403 each system. 404

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.

417

418 3. Cold chain equipment with PCM

Unlike in an insulated box, PCM in refrigerated equipment often enables energy 419 420 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., 421 422 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). 423 Several studies showed that PCM allows the extension of the cooling period following power 424 failure (Ben-Abdallah et al., 2019; Oró, Miró, et al., 2012; Yilmaz et al., 2020). Use of PCM 425 can also decrease the temperature of the system with greater homogeneity (Alzuwaid et al., 426 2015, 2016; Azzouz et al., 2009; Ben-Abdallah et al., 2019; Maiorino et al., 2019; Sonnenrein, 427 428 Baumhögger, et al., 2015).

429

### 430 3.1 PCM in refrigerated trucks

431 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 432 of salts with different concentrations were used: an in-house inorganic salt solution with a 433 melting point of -26.7°C (M. Liu et al., 2012), a NaCl solution with a melting point of -21.2°C, 434 (Xiaofeng et al., 2017) and commercial blends of salts with melting points of -26°C, -29°C and 435 -32°C, (Mousazade et al., 2020). For PCMs with higher melting points (7°C to 45°C) which are 436 inserted between the external and internal walls, paraffin and salt hydrate were used (Ahmed et 437 al., 2010; Copertaro et al., 2016; Fioretti et al., 2016). 438

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.

456 Copertaro et al. (2016) developed a model in order to choose the PCM with the most 457 suitable melting point to be inserted between the external and internal walls of refrigerated 458 trucks. They recommended that with a melting point of 35°C for the truck operating under 459 ambient temperatures varying from 20°C to 33°C as observed in various cities in Italy in 460 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: 387 466 km), but the longest distance covered was 491 km in the case of a truck moving at a speed of467 110 km/h (4.46 h cooling period).

468

469 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.

476 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 & 477 Hossainpour 2020). For potatoes cold storage at temperatures above 0°C, Pirdavari & 478 479 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 480 potatoes and the insulation type. They indicated that a greater amount of PCM, a lower PCM 481 482 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 483 point of the PCM between -23.3°C and -17.5°C. They showed that the use of PCM reduced ice 484 crystal growth by 2.7% to 9.0% thanks to fewer temperature fluctuations. 485

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.

489

#### 490 3.3 PCM in display cabinets

The application of PCM in display cabinets is summarized in Table 4. Pure ice placed 491 near the evaporator was generally used (Alzuwaid et al., 2016; Ben-Abdallah et al., 2019; Ezan 492 493 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, 494 et al. (2012) applied commercial PCM (Climsel C-18 and Cristopia E-21), with melting point 495 of -18 °C and -21.3 °C respectively, over evaporator tubes located at different shelves of a 496 closed display cabinet. The authors reported that for empty closed display cabinet, the air 497 temperature rose from -22 °C to 0 °C within 1.5 h (without PCM), 6.5 h (-18°C PCM) and 8 h 498 499 (-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 500 results demonstrated the interest of PCM to slow down the product temperature when the 501 display cabinet was turn off, due to machine failure for example. 502

503 PCM decreased the compressor operating time by 4% to 10% and reduced energy 504 consumption by 5.0% to 6.4% (Alzuwaid et al., 2015, 2016; Ezan et al., 2017). In fact, for a 505 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 506 507 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 508 509 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 510 511 efficiency of PCMs with a thickness varying from 2 mm to 10 mm and reported that the 512 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 513 position of the PCM is another challenge in the application because PCM in an inappropriate 514

515 place led to a worse outcome than in a context where no PCM was used. Yilmaz et al. (2020)
516 reported that when a PCM was used at the back of a closed display cabinet, the system
517 consumed 8% more energy than a system without a PCM due to the delay in cabinet temperature
518 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).

