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

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

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

44 Transportation using insulated boxes plays an important role in the cold chain,
45 particularly when passive cooling devices such as Phase Change Material (PCM) are used, e.g.
46 during shipment from the producer to the retailer, then to the consumer (Robertson et al., 2017).
47 Transport may involve a short distance (a few kilometers for locally produced food) or long
48 distances, e.g. from Glasgow to London (Elliott & Halbert, 2008), from Sydney to Melbourne
49 (East et al., 2009), or from New Zealand to Singapore (Navaranjan et al., 2013). The ambient

50 temperature during delivery can vary according to the season, e.g. -10°C in winter and 35°C in
51 summer (East et al., 2009). Among the different links in the cold chain, the final transport to
52 the consumer has been found to be one of the weakest. Laguerre et al., (2013) and Mercier et
53 al., (2017) reviewed temperature abuse in the cold chain and reported that this last step had the
54 highest average temperature and the highest temperature variation. Accordingly, a cold storage
55 system such as a PCM could provide a solution that maintains the product temperature,
56 especially during delivery of temperature-sensitive products (Nie et al., 2020; Y. Zhao, Zhang,
57 Xu, et al., 2020).

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.,
60 2021). Despite the ease of use of this technology and its relatively low cost, temperature abuse
61 can be observed, particularly due to insufficient PCM mass and inappropriate PCM position
62 causing temperature heterogeneity inside the box. In fact, controlling the product temperature
63 in a closed cavity is complex because of several simultaneous heat transfer modes: conduction,
64 natural convection and radiation (Laguerre & Flick, 2010; Rincón-Casado et al., 2017; Shinoda
65 et al., 2019). These transfer modes are of the same order of magnitude; thus, it is necessary to
66 take all of them into account (Laguerre & Flick, 2010).

67 PCM is also used in other cold equipment such as refrigerated trucks, cold rooms,
68 display cabinets and domestic refrigerators. Here, PCM plays an important role, not only in
69 temperature control, but also in energy management (Schalbart et al., 2013; Sonnenrein, Elsner,
70 et al., 2015; Yilmaz et al., 2020). However, determining the optimal PCM position and mass
71 is still the challenge in these applications (Azzouz et al., 2009; Pirdavari & Hossainpour, 2020;
72 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

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

95

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

100 walls, the phase change process and food quality evolution. Standard solutions cannot be widely
101 applied as all these phenomena are impacted by the type of product itself, the operating
102 conditions (external temperature and duration), the box dimensions, the type of PCM (latent
103 heat, heat capacity and melting temperature), its quantity and its position in the box. The
104 objectives of this section are to describe the existing studies in terms of the product quality
105 (Section 2.1), type of product transported (Section 2.2), box design (Section 2.3), PCM
106 characteristics (Section 2.4), operating conditions (Section 2.5) and influence of each factor in
107 application and modeling (section 2.6) to identify the overall findings as well as the knowledge
108 gaps.

109

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

111 The interest of PCM application is to maintain low temperature and reduce temperature
112 fluctuations during food transport, which leads to better food quality particularly for high
113 perishable products. In the case of fresh fruit and vegetable, the product respire continuously
114 during storage, which leads to heat generation. High respiration rate, a major factor contributing
115 to the product loss, depends on product (e.g. strawberry respiration rate is 4 times higher than
116 that of apple) and on storage temperature (e.g. strawberry respiration rate at 15°C is 5 times
117 higher than that at 0°C) (Chakraverty & Singh, 2001). Numerous studies have shown the
118 interest of Modified Atmosphere Packaging (MAP) for the product shelf life extension because
119 the gas composition in the headspace (O₂, CO₂) decreases the respiration rate. X. Zhao et al.
120 (2019) studied fresh strawberry quality change using MAP in an expanded polystyrene box
121 exposed to ambient temperature at 10°C and 20°C. Three PCM packs, previously froze at -18°C
122 for 24 h, were placed at the top of the box. The results were compared with the current package
123 (air in headspace) and a control configuration where the product was directly in contact with
124 ambient air (Fig. 1). It was observed that MAP allowed product weight loss 30% lower than

125 that in current package and about 160% lower than that of control after 4 days at 10°C, this
126 effect was more significant at storage temperature at 20°C (Fig. 1a). These authors also reported
127 that the combination of MAP, PCM and the insulated box allows the strawberry quality
128 preservation in terms of firmness, color, total soluble solids and global appearance (results not
129 shown). The better quality preservation under this combination can be explained by first, MAP
130 allows a reduction of product respiration rate (Fig. 1b) and second, PCM allows low product
131 temperature fluctuation. These results confirm the interest of the combination of MAP, PCM
132 and the insulated box for delivery when the ambient temperatures are not well controlled. Gin
133 and Farid, (2010) stored frozen meat and ice cream in a domestic freezer without and with PCM
134 (melting temperature -15.4°C). For meat, these authors reported the reduction of drip loss from
135 17% (without PCM) to 10% (with PCM) after 2-week storage and for ice cream, the average
136 crystal size decreased from 70 µm - 80 µm (without PCM) to 40 µm -50 µm (with PCM). It is
137 to be emphasized that the higher temperature fluctuation during frozen storage, the bigger ice
138 crystals and lowers the food quality (Oró, de Gracia, et al., 2012; Phimolsiripol et al., 2008;
139 Vicent et al., 2019, 2020).

