Journal of Energy Storage 111 (2025) 115391

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Review article

An extensive analysis of the utilisation of phase change materials in food storage process

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ARTICLE INFO

Keywords:
Phase change materials
Thermal energy storage
Food storage
Energy efficiency
Food quality

ABSTRACT

With improving living standards, the demand for high-quality food is escalating. Conventional food storage methods often entail issues such as limitations in sustaining food quality and related energy wastage. The utilisation of PCMs in the food storage sector offers a means to achieve energy conservation whilst preserving food quality due to the inherent benefits of PCMs. This article presents a literature review on the application of PCMs in food storage, primarily focusing on drying and refrigeration techniques. The first part of this study summarises the utilisation of PCMs in food storage industry, conducting data analysis to uncover their developmental trends. The utilisation of PCMs in the domains of drying and cooling holds the capability to effectively diminish temperature fluctuations by (7.5/8 °C), enhance storage efficiency by (43.42/11.5 %), curtail energy consumption by (33/39 %), and uphold the physical, chemical, and nutritional content of food. Paraffin wax stands out as the prevalent PCM, and the phase change temperature predominantly falls within the range of 40–60 °C (46.57 %). Furthermore, there exists a research gap in the combined utilisation of different PCMs and the deployment of single/multi-function PCM refrigeration systems. This article offers insights into future research directions concerning PCM applications in the realm of food storage.

1. Introduction

Over the past few decades, the issue of agricultural product waste has garnered significant attention due to its detrimental impacts on human society, economic trade, and environmental conservation. According to data from the Food and Agriculture Organization (FAO), the average annual food waste per person ranges is about 74 kg (70 kg/person in UK) [1], necessitating an estimated global expenditure of $2.6 trillion for waste disposal annually [2]. Simultaneously, the recent "State of Food Security and Nutrition in the World" report highlights a concerning rise in the number of people facing hunger globally. The population of those experiencing food insecurity has escalated to about 828 million in 2023, a significant increase from 613 million in 2019 [3]. The primary cause of resource wastage stems from the high moisture content and susceptibility to decay and deterioration of agricultural products, including vegetables, fruits, and wood. As a scientific field, food storage seeks to extend the shelf life of food while maintaining its nutritional value as much as possible [4]. Among the various techniques, drying and refrigeration have become widely used and cost-efficient methods in the food industry [5]. Drying primarily aims to lower water activity, allowing dried products to be stored safely for long durations [6]. Conversely, refrigeration inhibits metabolic processes such as respiration and transpiration, as well as microbial activity, by lowering the temperature during food storage, thereby effectively preserving product quality [7].

There are many food storage methods commonly used at present, including hot air drying, heat pump drying, vacuum freeze drying, cooling, microwave drying, freezing, etc. [4,8–11] However, the above methods require a large amount of electricity, which is still largely dependent on fossil fuels [12], which is contrary to the current popular energy conservation and emission reduction policies. Fig. 1 illustrates that drying and cooling processes consume as much as 75 % of the total energy used in the food industry.

Abbreviations: CMs, Phase change materials; WPCM, With PCM; WOPCM, Without PCM; FAO, Food and agriculture organization; TES, Thermal energy storage; CTES, Cold thermal energy storage; LHS, Latent heat storage; DTSD, Direct type solar dryer; SAH, Solar air heater; CFD, Computational fluid dynamics; UDF, User Defined Function; ITSD, Indirect type solar dryer; MTSD, Mixed-type solar dryer; HTSD, Hybrid type solar dryer; TFC, Total flavonoid content; TPC, Total phenolic content; GTSD, Greenhouse type solar dryer; MAP, Modified atmosphere packaging; HNTs, Halogenated nanotubes; SAR, Super absorbent resin; SCD, Sodium carbonate decahydrate; IoT, Internet of Things.

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https://doi.org/10.1016/j.est.2025.115391
Received 18 September 2024; Received in revised form 18 December 2024; Accepted 8 January 2025
Available online 13 January 2025

Nomenclature

Q	Storage capacity (J)
t_m	Melting temperature (°C)
t_f	Final temperature (°C)
m	Mass of material (kg)
C_{SP}	Average specific heat of the solid phase between t_i and t_m (kJ/(kg·K))
C_{lP}	Average specific heat of the liquid phase between t_m and t_f (kJ/(kg·K))
f	Melt fraction
Δq	Latent heat of fusion (J/kg)

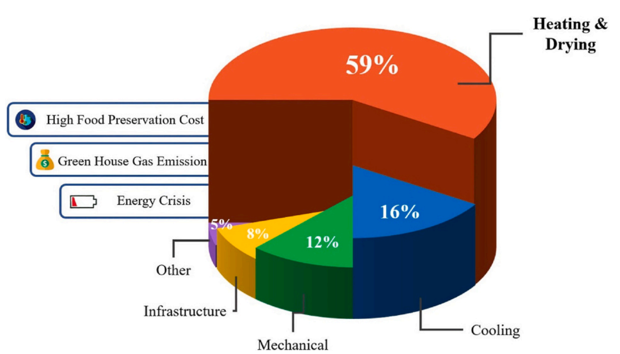

Fig. 1. The energy distribution across different sectors within the food industry. [13].

Integrating thermal energy storage (TES) and cold thermal energy storage (CTES) modules into the food storage process is regarded as an effective solution to this issue, capable of reducing fossil fuel consumption and achieving peak energy savings. [14,15]. PCM utilises a latent heat storage (LHS) mechanism, leveraging the absorption or release of latent heat during phase transitions for energy storage and release. These materials boast several advantages, including high energy storage density, significant latent heat values, non-corrosiveness, and temperature maintenance ability [16,17]. Due to these properties, PCM has garnered significant attention and finds extensive application in the realm of food storage [18]. Given the urgent need within the food industry for energy-efficient temperature control methods for both food storage and environmental conservation, PCMs are able to address these dual objectives simultaneously [13]. PCMs can be utilised at different temperature ranges within the food industry to harness waste heat or cold energy, ensuring temperature stability in various applications like storage and transportation [19]. Numerous researchers have examined the utilisation of PCMs in food storage processes. Leungtongkum et al. [20] have provided a comprehensive summary of the impact of research parameters, including PCM melting point, location, and mass, on air/product temperature and energy consumption. Nie et al. [21] presented an extensive review of contemporary applications of cold energy storage, encompassing air conditioning and natural cooling. The review also detailed the primary challenges and engineering methods for both cold and hot energy storage. In food refrigeration, employing PCMs as regenerators in refrigeration environments enhances food quality and energy management. Abuelnuor et al. [22] provided a review on the influence of PCM utilisation on the performance of solar dryers, focusing on drying temperatures and rates. In the food drying process, integrating PCM modules into solar dryers not only achieved energy savings, but also enhanced the quality of dried products by effectively controlling moisture content.