525

## 526 3.4 PCM in domestic refrigerators

Several studies have investigated PCM application in domestic refrigerators as 527 528 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 529 (Sonnenrein, Baumhögger, et al., 2015), or an eutectic solution with a melting point between 530 531 -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 =  $34^{\circ}$ C) and a copolymer 532 533 (melting point =  $34^{\circ}$ C to  $35^{\circ}$ C) at the condenser. Some nervi et al. (2020) studied the application of a copolymer PCM (melting point =  $9^{\circ}$ C) in the load compartment. 534

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 539 540 =  $-3^{\circ}$ C) at the evaporator lowered the internal temperature by up to  $1.5^{\circ}$ C. However, the compressor operating period was 0.4 h longer. Thus the COP was lower in comparison with the 541 542 system using ice. Sonnenrein, Baumhögger, et al. (2015) and Sonnenrein, Elsner, et al. (2015) reported that paraffin and copolymer PCM (melting point =  $34^{\circ}$ C to  $35^{\circ}$ C) were more efficient 543 than ice at the condenser since they allowed a temperature that was 5°C to 6°C lower to be 544 achieved at the condenser, leading to 2% to 17% lower energy consumption. The thickness of 545 546 the PCM slab should also be optimized to achieve the highest efficiency (Azzouz et al., 2008; Berdja et al., 2019). 547

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.

559

560 4. General discussion

561 The application of PCMs in the cold chain has been widely studied with a wide variety562 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 energymanagement-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.

571 What clearly appears from the existing studies is the absence of an ideal general solution 572 to apply PCM in equipment and boxes as it involves complex interactions between the 573 parameters of the studied system such as the insulating material, the external temperature, the 574 product load, the melting point and the quantity of the PCM.

575 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 576 577 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 578 to quantify heat flux by conduction, convection, and radiation since none of them can be 579 neglected. Therefore, further studies are essential to better understand the relationship between 580 heat transfer and airflow by natural convection. Studies on the effect of the load porosity on 581 582 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. 583

584 Other concerns in the application of PCMs are related to chilling injury, particularly 585 when a PCM is directly in contact with sensitive products. To avoid this problem, some studies 586 proposed, for instance, to precondition the PCM before product loading.

The use of PCMs in insulated boxes exerts environmental impacts because of the PCM 587 588 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 589 590 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 591 592 less environmental impacts. For example, Jiang et al. (2021) and Khalaf et al. (2021) fabricated 593 cellulose-based and chitosan-based insulating materials, respectively. Melone et al. (2012) also 594 developed a composite cellulose and paraffin (melting point 0°C to 10°C) insulating material acting as phase change material for transporting perishable products. 595

596

## 597 5. Conclusions and suggested future research

598 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 599 600 factors should be considered: insulating material (thermal conductivity and thickness), PCM 601 type (i.e. heat storage capacity and its melting point), its quantity and position, load 602 characteristics (load nature, mass and arrangement), and operating conditions (i.e. ambient temperature and storage and transport duration). These factors significantly affect the efficiency 603 604 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 605 606 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 612 acquired by using innovative optical techniques such as Laser Doppler Velocimetry (LDV) and 613 Particle Image Velocimetry (PIV). These techniques are already used for several types of 614 refrigerated equipment (refrigerated trucks, display cabinets and domestic refrigerators) but are 615 not yet applied to insulated boxes with PCM in which the air velocity is very low because 616 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 (cellulosebased 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.

635

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not-for-profit sectors.