140

141 2.2 Type of food product transported

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

150 dealing with fruit and vegetable transportation by means of insulated boxes equipped with
151 PCM. This may be due to the fact that fruit and vegetable are not as perishable as meat products,
152 thus, they are less sensitivity to temperature abuse (Committee, 2014). However, it could be
153 valuable to investigate such applications as higher demand for fresh tropical produce from cold
154 climate countries has emerged recently (ICI Business on behalf of Centre for the Promotion of
155 Imports from developing countries, 2020; Loria, 2021).

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

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

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

174 thus, greater cooling capacity. It was observed that the PCM placed at the top and the bottom
175 of the box gives almost the same warming time.

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

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

193

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

198 ambient temperature varies, as is often observed in the supply chain (Fioretti et al., 2016). Low
199 thermal conductivity rigid materials have been used above all, for example, expanded
200 polystyrene and polyurethane (East & Smale, 2008; Kacimi & Labranque, 2019; Margeirsson
201 et al., 2011). Many studies have shown that a change in the insulating material significantly
202 impacted the temperature profile and product quality (Du et al., 2020; East et al., 2009; East &
203 Smale, 2008; Kozak et al., 2017; Margeirsson et al., 2011). For instance, Margeirsson et al.
204 (2011) reported that the average rates of fish temperature rise were 0.51°C/h and 1.41°C/h using
205 expanded polystyrene and corrugated plastic, respectively. Kozak et al. (2017) showed that an
206 optimal configuration can be reached, which allows maximizing the melting time of the PCM.
207 The ratios of insulation and PCM thicknesses and their thermal conductivities are the
208 determining factor of this optimal condition (allowing longest period at low temperature).

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

223 In addition to the thermal conductivity of the material, box insulation also depends on
224 its design. Margeirsson et al. (2012) reported that using an expanded polystyrene box with
225 rounded corners helped to decrease the temperature difference of 2.0°C between fish at the
226 center and at the corners, while this difference was 4.4°C for sharp corners and it also led to
227 extending the product shelf life for an additional 2 days. This may be due to a lower exchange
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
230 usable volume in comparison with the total box volume and cost (East & Smale, 2008).

231 Heat flow resistance (R value – m² K/W) is a factor determining the insulation
232 effectiveness of a box. Singh et al. (2008) and Navaranjan et al. (2013) placed a known quantity
233 of ice in a box, left it in a constant temperature chamber for a certain period to allow the ice to
234 partially melt, then determined the amount of liquid water and calculated the R value.
235 Navaranjan et al. (2013) pointed out that there was a good correlation between the R value and
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
238 (United Nations, 2020). For the internal heating method, a heat resistance (with a known heating
239 power) and temperature sensors are placed in an empty box at locations suggested in the
240 guidelines and the temperature profile is recorded continuously. When steady state is reached,
241 the difference between the internal/external air temperatures and the heating power allow the R
242 value to be calculated.

243 The box can be composed of multiple partitions to allow delivery of various types of
244 products with different recommended storage temperatures in the same box. Xiaofeng & Xuelai
245 (2021) developed an insulated box with partitions making it possible to transport three different
246 product categories: no PCM for ambient storage, with PCM with a melting point of 7.1°C (87%
247 n-caprylic acid and 13% myristic acid) for chilled storage and with a PCM with a melting point

248 of -2.1°C (potassium sorbate solution) for storage at temperatures below 0°C . They reported
249 that this box could maintain the internal temperature within the expected range for each partition
250 for up to 16 h.

251

252 2.4 PCM properties, position and usage

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

261 There are numerous thermal energy storage materials e.g. water, salt solution, paraffin
262 (Oró et al., 2012). Various compounds were applied as PCMs in an insulated box, e.g. ice or an
263 ice pack with a melting point ranging from -0.5°C to 0.5°C (East et al., 2009; East & Smale,
264 2008; Laguerre et al., 2018, 2019; Margeirsson et al., 2011, 2012; Navaranjan et al., 2013). To
265 achieve a temperature range below 0°C , Kozak et al. (2017) used salt solutions with melting
266 points of -10°C and -33°C while Elliott & Halbert (2008) studied the system with dry ice (CO_2 :
267 phase change temperature = -78.5°C). Elliott & Halbert (2005) used Icebrix® frozen gel packs
268 which froze at -20°C . Commercially available PCMs with various melting points between -2°C
269 and 21°C were also investigated (East et al., 2009; East & Smale, 2008; Kacimi & Labranque,
270 2019; X. Zhao et al., 2019).