Numerous researchers have extensively investigated the utilisation of PCMs in drying and refrigeration processes. However, the author has identified systematic discussions on the application of PCM in food storage processes (including refrigeration and drying) are relatively limited. Furthermore, existing studies often lack in-depth analyses of the effects of PCM-integrated food storage systems on food quality, such as the preservation of color, texture, flavor, and nutritional content. Given the urgent need for environmental protection and the growing interest in the energy storage capabilities of PCM, this paper aims to fill these research gaps by reviewing and systematically summarizing the applications of PCM in food preservation processes, providing a scientific basis for its future optimization and broader applications. Initially, the energy storage principles, classification, and characteristics of PCMs are elucidated. Subsequently, the application of PCMs in the drying process is comprehensively explored, encompassing aspects such as dryers and optimisation effects. Following this, a thorough examination of CTES materials applied to food transportation, refrigeration, and packaging is presented. Finally, future research directions and existing challenges are outlined.

2. Classification and analyse of PCMs

2.1. Introduction of PCMs

LHS entails storing or releasing heat in a medium that changes its physical state (phase change) during the charging or discharging process. In contrast to sensible heat storage systems, LHS techniques have attracted more interest because they offer higher energy storage density, as depicted in Fig. 2, utilisation of additional latent heat energy, and superior hot spot temperature control capabilities [23,24]. In the majority of LHS applications, the mechanism for storing or releasing heat is triggered by the physical phase transition of PCMs [25,26]. PCMs can be categorised into five types: liquid-solid, solid-liquid, solid-gas, solid-solid, and liquid-gas; however, only the transitions between liquid-solid, solid-gas and solid-liquid states are practically feasible [13,27]. The liquid-gas transition process involves a significant amount of heat conversion but requires high-pressure storage and is prone to leakage [28]. Conversely, the solid-solid transition poses challenges regarding heat conversion efficiency, making them unsuitable for application in the food industry [29]. Most PCMs employed in LHS achieve a phase transition through material melting and solidification. During melting, heat is absorbed by the material, enabling the accumulation of thermal energy at a constant temperature, while heat is released during solidification [30]. The storage capacity of LHS with PCMs (WPCM) can be calculated using the following Eqs. (1)–(2) [31,32].

$$Q = \int_{t_i}^{t_m} mc_p dt + mf\Delta q + \int_{t_m}^{t_f} mc_p dt \tag{1}$$

$$Q = m\left[C_{SP}(t_m - t_i) + f\Delta q + C_{lP}\left(t_f - t_m\right)\right] \tag{2}$$

where: Q represents the storage capacity (J); t_m is the melting

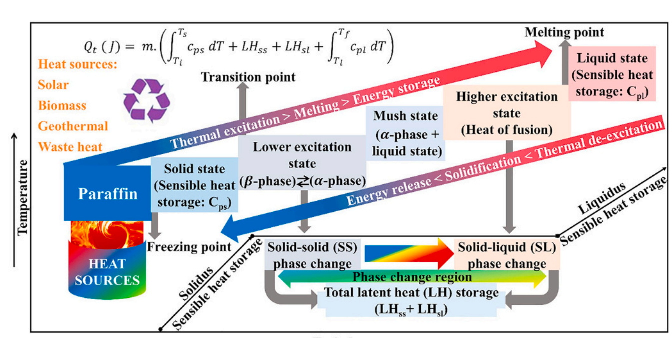

Fig. 2. Summary of latent heat storage PCMs [33].

temperature (°C); m denotes the mass of material (kg); C_{SP} is the average specific heat of the solid phase between t_i and t_m (kJ/(kg·K)); C_{lP} is the average specific heat of the liquid phase between t_m and t_f (kJ/(kg·K)); f is the melt fraction; Δq is the latent heat of fusion (J/kg).

2.2. Classification of PCMs

According to the previous study from Sarbu [32], PCMs can be broadly classified into three categories: organic, inorganic, and eutectic materials, as illustrated in Fig. 3. Furthermore, organic materials are divided into paraffin and non-paraffin types. Metallics and salt hydrates are the two additional branches into which inorganics can be divided [34]. Inorganic-inorganic, organic-organic, and inorganic-organic type pairings are examples of eutectic types [35]. Below is an in-depth review of each PCM unit, including all of its benefits and drawbacks.

2.2.1. Organic PCMs

2.2.1.1. Paraffin. Paraffin, primarily composed of carbon and hydrogen, constitutes a mixture of alkanes (CH_3). As the number of carbon atoms or molecular weight increases, the latent heat of the organic phase correspondingly increases. [36]. Paraffin wax is of considerable interest owing to several advantages:

(i) High energy storage density: Paraffin wax exhibits a high latent heat value during phase change, allowing it to preserve a significant amount of energy within a relatively small volume. [37].
(ii) Environmental sustainability: Paraffin wax is considered relatively environmentally friendly, and does not contain harmful substances as a natural compound, rendering it a sustainable choice in certain applications [38].
(iii) Temperature control: The phase transition temperature of paraffin wax can be tailored by adjusting its molecular structure, facilitating flexible temperature control according to specific requirements [36].
(iv) Cost-effectiveness: Paraffin wax is generally an inexpensive material, offering an important advantage in many large-scales applications [13].

Due to its robust chemical stability economic feasibility, ease of processing, and application flexibility, paraffin is extensively utilised in the field of food storage. However, paraffin waxes often exhibit relatively low thermal conductivity during phase changes, which may limit their suitability in certain high-power applications. Overall, while paraffin wax has significant potential as a PCM in energy storage applications, its advantages and disadvantages must be carefully considered in specific contexts. Currently, there is no detailed summary of the use of paraffin waxes in food storage. The thermal properties of select paraffins employed in food storage are presented in Table 1.

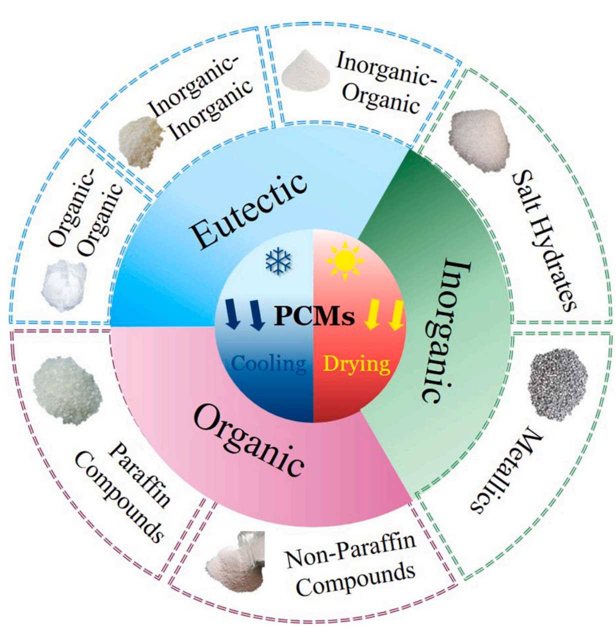

Fig. 3. Classification of PCMs.