Table 1 Summary	y of studie	s using PCM	in in	sulated	boxes
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Reference /	PCM (melting	Box material (internal	Type of the study	Main observation(s)
Product	point) / position	dimensions)		
Margeirsson et	Ice pack $(0^{\circ}C)$ / on	- Expanded polystyrene	Experimental and	- The warmest position was at the bottom corner
al. (2011) /	top of the product	(EPS) (35.6 cm x 22.0	numerical (3D CFD)	- The coldest position was at the top center
Haddock		cm x 8.5 cm)		- After 6 h, the temperature increase in EPS and CP
fillets		- Corrugated plastic		boxes was 8°C and 14°C, respectively
		(CP) (37.0 cm x 23.0		- Ice pack decreased the product temperature by
		cm x 8.0 cm)		around 4°C but increased its heterogeneity (up to
				8°C compared with 3°C in the box without an ice
				pack).
Margeirsson et	Ice pack	EPS with	Experimental and	- The warmest position was at the bottom corner
al. (2012) /	(-0.5°C to 0.5°C)/	- Sharp corners (35.6	numerical (3D CFD)	- The coldest position was at the top center
Cod fillets	on top of the	cm x 22.0 cm x 10.9		- Fillets in rounded box had a 2°C lower temperature
	product	cm)		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	Ice pack (0°C) / in	6 Boxes with the same	Experimental	- The warmest position was at the corner
al. (2013) /	the center at the top	dimensions (55.0 cm x		- The coldest position was at the center
New Zealand	of the box	37.5 cm x 12.0 cm)		- Thermal resistance (R) of B2 is twice that of B1
terakihi		- 3 In-house EPS with		but less than CE and it positively related to the
(Nemadactylus		1.0 cm, 1.5 cm and 2.5		thickness of in-house EPS box.
macropterus)		cm thickness (E10, E15		- Fish quality estimated by time- temperature profile
		and E25)		related to R value of the insulating material with a
		- 1 Commercial EPS		coefficient of determination > $0.80$ .
		box (CE)		
		- 1 box-in-box using CP		
		with 1.5 cm gap (B1)		
		- 1 improved box-in-		
		box with 2.1 cm gap		

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

Laguerre et al.	Ice pack	2 EPS box with	Experimental and	- The warmest position was at the bottom corner
(2019) /	(-0.1°C to 0.1°C)/	different dimensions.	numerical (1D	- The coldest position was at the top
Sardine	top of the fish stack	A: 21.0 cm x 21.0 cm x	analytical model and	- 1D analytical model could roughly predict melting
		17.9 cm with 1.8 cm	3D Finite Element	time and highest product temperature.
		thickness	Method or 3D FEM)	- 3D FEM could determine temperature profile
		B: 17.5 cm x 23.5 cm x		more accurately, particularly under real conditions.
		15.3 cm with 2.5 cm		
		thickness		
X. Zhao et al.	Commercial PCM	EPS (29.0 cm x 17.5	Experimental	- The stored sample packed in the box and PCM
(2019) /	(-2.0°C to -1.2°C)/	cm x 13.0 cm)		had a higher organoleptic quality than that without
Strawberries	top wall of the box			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.	PCM (0°C, 2°C,	Polyurethane (PU) or	Numerical (3D heat	- A PU box + PCM with melting points of 2°C and
(2020) / No	3°C, 4°C, 5°C and	vacuum insulated	transfer model) with	8°C gave the highest cooling time (9.6 h) and
load	8°C) / 5	panels (VIPs) (35.5 cm	experimental	lowest cooling time (2.1 h), respectively.
	configuration	x 21.5 cm x 26.5 cm)	validation	- Configuration B led to highest cooling time (9.6 h)
	- 100% top (A)			while configuration A and E had the lowest values
	- 20% each side and			(around 0.6 h).
	top (B)			- VIPs allowed a longer cooling duration than PU
	- 25% each side (C)			(up to 36.9 h).
	- 20% each side and			
	bottom (D)			
	- 100% bottom (E)			
Xiaofeng &	2 PCM type:	PU and VIP (145 cm x	Numerical (3D	- The warmest position was at the top corner of first
Xuelai (2021)	A: 87% n-caprylic	75 cm x 65 cm) divided	unsteady model) with	compartment
/ No load	acid and 13%	into 3 compartments for	experimental	- The coldest position was at the wall's surface
	myristic acid	1) ambient storage (no	validation	between second and third compartment
		PCM), 2) chilled		