271 Today, there is greater demand for produce from different regions in the world, hence,
272 long transport duration and fluctuating ambient conditions are unavoidable (Loria, 2021). It is

273 challenging to establish a common guideline for various types of products and transportation
274 conditions, e.g. transportation ranged from 3 h to 96 h under extremely cold (-10°C) or hot
275 (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
277 the internal and external walls to compensate for heat exchange with the ambient. East et al.
278 (2009) and East & Smale (2008) placed PCM only at the bottom of the box. Kacimi &
279 Labranque (2019) put PCM at top, bottom and side walls while Laguerre et al. (2008) applied
280 ice pack at top, middle and bottom layer of the box. Du et al. (2020) and Elliott & Halbert
281 (2005) compared the effect of PCM position on temperature profile. Some studies
282 recommended the position of the PCM on the top or side walls because this allows internal
283 airflow by natural convection, thus generating a more uniform temperature. The PCM placed
284 on the bottom leads to conduction alone along with greater temperature heterogeneity (Du et
285 al., 2020; Laguerre et al., 2008). In an insulated box with PCM at the top, middle and bottom,
286 Laguerre et al. (2008) indicated that PCMs on the top of the container completely melted within
287 32 h during an experiment on transport, while those at the bottom remained partially frozen for
288 more than 72 h, while the product temperature reached 21.5°C at the level of the top layer.

289 A composite box wall with PCM was studied (Melone et al., 2012). Mixtures of paraffin
290 (melting point 0°C to 10°C) and cellulose solutions with different concentrations (0%, 25% and
291 50% w/w) were prepared to obtain cellulose sheets with PCM. It was observed that the
292 maximum cooling period of 87 minutes was achieved for the sample with a paraffin
293 concentration of 50% w/w.

294 Some studies focused on maintaining the temperature of the load inside the box by
295 placing the PCM close to the most sensitive product such as fish and meat (Elliott & Halbert,
296 2008; Laguerre et al., 2018, 2019; Margeirsson et al., 2011, 2012; Navaranjan et al., 2013;
297 Paquette et al., 2017). Paquette et al. (2017) showed that placing PCM at the center of the box

298 provided better efficiency by comparing the duration required for the temperature of meat to
299 increase from 3.5°C to 10.0°C. It was found that this temperature rise took 32.1 h with PCM at
300 the center and 8.6 h with PCM on the side of the box. They also pointed out the decrease in the
301 temperature of meat during the initial period when 1 kg of PCM was placed on top of the meat
302 and another kg of PCM was placed on the bottom, whereas this phenomenon was not noticed
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
305 reached 18°C after a 48-h interval when the PCM was split into two layers compared with only
306 15°C when all the PCM was placed at the same position.

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

314 The weight of the PCM influences the product temperature profile and should be
315 optimized with respect to the size of the box. Kacimi & Labranque (2019) recommended that a
316 moderate amount of PCM should be applied, since too little or too much PCM decreases the
317 efficiency and causes undesirable outcomes i.e. temperature abuse and chilling injury. Xiaofeng
318 & Xuelai (2021) increased the volume of the compartment by 25% while maintaining the same
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
321 reported that an inappropriate amount of PCM led to temperature abuse during delivery because
322 the products were either too warm or frozen.

323

324 2.5 Effect of the external temperature

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

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

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

351

352 2.6 Influence of each factor in application and modeling

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

371 and air velocity, but this approach requires more computational time and resources (Du et al.,
372 2020; Laguerre et al., 2018, 2019; Margeirsson et al., 2011, 2012; Paquette et al., 2017). A data-
373 based model, which needs less background in physics, is simpler to use. This model represents
374 a simple relationship between the input parameters and the intended responses, for example,
375 using the thermal resistance of the insulated box to predict food quality (Navaranjan et al.,
376 2013).

377 This complexity also impacts system design. To find the best compromise between these
378 constraints, the objectives must be clearly identified depending on the application. For example,
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
381 this objective might impact the design of the box and the PCM. For instance, if the box is
382 designed to transport fruit and vegetables with an optimal temperature range (e.g. from 4°C to
383 10°C), the temperature heterogeneity might not be crucial. Hence, there will be more flexibility
384 in the choice of the box material and the PCM position in the box. A specific design is required
385 during transportation of highly temperature sensitive products e.g. superchilled food products
386 (Kaale et al., 2011). These authors reported that temperature fluctuations lead to ice
387 recrystallization and drip loss leading to product quality degradation. East & Smale (2008) and
388 East et al. (2009) optimized insulated box design using a hybrid genetic algorithm to obtain the
389 box with the lowest cost regarding material, transportation and penalty due to temperature
390 abuse. They suggested that the boxes used in summer should have a thicker insulating material
391 and a larger quantity of PCM to withstand the heat flux from ambient than that in winter while
392 the other factors remained almost identical.

393 Among the studies examined in our review, several focused on how to improve the
394 insulation of a classic box, i.e. a box made of expanded polystyrene, polyurethane, or a
395 corrugated box by increasing the air gap, adding spacers, vacuum panels and metallizing the

396 surface. The rounded corner box design was also suggested to deal with temperature
397 heterogeneity. The methods used to determine insulation efficiency was developed by
398 measuring the heat flow resistance (R) value and was tested in real application. The external
399 temperature and load type and mass inside the box were also investigated. The effect of each
400 factor was described and predicted by basic heat transfer equations. There was substantial
401 evidence proving that the application of PCM could lower the temperature of the system and
402 possibly improve thermal homogeneity. However, the PCM melting point, the amount of PCM
403 and optimization of its position are still necessary to achieve the most efficient conditions for
404 each system.