2.2.1.2. Non-paraffin. Non-paraffin organic materials constitute the most abundant category of PCMs with diverse properties, including fatty acids, polyalcohols, and others [39–41]. Unlike paraffins, which share similar properties, almost all non-paraffin materials possess unique characteristics. In contrast to paraffin wax, non-paraffin PCMs offer greater customisability through the selection of various organic ingredients and auxiliary substances to meet specific requirements. Owing to the diversity of organic components, these materials can be employed across multiple temperature ranges and application scenarios [42]. Fatty acids ($CH_3(CH_2)_2nCOOH$) exhibit high stability against deformation and phase separations over numerous cycles. Derived from animals or plants, fatty acids are digestible by the human body, making them particularly suitable for the food industry. Non-paraffinic materials typically share common characteristics such as high heat of fusion, flammability, low thermal conductivity, and low flash points [43]. However, the primary drawback associated with non-paraffinic substances is their cost, typically ranging from 2 to 2.5 times higher than that of technical grade paraffin wax, thereby limiting their applicability [44]. Thermophysical properties of select non-paraffins utilised in food storage are summarised in Table 2.

2.2.2. Inorganic PCMs

As mentioned previously, inorganic PCMs can be categorised into two groups: salt hydrates and metallics. Most of the storage temperature utilises required in the food industry occur below the melting point of metallic PCMs, which is over hundreds of degrees Celsius. Therefore, metallic PCMs are less applicable for food storage. Different types of salt hydrates utilised in drying and refrigeration are concluded in this paper.

2.2.2.1. Salt hydrates. Salt hydrates constitute a significant category of inorganic PCMs [87], characterized as combinations of inorganic salts and water ($AB \times nH_2O$), as depicted in Eqs. (3) & (4).

$$MN.nH_2O \rightarrow MN.mH_2O + (n-m)H_2O \quad (3)$$

$$MN.nH_2O \rightarrow MN + nH_2O \quad (4)$$

The energy storage mechanism of salt hydrates primarily involves moisture absorption and dehumidification processes. Throughout the phase change process, water molecules undergo either absorption or release, leading to a modification in the material's crystalline structure known as hydration. This alteration is accompanied by the release or absorption of significant heat [88]. Salt hydrates are extensively utilised in latent heat TES systems due to several distinctive characteristics.

(i) High latent heat value per unit volume.
(ii) Relatively high thermal conductivity (approximately twice that of paraffin)
(iii) Inherent stability with low susceptibility to decomposition or damage.
(iv) Comparatively low cost [89].

However, a significant drawback arises from the inconsistent melting behavior of salt hydrates, whereby the released water during dehydration may be insufficient to fully dissolve the salt. Consequently, salt precipitation occurs, leading to phase separation and a subsequent reduction in performance or even structural damage of the PCM. In

Table 1
Thermophysical properties of paraffins utilised in food storage.

Materials	Application	Melting point (°C)	Latent heat (kJ/kg)	Density (kg/m^3)	Volumetric expansion coefficient (K)	Specific heat (kJ/kg·K)	Thermal conductivity (W/m·K)
Paraffin RT-58 [45]	Drying	58	180	840 (solid) 775 (liquid)	–	2.1	0.2
n-Pentacosane [46]	Drying	45–60	238		–	–	–
Paraffin wax C31–33 [47]	Drying	68–70	232	865–913 (s) 706–770 (l)	–	–	0.24
Paraffin wax C23–24 [47]	Drying	45–48	170	912 (s) 769 (l)	–	–	0.21
Paraffin wax [48]	Drying	44.15	166	783	–	2.1	0.2
Paraffin RT50S [49,50]	Drying	54.2	170	780	0.000561	2.165	0.185
paraffin wax [51]	Drying	37	220	–	–	–	–
paraffin wax [52,53]	Drying	49	–	820	–	–	–
Paraffin wax CAS:8002-74-2 [54]	Drying	56–60	–	–	–	–	0.2
Paraffin wax [55]	Drying	56.6	383.5	932.99	–	2.1(s) 1.16(l)	–
Paraffin wax [56]	Drying	56	220	861 (s) 778 (l)	–	1.85(s) 2.38(l)	0.4(s) 0.15(l)
Paraffin wax [57]	Drying	45	180	–	–	–	–
Paraffin wax [58]	Drying	55–60	256	850 (s) 775 (l)	–	2.94(s) 3.89(l)	0.4(s) 0.21(l)
Paraffin wax [59]	Drying	60–62	130	–	–	–	–
Bheem paraffin [59]	Drying	50–55	140	–	–	–	–
Paraffin wax [60]	Drying	56	213	–	–	–	–
Paraffin wax [61]	Drying	58–60	–	–	–	–	–
Paraffin wax [62]	Drying	48.85	243	814 (s) 775 (l)	0.000091	2.16 (s) 2.4 (l)	0.35 (s) 0.15 (l)
Paraffin wax [63]	Drying	41–55	176	835	–	2.8	0.21
Paraffin wax [64]	Drying	50	207.5	910	–	–	0.243
Paraffin Wax-6035 [65]	Drying	57.85	189	920 (s) 745 (l)	–	–	0.21
Paraffin wax [66]	Drying	40–45	–	900	–	2.4	0.21
Paraffin wax [67]	Drying	58	204	910 (s) 810 (l)	–	2 (s) 2.1 (l)	0.228 (s) 0.25 (l)
Paraffin wax [68]	Drying	44.15	165.2	781	0.000551	2.091	0.198
Paraffin wax [67]	Drying	60	190	840 (s) 786 (l)	–	2.4 (s) 2.2(l)	0.24(s) 0.21(l)
Paraffin wax PCM-OM-50 [69]	Drying	60–62	190	922 (s)	–	2.38(s)	0.24(s)
Paraffin wax [70]	Drying	56.6	383.87	968.99	–	1.16	0.11
Paraffin wax [71]	Drying	70	–	–	–	–	–
Paraffin wax [72]	Drying	58–60	–	–	–	–	–
Paraffin wax [73]	Drying	56–58	200–220	861 (s) 778 (l)	–	–	0.4(s) 0.15(l)
Paraffin wax [74]	Drying	56.6	383.5	932.99 (l)	–	2.1 (s) 1.16 (l)	–
Paraffin wax [75]	Drying	54	190	876 (s) 795 (l)	–	2.1	0.21
Paraffin wax [76]	Drying	49	260		–	–	–
Paraffin wax [77]	Drying	56–60	214.4		–	–	–
Paraffin wax RT42 [78]	Drying	42	165	880 (s) 760 (l)	–	2	0.2
Rubitherm RT2 [79]	Refrigeration	2–5	198	770	–	1.8 (l)	0.2
Rubitherm RT5 [80]	Refrigeration	5	–	880 (s) 770 (l)	–	2.17	0.2
Tetradecane [81]	Refrigeration	6.72 ± 0.53	246.70 ± 4.53		–	–	–

summary, salt hydrates hold considerable practical significance in thermal energy storage, particularly for low-temperature TES systems. However, it is imperative to carefully consider their specific physical and chemical properties and utilise them judiciously in specific applications. Thermophysical properties of salt hydrates are summarised in Table 3.