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

Elliott &	dry ice (CO <sub>2</sub> :	EPS box (32 cm x 32	Experiment and transit	- The warmest position was at the top
Halbert (2008)	-78.5°C) / bottom	cm x 29.5 cm)	test to maintain	- The coldest position was at the bottom
/ Small boxes	of the box		temperature below	- The preferable configuration was when dry ice
containing			-10°C	was placed closer to the product with the highest
empty				temperature at -21.9°C.
packages				- All transit tests during real transport yielded good
				results.
Laguerre et al.	PCM (-0.5°C) / top,	Corrugated cardboard	Experimental and	- The warmest position was at the middle of the side
(2008) /	middle and bottom	insulated with	numerical (excitation-	wall
Cartons of	of the container	polystyrene plates (108	response model)	- The coldest position was at the bottom center
several		cm x 72 cm x 137 cm)		- The model was validated and able to predict the
product units				product temperature inside the container exposed to
				a variable ambient temperature when the PCM was
				not completely melted.
Kacimi &	- Organic PCM	VIPs with 15 L, 27 L,	Experimental	- The warmest position was at the top
Labranque	(5°C) / all box faces	40 L and 64 L		- The coldest position was at the bottom

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

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

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

 Table 2 Summary of studies about using PCM in refrigerated trucks

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

Fioretti et al. (2016) / Experimental	Paraffin wax (35°C) / inside	- The experiment demonstrated that PCM decreased heat flux
(stationary empty truck container in	refrigerated truck wall made of	(between 15 W/m <sup>2</sup> and 47.5 W/m <sup>2</sup> to between 13 W/m <sup>2</sup> and 25
laboratory test room and real	steel	W/m <sup>2</sup> ), decreased the external wall surface temperature (from $93.0^{\circ}$ C
climate conditions) and numerical		to 80.0°C), and the internal wall surface temperature (from 11.8°C to
study (2D heat transfer model)		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	Eutectic NaCl solution	- Higher climate temperature led to a shorter melting time (86 h and
(3D CFD of empty refrigerated	(-21.2°C) / in a plate installed	73 h at 20°C and 30°C, respectively), higher heat transfer rate (1.9
truck)	on the truck wall	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) /	Commercial PCM containing	- PCM melting at -26°C showed the best cooling efficiency with the
Experimental (stationary and	various blends of salts (-26°C,	longest melting time (5.11 h and 4.78 h in stationary and 81 km/h
moving empty truck)	-29°C and -32°C) / in a plate	truck, respectively).
	placed on the truck wall.	- 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) /	Main observation(s)
Tererence, Type or search	its location	
Schalbart et al. (2013) / Numerical	PCM with a melting	- From optimization, the melting point of the PCM was in the range of
(1D finite difference equation	point that was optimized	-23.3°C at the storage tank to -17.5°C at the walls.
system) of warehouse storage of ice	depending on the	- Without PCM, the predicted final ice crystal size was 58 $\mu$ m and there was
cream for a period of 90 days with	location / post-	±1.0°C temperature fluctuation with 13.6 GJ energy consumption.
different PCM positions.	evaporator, ceiling, wall,	- Predicted final ice crystal size was 53 $\mu$ m with PCM at storage tank to 57
	storage tank and product	$\mu$ m with PCM at the ceiling and the temperature fluctuation was only
	package	$\pm 0.01^{\circ}$ C with PCM at product package to $\pm 0.76^{\circ}$ 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	Ice plate $(0^{\circ}C)$ / on each	The upper part was 4°C warmer than the lower part due to external heat
(3D CFD) of cold storage facility	side of the wall, the floor	convection via the roof which had a heat transfer coefficient of 5 $W/m^2 K$ .
with a container of potatoes	and the roof	
Pirdavari & Hossainpour (2020) /	LiClO <sub>3</sub> ·3H <sub>2</sub> O PCM	The greater the quantity of PCM, the lower the melting point of the PCM
Optimization via numerical study	capsule (8.5°C, 9.0°C	and the lower thermal conductivity of insulation led to a longer melting time
(1D simplified dynamic model	and 9.5°C) / in a	and lower product temperature.
which is validated by using	cylindrical column	
experimental data from Azzouz et	placed in the stack of	
al. (2009)).	potatoes in the cold	
	room.	