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

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

417

418 3. Cold chain equipment with PCM

419 Unlike in an insulated box, PCM in refrigerated equipment often enables energy
420 management, temperature stabilization, etc. Many articles pointed out the capacity of PCM to
421 reduce the compressor operating time, thus lowering energy consumption (Alzuwaid et al.,
422 2015; Azzouz et al., 2008, 2009; Berdja et al., 2019; Ezan et al., 2017; Maiorino et al., 2019;
423 Sonnenrein, Baumhögger, et al., 2015; Sonnenrein, Elsner, et al., 2015; Yilmaz et al., 2020).
424 Several studies showed that PCM allows the extension of the cooling period following power
425 failure (Ben-Abdallah et al., 2019; Oró, Miró, et al., 2012; Yilmaz et al., 2020). Use of PCM
426 can also decrease the temperature of the system with greater homogeneity (Alzuwaid et al.,
427 2015, 2016; Azzouz et al., 2009; Ben-Abdallah et al., 2019; Maiorino et al., 2019; Sonnenrein,
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,
432 and the studies are summarized in Table 2. To obtain a very low melting point, different types
433 of salts with different concentrations were used: an in-house inorganic salt solution with a
434 melting point of -26.7°C (M. Liu et al., 2012), a NaCl solution with a melting point of -21.2°C ,
435 (Xiaofeng et al., 2017) and commercial blends of salts with melting points of -26°C , -29°C and
436 -32°C , (Mousazade et al., 2020). For PCMs with higher melting points (7°C to 45°C) which are
437 inserted between the external and internal walls, paraffin and salt hydrate were used (Ahmed et
438 al., 2010; Copertaro et al., 2016; Fioretti et al., 2016).

439 To facilitate experimental implementation, several studies investigated stationary
440 refrigerated trucks in a test chamber in which the ambient temperature alone was controlled. M.
441 Liu et al. (2012) determined the period during which the internal temperature was below -15°C
442 by using 136.8 kg of PCM salts in a tank connected to the truck evaporator when the ambient

443 temperature was about 30°C. The authors predicted that 163% more PCM would be necessary
444 for 10 h transportation during summer (maximum temperature = 41°C) in Adelaide, Australia.
445 The same authors also pointed out that a phase change thermal storage unit could replace the
446 cooling engine. This storage unit, charged at the distribution center before transportation, allows
447 51.0% - 86.4% cost savings depending on the COP of the system and the electricity tariff.

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

451 Other studies dealt with stationary refrigerated trucks under real climate conditions i.e.
452 ambient temperature, solar radiation. Ahmed et al. (2010) and Fioretti et al. (2016) investigated
453 the efficiency of their systems with PCM under real conditions and reported that the truck
454 equipped with PCM could decrease the total heat flux through the wall by 1.7% to 26.4%. This
455 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.

461 Mousazade et al. (2020) conducted an experiment in a moving truck and pointed out
462 that the speed needed optimization. In fact, a higher speed led to a greater distance covered and
463 lowered the PCM cooling time due to higher heat exchange. This was probably due to a higher
464 external convective heat transfer coefficient and more vibration. They reported that the longest
465 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 of
467 110 km/h (4.46 h cooling period).

468

469 3.2 PCM in cold rooms

470 According to the authors' knowledge, only a few studies have been conducted on PCM
471 application in cold storage facilities or warehouses, although it has been shown that higher
472 product quality can be achieved using PCM (Pirdavari & Hossainpour, 2020; Schalbart et al.,
473 2013). The difficulty in PCM charging and temperature control in a cold room may be one of
474 the main obstacles to implementation. The application of PCM in cold storage facilities is
475 summarized in Table 3.

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

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

489

490 3.3 PCM in display cabinets

491 The application of PCM in display cabinets is summarized in Table 4. Pure ice placed
492 near the evaporator was generally used (Alzuwaid et al., 2016; Ben-Abdallah et al., 2019; Ezan
493 et al., 2017). Ice with an additive (melting point -6°C to -2°C) was placed either near the
494 evaporator or below the cabinet shelves (Alzuwaid et al., 2015; Yilmaz et al., 2020). Oró, Miró,
495 et al. (2012) applied commercial PCM (Climsel C-18 and Cristopia E-21), with melting point
496 of -18°C and -21.3°C respectively, over evaporator tubes located at different shelves of a
497 closed display cabinet. The authors reported that for empty closed display cabinet, the air
498 temperature rose from -22°C to 0°C within 1.5 h (without PCM), 6.5 h (-18°C PCM) and 8 h
499 (-21°C PCM). This period extended when display cabinet was loaded by test product: 11.5 h
500 (without PCM), 15.6 h (-18°C PCM) and 21.5 h (-21°C PCM), as illustrated in Fig. 3. These
501 results demonstrated the interest of PCM to slow down the product temperature when the
502 display cabinet was turn off, due to machine failure for example.