2.2.3. *Eutectics*

Eutectics consist of two or more PCMs, with their melting points adjustable by varying the proportions of constituent components [105]. Typically, the melting and solidification temperatures of eutectics are lower than those of the individual components, and the transition between components does not entail a phase change. Consequently, eutectics exhibit characteristic features such as the absence of phase separation and supercooling phenomena [106]. Due to their relatively low melting points and adjustability, eutectics have garnered increasing interest in both organic-inorganic and organic-organic formulations. However, their high cost, typically two to three times that of commercial PCMs [107], poses a significant limitation to their widespread adoption. Thermophysical properties of eutectics utilised in food storage are

Table 2
Thermophysical properties of non-paraffins utilised in food storage.

	Materials	Application	Melting point (°C)	Latent heat (kJ/kg)	Density (kg/m^3)	specific heat/ (kJ/kg·K)	Thermal conductivity (W/m·K)
Fatty acids	Shear Butter [82]	Drying	45.17	60	927	8.1 (solid) 3.9 (liquid)	–
	Lauric acid [83]	Drying	43.6	184.4	867	–	0.442
	Stearic acid [84]	Drying	69.6	259	847	–	0.172
	PEG 600 [85]	Drying	17–23	127.2	1126	–	0.189
	PEG 1000 [85]	Drying	33–40	190	1212	–	–
Polyalcohols	halloysite nanotubes /PEG400 [86]	Refrigeration	−17.5	160	–	–	–
	halloysite nanotubes /PEG600 [86]	Refrigeration	−6.8	120	–	–	–
	PCL Polycaprolactone [80]	Refrigeration	–	–	1094	1.5	0.4
Others	PT − 15 from Rubitherm [79]	Refrigeration	-15	129	1030	2.06(s) 1.84(l)	–
	PT-63 from Rubitherm [79]	Refrigeration	63	199	840	2.16(s) 1.99(l)	–

Table 3
Thermophysical properties of salt hydrates utilised in food storage.

Materials	Application	Melting point (°C)	Latent heat (kJ/kg)	Density (kg/m^3)	specific heat/ (kJ/kg·K)	Thermal conductivity (W/m·K)
Cristopia E-21 [79,90]	Refrigeration	−21.3	233	1165(solid) 1099(liquid)	3.35	0.5
Ice pack [91–94]	Refrigeration	0	334	920	–	0.334
Ice pack [95]	Refrigeration	−0.5-0.5	334	920	–	0.334
Ice pack [96]	Refrigeration	−0.1-0.1	334	920	–	0.334
19.5 wt% NH_4Cl [97]	Refrigeration	−15/16	289.84	1053(s) 1048(l)	1.87(s) 3.25(l)	2.20(s) 0.468(l)
$Na_2SO_4{\cdot}10H_2O$ [98]	Drying	32.4	248, 254	1490	–	0.544
Water [99]	Refrigeration	0	333	998.2	4.18	0.6
Distilled water with a nucleating agent and thickening agent [100]	Refrigeration	−6	234–237	1017	3.98	0.568
Latest™ 15 [101]	Refrigeration	12–15	188	763	2.85	0.41
$Zn(NO_3)_2{\cdot}6H_2O$ [102]	Drying	35	140	2065	–	0.5–0.7
$NaOH.H_2O$ [103]	Drying	58	272	–	–	–
$Na_2S_2O_3.5H_2O$ [103]	Drying	48	209	1600	–	–
$CaCl_2{\cdot}6H_2O$ [104]	Drying	29.8	191	1802	–	1.08

summarised in Table 4.

2.3. Data analysis

Quantitative analysis of literature regarding the application of PCM in food storage is crucial for understanding the developmental trends in this field. In this section, the reviewed literature will be statistically analysed. To the best of our knowledge, the research conducted by Enibe et al. [108] firstly applied PCMs in solar dryers in 2002 to extend the storage period of grains and eggs, demonstrating over 20 years of PCM

Table 4
Thermophysical properties of Eutectics used in food storage.

Materials	Application	Melting point (°C)	Latent heat (kJ/kg)	Density (kg/m^3)	Specific Heat (kJ/kg·K)	Thermal conductivity (W/m·K)
Atlas wax SF 42 [109]	Drying	45	164	902 (Solid) 811 (Liquid)	2.20 (Solid) 2.12 (Liquid)	0.12(Solid) 0.1(Liquid)
water and ammonium chloride [110]	Refrigeration	−15.4	–	–	–	–
1.1 % super-absorbent polymer, 0.1 % sodium benzoate, 0.1 M mannitol and 0.07 M KCl [111]	Refrigeration	−2/−1.2	305.5–306.2	910(s) 970(l)	–	0.03–0.043
87 % $C_8H_{16}O_2$ + 13 % $C_{14}H_{28}O_2$ [112]	Refrigeration	7.1	146.1	–	–	0.2832
H_2O + 0.03 g/ml $C_6H_7KO_2$ [112]	Refrigeration	−2.5	256.2	–	–	0.9427
PlusIce E−10 [97]	Refrigeration	-10/−12	294.34	1120(s) 1090(l)	3.55	0.56
Eutectic potassium chloride solution [113]	Refrigeration	−10.7	253	–	–	–
Gel pack [114]	Refrigeration	0	333	920 (s) 1000 (l)	2.1(s) 4.18(l)	2.34(s) 0.6(l)
Capric-lauric acid/oleic acid mixture [115]	Refrigeration	14.2	125.5	–	1.825(s) 2.214(l)	0.572(s) 0.417(l)
Mixture of propylene glycol 60 %/ water 40 % *v*/v [116]	Drying	360	180	1630 (s) 1540 (l)	2.65(l)	0.285
Superabsorbent resin (SAR) acrylic acid and 10 % starches [117]	Refrigeration	2.44	330.4	–	–	–
21DHPT-79SCD-2SAT-0.5PAAS-2H_2O [118]	Refrigeration	4.3	90.7	–	–	–
9.96 % tetradecane, 2.3 % SA, and 9.24 % $CaCl_2$ [119]	Refrigeration	5.67	232.57	–	–	–

utilisation in food storage. Fig. 4 illustrates the application and performance statistics of PCM usage.