 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) /	ClimSel C-18 (-18°C) or Cristopia	- For an empty display cabinet, the air temperature rose from -22°C to
Experimental (closed display	E-21 (-21.3°C) / encapsulated in a	0°C within 1.5 h (without PCM), 6.5 h (C-18) and 8 h (E-21).
cabinet freezer)	stainless-steel thin plate placed on	- The presence of load in the display cabinet enabled this period to be
	top of the evaporator tube	extended: 11.5 h (without PCM), 15.6 h (C-18) and 21.5 h (E-21).
Ezan et al. (2017) / Numerical	Ice (0°C) / placed behind rollbond	- The coldest area was at the bottom corner and the warmest area was
(3D CFD) with experimental	evaporator at the rear of the empty	located at the top with up to 7.5°C temperature difference.
validation (closed display	cabinet	- Increasing PCM thickness explains the decreases of compressor run-
cabinet)		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) /	Distilled water with a nucleating	- PCM on the back wall generates minimum running cycles: 17 cycles
Experimental (closed display	agent and thickening agent (-6°C) /	(without PCM) to 11 cycles (PCM on shelves) and 9 (PCM on back
cabinet)	either on the back wall or on the	wall) over 8 h running.
	shelves	- 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) /	Ice gel PCM (-2°C) / above	Adding PCM led to 5% energy savings, 70% longer defrost period,
Experimental (open display	evaporator	2°C lower maximum cabinet temperature and more stable product
cabinet)		temperature: Tmax-Tmin 7.33°C (without PCM) and 6.50°C (with
		PCM).
Alzuwaid et al. (2016) /	Pure-water ice PCM (0°C) / above	- Installing PCM enabled 6.4% energy savings to be achieved and
Numerical study (2D CFD)	the evaporator	decreased the product temperature difference from 5.0°C (without
		PCM) to 4.2°C (with PCM).

with experimental validation		- The highest product temperature was at the front of the middle shelf
(open display cabinet)		and the lowest one was located at the back of top shelf.
Ben-Abdallah et al. (2019) /	Ice $(0^{\circ}C)$ / in a finned tube heat	- Adding PCM decreased the average air temperature from 8.4°C
Experimental (open display	exchanger placed in the rear duct	(without PCM) to 1.5°C (with PCM).
cabinet)		- 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

<b>Reference / Type of study</b>	PCM (melting point) / its location	Main observation(s)
Azzouz et al. (2008) /	Eutectic aqueous PCM (-9°C,	- Adding PCM increased the COP by 5% - 15 %, decreased operating time
Numerical study (1D	$-7^{\circ}$ C, $-5^{\circ}$ C, $-3^{\circ}$ C or $-1^{\circ}$ C) / on	by 28.5% - 32.5% and prolonged the cooling period by $4 h - 8 h$ when the
simplified dynamic model)	evaporator surface	compressor was off.
with experimental validation.		- 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) /	Ice (0°C) or eutectic mixture	- Eutectic mixture PCM led to 1.0°C to 1.5°C lower air temperatures but a
Experimental	(-3°C) / on evaporator surface	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) /	Paraffin (34°C), copolymer	- Paraffin PCM on the condenser led to a 5°C lower condenser temperature
Experimental	compound with 10% (w/w)	and 2% to 7% lower energy consumption compared with water (only
	graphite (34°C), or water (0°C) /	sensible heat variation).
	condenser	- Copolymer compound PCM on the condenser generated up to 10%
		energy savings.
Sonnenrein et al. (2015a) /	- Copolymer PCM (-4°C) /	- PCM increased the evaporator temperature between 6°C and 8°C and
Experimental	evaporator	decreased the condenser temperature by 6°C.
	- Another copolymer PCM	- 12% to 17% less energy consumption and a more constant compartment
	$(35^{\circ}C)$ / on the condensers of 2	temperature were observed in refrigerators with both types of PCM.
	different refrigerator models	
Berdja et al. (2019) /	PCM (-11°C) / covering the	- From the experiment, installing PCM resulted in 10% lower energy
Experimental and numerical	evaporator surface	consumption, 17.6% lower compressor operating time, 5.05% greater COP
(1D analytical model)		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) /	Ice $(0^{\circ}C)$ / above and below the	- PCM reduced and stabilized the product temperature.
Experimental	evaporator rack tube	- 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) /	Polymer-bound PCM (9°C) / in	- PCM decreased 16% - 33% cooling time and increased 75% - 145% the
Experimental	each load compartment	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))



(b)