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
506 heat has to be removed. However, the presence of PCM makes the temperature in the enclosure
507 more stable, so, a slightly higher evaporator temperature can be used. Thus, the COP is
508 increased and the electrical energy consumption is reduced. In this manner, the heat transfer
509 efficiency of the cold enclosure can be improved. The amount of PCM or the thickness of the
510 PCM slab had to be optimized (Ben-Abdallah et al., 2019). Ezan et al. (2017) compared the
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
513 cooling capacity without significantly obstructing the airflow inside the equipment. The
514 position of the PCM is another challenge in the application because PCM in an inappropriate

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.

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

525

526 3.4 PCM in domestic refrigerators

527 Several studies have investigated PCM application in domestic refrigerators as
528 summarized in Table 5. In most studies, the PCM was placed at the evaporator by using ice
529 (Azzouz et al., 2009; Maiorino et al., 2019), a copolymer with a melting point of -4°C
530 (Sonnenrein, Baumhögger, et al., 2015), or an eutectic solution with a melting point between
531 -9°C and -1°C (Azzouz et al., 2008, 2009). Sonnenrein, Baumhögger, et al. (2015) and
532 Sonnenrein, Elsner, et al. (2015) applied ice, paraffin (melting point = 34°C) and a copolymer
533 (melting point = 34°C to 35°C) at the condenser. Sonnenrein et al. (2020) studied the application
534 of a copolymer PCM (melting point = 9°C) in the load compartment.

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

539 (Azzouz et al., 2008). Azzouz et al. (2009) reported that placing a eutectic plate (melting point
540 = -3°C) at the evaporator lowered the internal temperature by up to 1.5°C . However, the
541 compressor operating period was 0.4 h longer. Thus the COP was lower in comparison with the
542 system using ice. Sonnenrein, Baumhögger, et al. (2015) and Sonnenrein, Elsner, et al. (2015)
543 reported that paraffin and copolymer PCM (melting point = 34°C to 35°C) were more efficient
544 than ice at the condenser since they allowed a temperature that was 5°C to 6°C lower to be
545 achieved at the condenser, leading to 2% to 17% lower energy consumption. The thickness of
546 the PCM slab should also be optimized to achieve the highest efficiency (Azzouz et al., 2008;
547 Berdja et al., 2019).

548 PCM (melting point = 9°C) in the load compartment has proved to be useful in several
549 commercialized domestic refrigerators by decreasing the cooling time (the time required to
550 reduce the product temperature from 25°C to 10°C) by 16% to 33%. It also makes it possible
551 to increase the temperature rise period (the time required to raise the package temperature from
552 8°C to 11°C after turning off the cooling system) by 75% to 145% (Sonnenrein et al., 2020).

553 Frost formation on evaporator was still a challenge since it exerted a greater effect on
554 airflow than the PCM due to higher thermal resistance (Berdja et al., 2019). Azzouz et al. (2008)
555 pointed out that greater numbers of door openings led to lower PCM efficiency as the PCM did
556 not completely melt by the time the compressor restarted and could not provide full cooling
557 capacity. Maiorino et al. (2019) indicated that an ambient temperature that was 7°C higher
558 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 variety
562 of types of equipment. PCMs can be used in complement with cold production in refrigerated

563 equipment or as alternative cooling systems. For example, when refrigeration equipment is not
564 available or the ambient temperature during transportation is not appropriate, an insulated box
565 with a PCM can be an alternative. It ensures a low, stable temperature, and thus preserves food
566 quality.

567 The incorporation of PCM in refrigerated equipment is mostly performed for energy-
568 management-related purposes. Many studies have been conducted on PCM in domestic
569 refrigerators and display cabinets, but fewer studies have been performed on cold rooms. This
570 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
576 models) can be used to simulate other configurations. These models often consider heat transfer
577 by conduction alone, although radiation and free convection can exert significant impacts in
578 insulated boxes, especially in terms of temperature heterogeneity. Consequently, it is important
579 to quantify heat flux by conduction, convection, and radiation since none of them can be
580 neglected. Therefore, further studies are essential to better understand the relationship between
581 heat transfer and airflow by natural convection. Studies on the effect of the load porosity on
582 heat transfer by convection and conduction and on the impact of the emissivity of walls or
583 product packages on heat transfer by radiation should be undertaken.

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.

587 The use of PCMs in insulated boxes exerts environmental impacts because of the PCM
588 production itself, the production of the insulating material and the energy consumption required
589 for charging the PCM before each use, along with PCM waste etc. Consequently, additional
590 specific studies on these issues may help evaluate the feasibility and sustainability of the use of
591 PCMs. Some progress has been achieved in the development of new insulating materials with
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
595 acting as phase change material for transporting perishable products.

596

597 5. Conclusions and suggested future research

598 Applying PCMs in the food cold chain provides several benefits: less temperature abuse,
599 and thus better product quality and better energy management. To achieve these benefits, many
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
603 temperature and storage and transport duration). These factors significantly affect the efficiency
604 of the system, especially when PCM is the only cold source (no refrigerating machine). Thus,
605 optimization of these factors is necessary in order to design the best configuration for achieving
606 the objective of each application.