As shown in Fig. 4 (a), paraffin wax emerges as the most prevalent PCM, with a utilisation rate of 56.68 %. Until 2016, the average annual publication rate of relevant articles in this field remained low. However, with the continuous validation of PCM feasibility in food storage, interest in this domain has gradually increased, resulting in a significant rise in the number of published papers from 2017 to present. Overall, PCMs are used more frequently in drying processes (68.3 %) compared to refrigeration processes (31.7 %) according to Fig. 4 (c).

Within the drying process, a substantial portion of researchers concentrate on ITSD (39 %), while in the refrigeration process, insulated boxes receive the most attention (15.9 %). It can be seen from Fig. 4(d) that researcher overwhelmingly focuses on PCMs with a phase change point between 40 and 60 °C (46.57 %).

3. Application of PCMs in drying processes

As summarised above, PCMs find widespread application in food drying, owing to their notable attributes such as high energy storage density, robust thermal conductivity, and remarkable stability. However, there is a dearth of literature on the utilisation of PCMs in non-solar drying methods. Dhananjay Kumar et al. [120] developed an innovative biomass-fired grain dryer that integrated paraffin wax for paddy drying. Their study demonstrated that employing paraffin wax as thermal energy storage effectively sustained the drying temperature, achieving a thermal efficiency of 10.67 %. Whilst solar drying offers environmentally friendly and cost-effective characteristics [121,122], it is influenced significantly by weather conditions, resulting in inconsistent drying stability [85]. Integrating PCMs into solar drying systems can synergistically harness the advantages of both methods, thereby substantially enhancing drying efficiency. Researchers have extensively investigated various food types, as depicted in Fig. 5(a), 92.9 % of researchers studied the influence of PCM incorporated into solar dryers on vegetables and fruits.

3.1. PCMs incorporated into the direct type solar dryer (DTSD)

DTSD, also referred to as cabinet dryers, harness solar radiation that permeates a transparent glass cover, directly impacting the dried products. Investigating the impact of PCMs and their thickness on Solar Air Heater (SAH) performance, Dounia Chaatouf et al. [45] conducted research on apricot drying conditions and requirements. They optimised the SAH using Computational Fluid Dynamics (CFD) methods and a User Defined Function (UDF) subroutine written in C++. Numerical simulations indicated that a PCM thickness of 4 cm is optimal for maintaining the ideal drying temperature of apricots, while a tilt angle of 60° maximises the mass flow rate. In a separate study, Hana Ebrahimi et al. [49] utilised Ansys to evaluate the effects of four different PCM positions on thermal efficiency and energy consumption in a WPCM cabinet dryer under ambient air temperature of 19.5–37.5 °C, air velocity of 0.1–1.2 m/s, and relative humidity of 12.9 %–23.3 %. As depicted in Fig. 6, the specific energy consumption for dried tomato slices fluctuated between 11.12 and 9.01 MJ/kg, with the overall efficiency ranging from 21.92 % to 25.72 %, contingent on the PCM's placement. Remarkably, positioning the PCM at the collector's end decreased tomato slice drying time by 21.87 %, while significantly improving the sensory quality of the dried products (Fig. 7). To enhance energy conservation and reduce

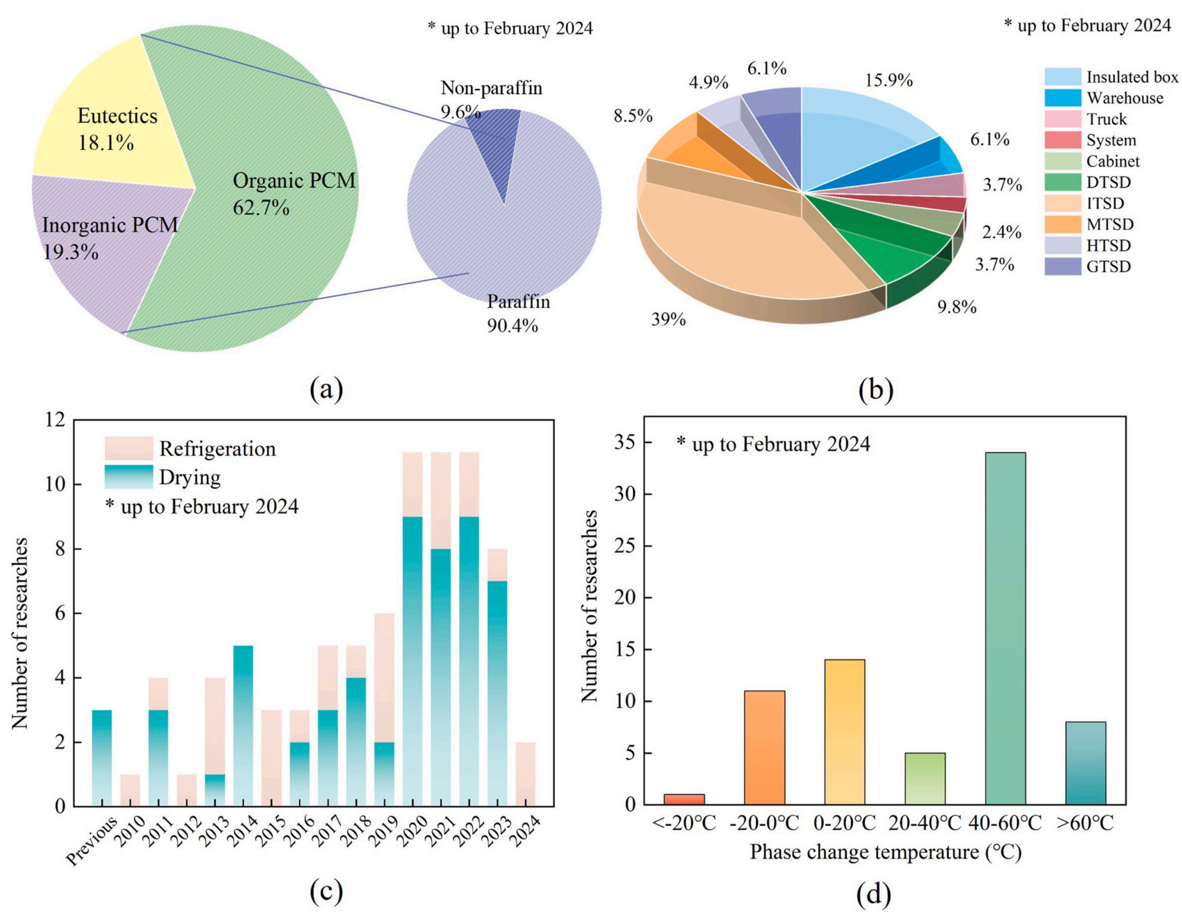

Fig. 4. Statistic of PCMs applications and properties employed in food storage process: (a) types of PCMs (b) PCMs applied in different devices (c) number of publications over the years (d) number of publications under different PCMs phase change temperature.

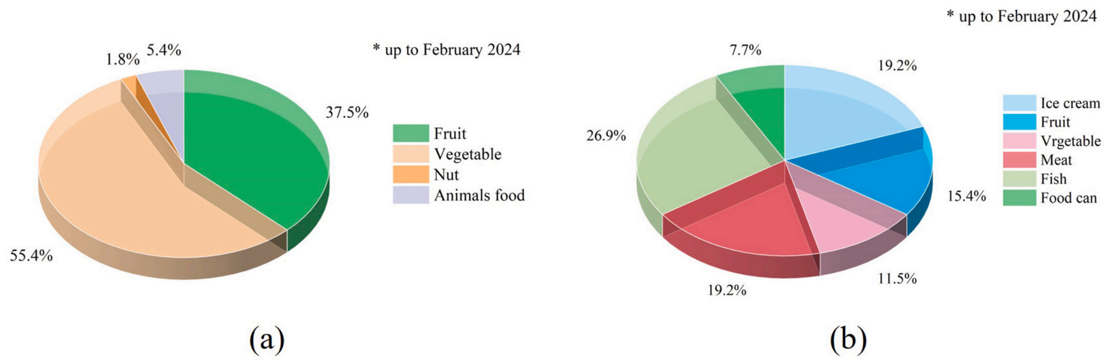

Fig. 5. Statistic of different items utilised in reviewed papers: (a) drying; (b) refrigeration.

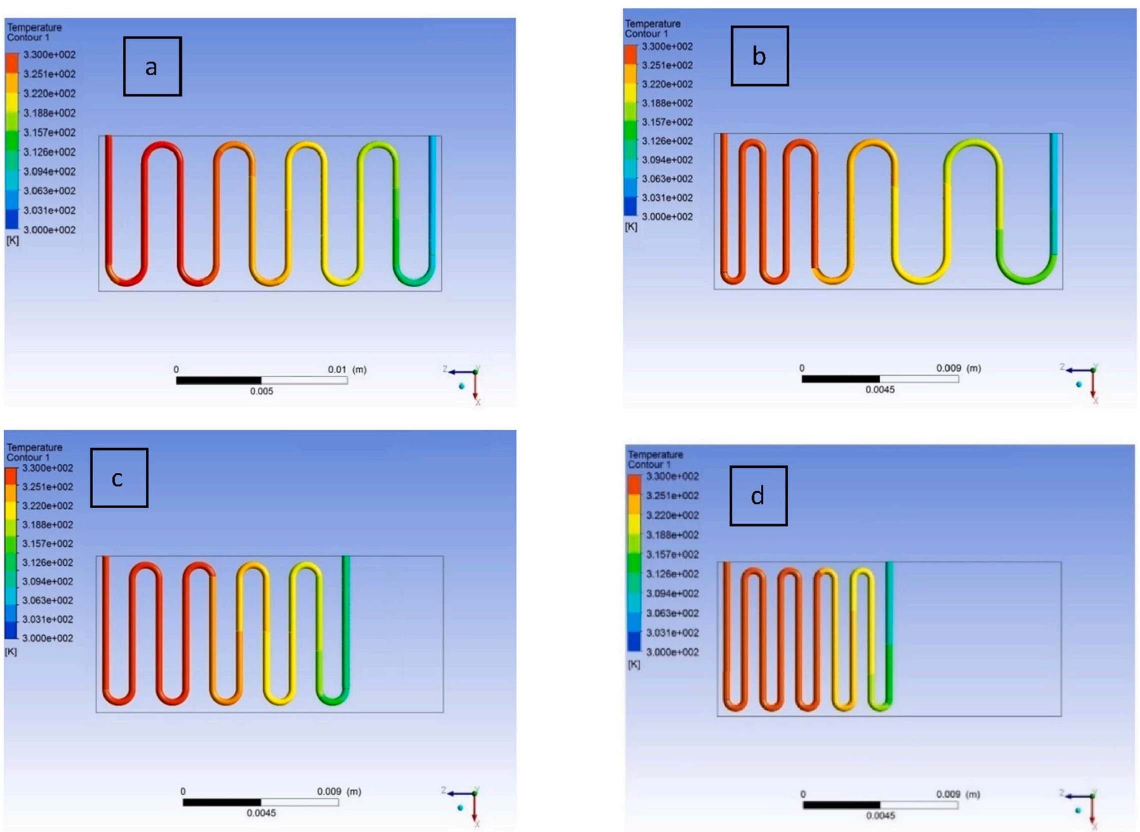

Fig. 6. Temperature readings for various distributions of PCM tubes along the Flat Plate Collector (FPC) at 9:00, considering an airflow rate of 0.025 kg/s [49].

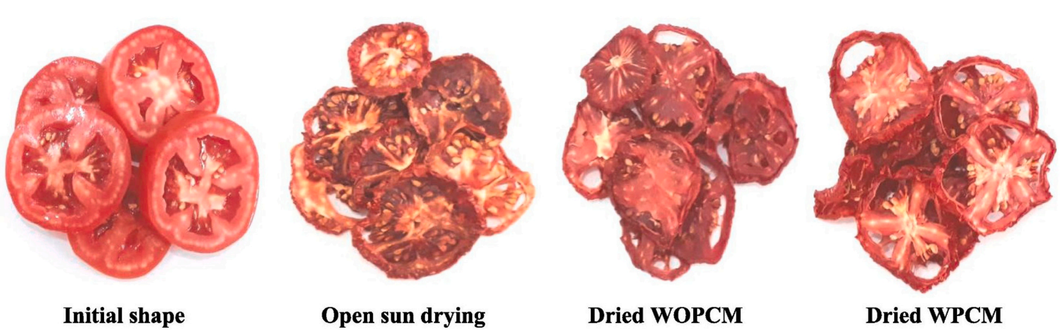

Fig. 7. Changes in color and shape of dried tomato slices resulting from various drying methods. [49].

drying duration, the integration of LHS WPCM for storing excess solar energy can markedly enhance the efficiency of DTSD [47,109,123]. As shown in Table 5, Iranmanesh et al. [48] found that using WPCM DTSD to dry apple slices resulted in the highest total drying efficiency of the PCM system, at 39.9 %, when the air flow rate was 0.025 kg/s. Under operating conditions with hot air temperature maintained at 60 °C, air velocity at 0.2 m/s, and relative humidity at 74 %, Pati et al. [46] found that WPCM DTSD can effectively improve the quality of dried ginger slices. Yadav et al. [124] reported that incorporating PCM extended the DTSD drying time by 1 h and 48 min, resulting in higher-quality dried tomato products. In summary, integrating a PCM module with DTSD can effectively extend the drying time, reduce temperature and humidity fluctuations within the drying chamber, and enhances the color, texture, and overall quality of dried products.