607 Modeling is a complementary experimental approach but is more complicated to
608 develop. By using modeling, the prediction of results under unexplored operating conditions is
609 possible e.g. ambient temperature, transport/storage duration, load type and its initial
610 temperature. Existing models could be improved by acquiring a better understanding of the
611 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.

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

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

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

635

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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 (<i>Nemadactylus macropterus</i>)	Ice pack (0°C) / in the center at the top of the box	<p>6 Boxes with the same dimensions (55.0 cm x 37.5 cm x 12.0 cm)</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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 (<i>Trachurus</i>)	Flaked ice (0°C) / top of fish stack	EPS box with 3 cm thickness	Experimental and numerical (1D analytical model and 2D CFD)	<ul style="list-style-type: none"> - 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.

<p>Laguerre et al. (2019) / Sardine</p>	<p>Ice pack (-0.1°C to 0.1°C) / top of the fish stack</p>	<p>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</p>	<p>Experimental and numerical (1D analytical model and 3D Finite Element Method or 3D FEM)</p>	<ul style="list-style-type: none"> - 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.
<p>X. Zhao et al. (2019) / Strawberries</p>	<p>Commercial PCM (-2.0°C to -1.2°C) / top wall of the box</p>	<p>EPS (29.0 cm x 17.5 cm x 13.0 cm)</p>	<p>Experimental</p>	<ul style="list-style-type: none"> - 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.

<p>Du et al. (2020) / No load</p>	<p>PCM (0°C, 2°C, 3°C, 4°C, 5°C and 8°C) / 5 configuration</p> <ul style="list-style-type: none"> - 100% top (A) - 20% each side and top (B) - 25% each side (C) - 20% each side and bottom (D) - 100% bottom (E) 	<p>Polyurethane (PU) or vacuum insulated panels (VIPs) (35.5 cm x 21.5 cm x 26.5 cm)</p>	<p>Numerical (3D heat transfer model) with experimental validation</p>	<ul style="list-style-type: none"> - 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).
<p>Xiaofeng & Xuelai (2021) / No load</p>	<p>2 PCM type: A: 87% n-caprylic acid and 13% myristic acid</p>	<p>PU and VIP (145 cm x 75 cm x 65 cm) divided into 3 compartments for 1) ambient storage (no PCM), 2) chilled</p>	<p>Numerical (3D unsteady model) with experimental validation</p>	<ul style="list-style-type: none"> - 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.		<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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.

<p>Elliott & Halbert (2008) / Small boxes containing empty packages</p>	<p>dry ice (CO₂: -78.5°C) / bottom of the box</p>	<p>EPS box (32 cm x 32 cm x 29.5 cm)</p>	<p>Experiment and transit test to maintain temperature below -10°C</p>	<ul style="list-style-type: none"> - 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.
<p>Laguerre et al. (2008) / Cartons of several product units</p>	<p>PCM (-0.5°C) / top, middle and bottom of the container</p>	<p>Corrugated cardboard insulated with polystyrene plates (108 cm x 72 cm x 137 cm)</p>	<p>Experimental and numerical (excitation-response model)</p>	<ul style="list-style-type: none"> - 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.
<p>Kacimi & Labranque</p>	<p>- Organic PCM (5°C) / all box faces</p>	<p>VIPs with 15 L, 27 L, 40 L and 64 L</p>	<p>Experimental</p>	<ul style="list-style-type: none"> - 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.

			<p>material, shipping and penalty due to temperature abuse by using zonal based heat transfer model coupled with a hybrid genetic algorithm</p>	<p>- The cost of the boxes is almost the same, whatever the design.</p>
<p>East et al. (2009) / Beverage cans</p>	<p>Same as East & Smale (2008)</p>	<p>Same as East & Smale (2008)</p>	<p>- 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,</p>	<p>- In winter, a 10 mm polystyrene box and a 10 mm of ice pack were proposed and caused 86% heat failure.</p> <p>- In summer, it required a polyurethane box thickness of 90 mm and 53.9 mm ice pack but led to 26% freezing failure.</p> <p>- 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.</p>

			<p>24 h), and both summer-winter (-18°C to 35°C, 48 h) transport.</p> <p>- These boxes were numerically tested against 1095 ambient temperature profiles that varied according to climate conditions.</p>	<p>- The box for winter climate conditions only is about twice as cheap as those used in summer only or both in summer and winter.</p>
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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	<ul style="list-style-type: none">- 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.	<ul style="list-style-type: none">- 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.

<p>Fioretti et al. (2016) / Experimental (stationary empty truck container in laboratory test room and real climate conditions) and numerical study (2D heat transfer model)</p>	<p>Paraffin wax (35°C) / inside refrigerated truck wall made of steel</p>	<ul style="list-style-type: none"> - The experiment demonstrated that PCM decreased heat flux (between 15 W/m² and 47.5 W/m² to between 13 W/m² and 25 W/m²), 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.
<p>Xiaofeng et al. (2017) / Numerical (3D CFD of empty refrigerated truck)</p>	<p>Eutectic NaCl solution (-21.2°C) / in a plate installed on the truck wall</p>	<ul style="list-style-type: none"> - 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.

<p>Mousazade et al. (2020) / Experimental (stationary and moving empty truck)</p>	<p>Commercial PCM containing various blends of salts (-26°C, -29°C and -32°C) / in a plate placed on the truck wall.</p>	<p>- 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).</p> <p>- 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.</p>
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Table 3 Summary of studies using PCM in cold storage facilities

Reference / Type of study	PCM (melting point) / its location	Main observation(s)
<p>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.</p>	<p>PCM with a melting point that was optimized depending on the location / post-evaporator, ceiling, wall, storage tank and product package</p>	<ul style="list-style-type: none"> - 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.

<p>T. Yang et al. (2017) / Numerical (3D CFD) of cold storage facility with a container of potatoes</p>	<p>Ice plate (0°C) / on each side of the wall, the floor and the roof</p>	<p>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/m² K.</p>
<p>Pirdavari & Hossainpour (2020) / Optimization via numerical study (1D simplified dynamic model which is validated by using experimental data from Azzouz et al. (2009)).</p>	<p>LiClO₃·3H₂O 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.</p>	<p>The greater the quantity of PCM, the lower the melting point of the PCM and the lower thermal conductivity of insulation led to a longer melting time and lower product temperature.</p>

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	<ul style="list-style-type: none">- 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	<ul style="list-style-type: none">- 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.

<p>Yilmaz et al. (2020) / Experimental (closed display cabinet)</p>	<p>Distilled water with a nucleating agent and thickening agent (-6°C) / either on the back wall or on the shelves</p>	<ul style="list-style-type: none"> - 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.
<p>Alzuwaid et al. (2015) / Experimental (open display cabinet)</p>	<p>Ice gel PCM (-2°C) / above evaporator</p>	<p>Adding PCM led to 5% energy savings, 70% longer defrost period, 2°C lower maximum cabinet temperature and more stable product temperature: T_{max}-T_{min} 7.33°C (without PCM) and 6.50°C (with PCM).</p>
<p>Alzuwaid et al. (2016) / Numerical study (2D CFD)</p>	<p>Pure-water ice PCM (0°C) / above the evaporator</p>	<p>- 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).</p>

<p>with experimental validation (open display cabinet)</p>		<ul style="list-style-type: none"> - The highest product temperature was at the front of the middle shelf and the lowest one was located at the back of top shelf.
<p>Ben-Abdallah et al. (2019) / Experimental (open display cabinet)</p>	<p>Ice (0°C) / in a finned tube heat exchanger placed in the rear duct</p>	<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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.

<p>Sonnenrein et al. (2015b) / Experimental</p>	<p>Paraffin (34°C), copolymer compound with 10% (w/w) graphite (34°C), or water (0°C) / condenser</p>	<p>- 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.</p>
<p>Sonnenrein et al. (2015a) / Experimental</p>	<p>- Copolymer PCM (-4°C) / evaporator - Another copolymer PCM (35°C) / on the condensers of 2 different refrigerator models</p>	<p>- 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.</p>
<p>Berdja et al. (2019) / Experimental and numerical (1D analytical model)</p>	<p>PCM (-11°C) / covering the evaporator surface</p>	<p>- 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).</p>

		<ul style="list-style-type: none"> - 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.
<p>Maiorino et al. (2019) / Experimental</p>	<p>Ice (0°C) / above and below the evaporator rack tube</p>	<ul style="list-style-type: none"> - 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.
<p>Sonnenrein et al. (2020) / Experimental</p>	<p>Polymer-bound PCM (9°C) / in each load compartment</p>	<ul style="list-style-type: none"> - PCM decreased 16% - 33% cooling time and increased 75% - 145% the temperature rise period. - Energy consumption was not significantly different.