3.2. PCMs incorporated into the indirect type solar dryer (ITSD)

The ITSD consists of two main components: the drying cabinet, designed to hold the material on pallets, and the solar collector unit, comprising glass and absorber panels. Solar radiation striking the glass cover undergoes partial reflection, while a portion penetrates through the glass. [128]. The absorber plate captures a fraction of the energy, while the rest is transformed into heat, heating the air as it enters the chamber. The heat absorbed by the food inside the drying cabinet initiates moisture loss, thereby facilitating the drying process of the product [67,74,103]. The thin-layer drying equation serves as the fundamental method for drying simulation, illustrating the moisture exchange between a thin layer of the drying product and the surrounding air [129]. In a study by El-Sebaii et al., [130] eleven thin-layer drying models (Table 6) were compared, with the four-parameter logistic model identified as the most suitable for predicting the moisture transportation process during the drying of Thymus leaves. Furthermore, employing PCMs with ITSD can significantly reduce drying time by up to 50 %.

Çakmak et al. [131] proposed a novel dryer design incorporating a solar air collector to achieve uniform drying. The system employs Calcium chloride hexahydrate in swirl flow media to accelerate the drying process of seeded grapes, leading to reduced moisture levels in a shorter duration. The Midilli model was identified as the most appropriate for predicting drying behavior. Additionally, Çakmak et al. [104] found that a feedforward neural network provided more accurate estimates of the drying rate of seeded grapes. In the context of PCM-integrated ITSD drying processes, the Midilli model was found suitable for predicting drying behaviours of garlic cloves [116] and blood fruit [69], while the Henderson and Pabis model and parabolic fit offered optimal mathematical predictions for oleaster fruit and ginger drying, respectively [50,51].

The primary aim of integrating PCMs as heat storage units with ITSD is to reduce drying time and enhance energy efficiency. Enibe et al. [108] observed a 22 % increase in efficiency by incorporating solar thermal collectors WPCM thermal storage systems, suggesting potential applications in crop drying and poultry egg hatching. Sabareesh et al. [51] introduced a novel method for the indirect solar drying of ginger, incorporating liquid desiccant (liquid calcium chloride) and paraffin wax for thermal energy storage. Results depicted in Fig. 8 indicate that ginger necessitates 13 h less drying time with desiccant application compared to open sun drying, and 9 h less time without desiccant.

Panchal et al. [59] utilised two different types of paraffin within a rectangular chamber positioned below the absorber plates on both the inlet and outlet sides to improve the performance of a conventional ITSD. Comparing the upgraded ITSD to the standard ITSD, the results indicated a decrease in unit energy usage of 22.87 % and an overall drying efficiency increase of 29.69 %. Some other investigations about the application of PCMs in ITSD to improve drying efficiency have been concluded in Table 7.

Table 5
Summary of PCM's impacts on food storage quality.

Ref.	Type of food	Type of PCM	Impact on food quality
Iranmanesh [48]	Apple	Paraffin wax	The quality of apple slices dried using PCM was better than that of samples dried in the sun.
Pati et al. [46]	Ginger	Paraffin wax	The treated sample demonstrated improved color, texture, and aroma.
Yadav et al. [124]	Tomato	Paraffin wax	Dried tomatoes produced using DTSD exhibit superior quality and texture.
Ebrahimi al. [49]	Tomato	Paraffin wax	The quality of tomato slices and the shape are better than the slices dried by the dryer without PCM or dried in front of the Sun.
Malakar et al. [55]	Pumpkin	Paraffin wax	PCM-assisted drying results in higher total phenolic and flavonoid content, enhanced antioxidant activity, greater total carotenoid content, and reduced color difference.
Reyes et al. [56]	Kiwifruit	Paraffin wax	Kiwifruit slices with a thickness of 8 mm showed minimal loss of polyphenols and antioxidant capacity even without the control system.
Choudhary et al. [103]	Mango, Litchi, Aonla, Jamun	$NaOH.H_2O$, $Na_2S_2O_3.5H_2O$, and Acetamide	Small temperature swing of PCM, combined with High Heat Capacity Material, enables the produce to dry within a single day without any loss of vitamins or alterations in taste and odor.
Rouzegar et al. [64]	Mint	CuO + parrffin	Mint samples exposed to nano-enhanced PCM exhibited the highest rehydration capacity and overall quality.
Gopinath et al. [67]	Grape	Paraffin wax	Solar dryers utilising PCM can effectively reduce volume shrinkage and color differences in grapes.
Radhakrishnan et al. [125]	Coconut	Paraffin wax	The solar-dried WPCM coconut sample exhibited superior color, taste, flavor, quality, and texture, compared to the sun-dried sample.
Arun et al. [72]	Unripe banana	Paraffin wax	dried banana flakes had good color, texture, and natural aroma
Malakar et al. [74]	Pineapple	Paraffin wax	Superior TFC, TPC, and antioxidant activity were observed in pineapple dried with PCM-assisted and PCM + IR-assisted drying.
Tas et al. [86]	Meat ball	Polyethylene glycol (PEG) 400/600	Flexible food packaging films composited with PCM and halloysite nanotubes (HNT) have great potential in

(continued on next page)

Table 5 (continued)

Ref.	Type of food	Type of PCM	Impact on food quality
			improving the quality and food safety of meatballs.
Oró et al. [126]	Ice cream	E-21	Using PCM packaging improves the quality of ice cream outside the refrigerator.
Wang et al. [127]	Chinese pork meatballs	n-tetradecane	Temperature buffered packaging using PCM microcapsules can effectively improve the physicochemical properties and bacterial load of Chinese pork meatballs.
Zhao et al. [111]	Strawberry	Commercial PCM	The stored sample packed in the box WPCM had a higher organoleptic quality than that WOPCM.
Nabi et al. [119]	Meat	Tetradecane was capsulated within a calcium alginate shell	The physicochemical parameters of the meat in PCM-incorporated package were less changed

Table 6
Statistical outcomes from the mathematical modelling of drying curves for Thymus (cut leaves WPCM) [130].