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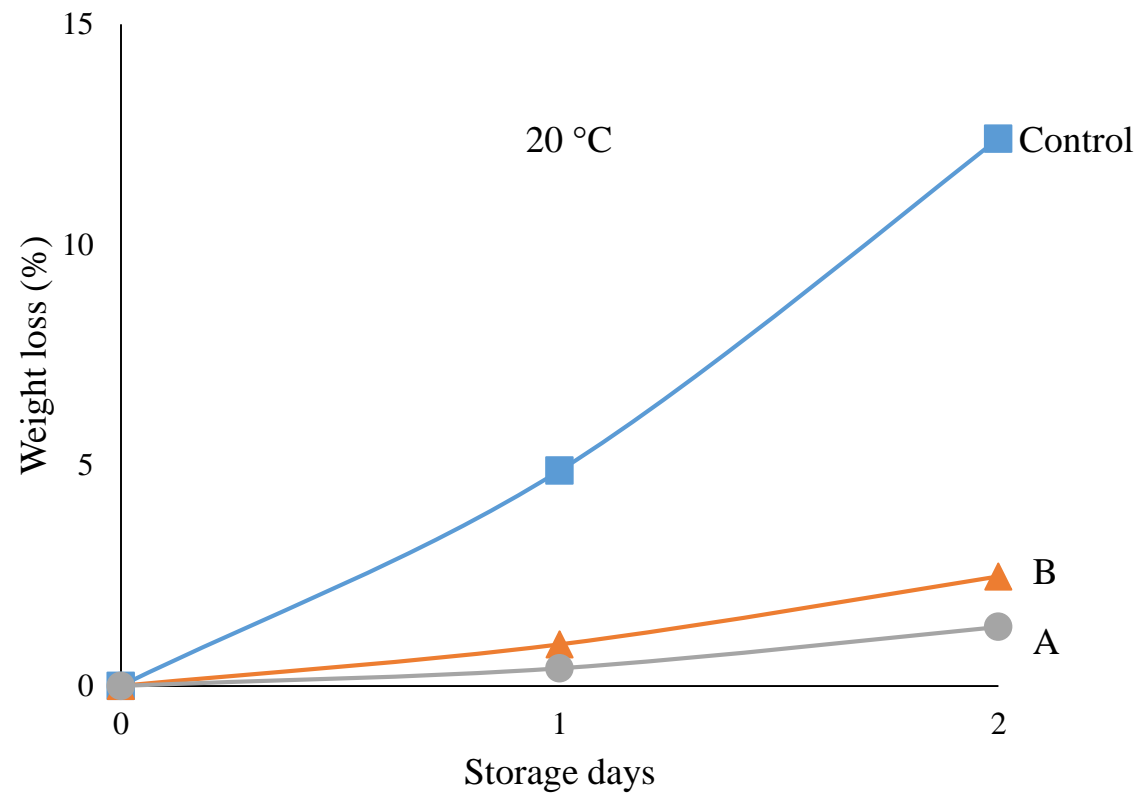
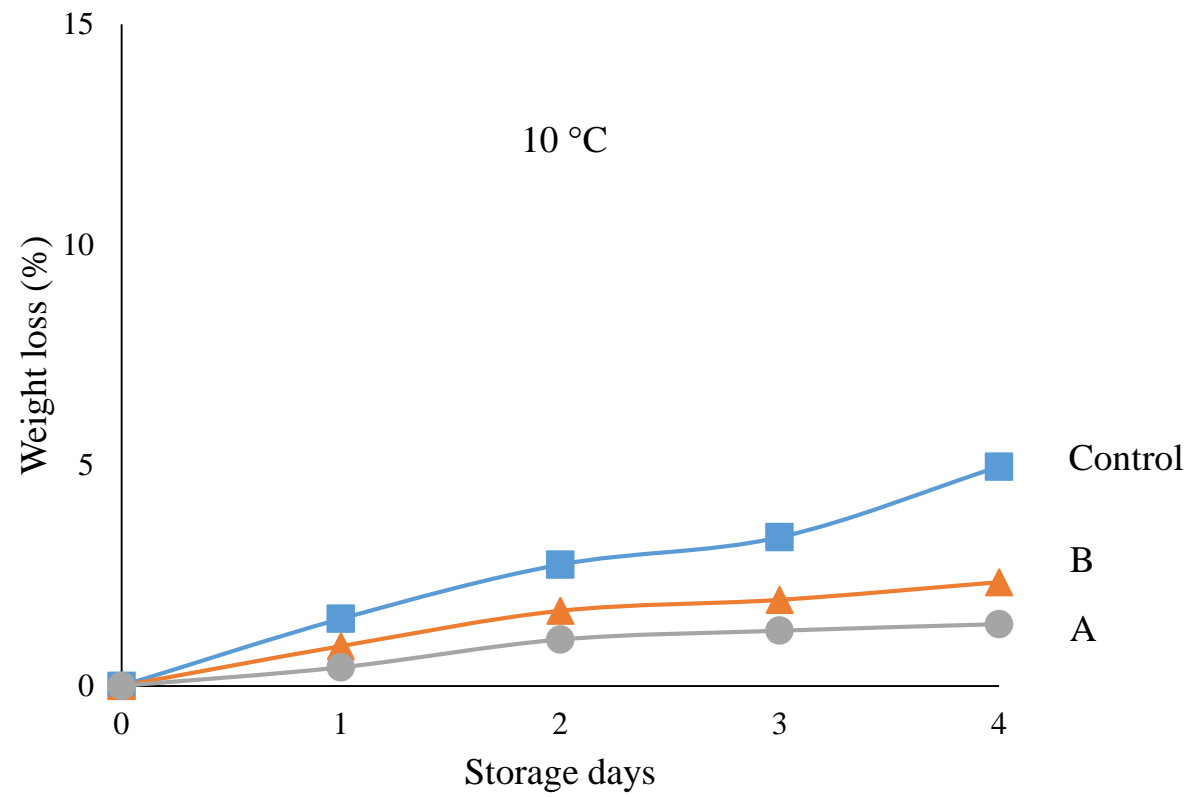
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Fig 1: Evolution of (a) product weight loss and (b) product respiration rate of a strawberry packed in an expanded polystyrene box with PCM. A = MA pack (10% O₂, 0% CO₂), B = air pack and C = Control (product directly in contact with ambient air). (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)



(b)