Model	Coefficients	R	X^2	Standard error
Lewis	k = 0.0963	0.9329	0.0169	0.1300
Page	k = 0.0056, n = 2.3941	0.9757	0.0066	0.0815
Modified page	k = 0.1150, n = 2.3941	0.9757	0.0066	0.0815
Henderson and Pabis	a = 1.17, k = 0.1178	0.9493	0.0136	0.1168
Logarithmic	a = 1.1312, k = 0.1309, c = 0.0525	0.9513	0.014	0.1181
Two term	a = 0.6318, k_0 = 0.1178, b = 0.5382, k_1 = 0.1178	0.9493	0.0155	0.1244
Wang and Singh	a = −0.0854, b = 0.0019	0.9516	0.003	0.1142
Modified Henderson and Pabis	a = 0.4222, k = 0.1178, b = 0.3931, g = 0.1178, c = 0.3547, h = 0.1178	0.9493	0.0178	0.1336
Verma et al.	a = 40.5858, k = 0.0778, g = 0.0778	0.9332	0.0189	0.1377
Midilli and Kucuk	a = 1:00, k = 182.83, n = 16.969, b = 0.0118	0.00	0.3269	0.5717
Four-parameter logistic equation	a = 1278, b = 0.983, c = 6.7094, d = −4.9627	0.9996	0.0001	0.0106

3.3. PCMs incorporated into the mixed-type solar dryer (MTSD)

A MTSD consists of a solar collector linked to a drying chamber, where air is heated by solar radiation upon entry into the collector. Subsequently, the heated air rises through the drying chamber, extracting moisture from the food. This configuration reduces product drying time by enabling solar radiation to reach both the solar collector and the drying chamber simultaneously. [132]. Ndukwu et al. [133] conducted an investigation to assess the potential enhancement of red chili drying rates by integrating sodium sulphate decahydrate as PCM in solar drying. Similar conclusions were drawn by Baniasadi et al. [71] and Arun et al. [72] through experimental approaches. Baniasadi et al. [71] conducted experiments on apricots with approximately 86 % moisture content in Isfahan and discovered that incorporating paraffin into an MTSD solar dryer improved the thermal efficiency of apricot drying by 11 % compared to a single-function solar dryer. Arun et al.

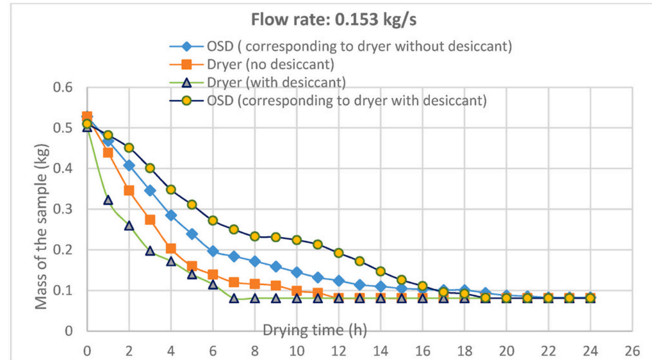

Fig. 8. The variation of the sample's mass over time in different drying modes. [51].

[72] investigated the performance of a multi-tray mixed-mode solar cabinet dryer on unripe bananas with an average initial moisture content of 180 % (db), mass flow rates ranging from 0.015 kg/s to 0.03 kg/s, and slice thicknesses between 0.002 and 0.004 m. The study revealed an improved drying efficiency of 42.52 %, a drying cost of \$0.35 per kilogram of dried product, and a payback period of nine months. Dheerandra Singh's ongoing research focuses on drying apple slices using a MTSD integrated with paraffin and natural sand as PCM [134]. The lower tray exhibits superior average moisture diffusion rates, drying rates, and efficiency compared to the upper tray and natural drying. Babar [70] investigated the impact of PCMs on green chili properties, revealing that green chili dried by PCMs-assisted mixed-mode forced convection solar dryers exhibited better retention of total phenols, total flavonoids, antioxidant activity, and ascorbic acid. As depicted in Fig. 9, PCM successfully limits Aflatoxin B1 to below 0.25 ppb in solar-dried chili. Compared to open sun drying, unripe bananas subjected to paraffin wax-assisted mixed-mode solar drying exhibit noticeable improvements in color, texture, and natural aroma [72].

3.4. PCMs incorporated into the hybrid type solar dryer (HTSD)

A HTSD incorporates an intelligent inverter that efficiently converts DC power to and from batteries, managing AC power between the grid and the home based on energy requirements. The system offers flexibility in power consumption management while maintaining grid connectivity for backup power during outages. Adopting a hybrid system reduces reliance on grid electricity and enables greater cost savings [139–141]. Ananno et al. [75] introduced an innovative hybrid geothermal-PCM flat plate solar collector, designed to function as a renewable energy system for food storage.

Numerical simulations demonstrated that this HTSD achieves 20.5 % higher efficiency compared to conventional collectors at a mass flow rate of 0.02 kg/s (Fig. 10). In research by Santanu Malakar et al. [74], the Modified Page model accurately described the moisture migration pattern of pineapples during drying. Employment of PCM + IR-assisted drying resulted in the shortest drying time and highest total flavonoid content (TFC) and total phenolic content (TPC) in dried pineapples (Table 5). Additionally, the application of PCMs in HTSD for date palm [85] and mushrooms [73] significantly enhanced the drying efficiency.

3.5. PCMs incorporated into the greenhouse type solar dryer (GTSD)

A GTSD consists of enclosed frames made from materials such as plastic, metal, or wood, covered with appropriate cladding material. It houses trays for distributing the products to be dried and is equipped with a vent to facilitate air movement. [142]. This design offers a cost-effective and straightforward solution for drying applications [143]. Azaizia et al. [77] introduced a novel GTSD utilising PCM for red pepper

Table 7
Previous research summary of PCM incorporated in ITSD.

Authors	Type of study	Drying items	PCM	Findings
S.M. Shalaby et al. [52]	Experimental	Basil leaf	Paraffin wax	The indirect solar dryer can save 48.3 % of the time when using PCMs.
Mulatu C. Gilago et al. [54]	Experimental	Ivy gourd	Paraffin wax	Drying efficiencies were 13.15 and 15.2 % for passive/active indirect-type solar dryer, respectively
Reyes et al. [56]	Experimental	Kiwifruit	Paraffin wax	Drying system WPCM fuzzy logic control systems can saved 33 % energy
Mohadeseh Ahmadi et al. [50]	Experimental	Oleaster fruit	Paraffin wax	Employing air recirculation and PCMs can markedly enhance drying and thermal efficiency, achieving approximately 43.42 % and 16.75 %, respectively.
Ahmed Sabah Thaker et al. [135]	Numercial	Banana	Paraffin wax	The maximum predicted efficiency of the system is a 67.40 % (operated within the range of 60–65 °C).
D.K. Rabha et al. [61]	Experimental	Red chili	Paraffin wax	The electrical energy consumption of the dryer, incorporating two double-pass solar air heaters, accounted for only 10.3 % of the overall specific energy consumption for drying chilies.
Mu Song et al. [136]	Experimental	Grape	Paraffin wax	The solar dryer equipped WPCM attained an instantaneous thermal efficiency of 56 %, with the collector demonstrating a minimum heating efficiency of 70 % and an average heat storage efficiency of 66 %.
Preeti sain et al. [137]	Experimental	Ginger	Paraffin wax	The solar dryer WPCM demonstrated an average daily drying efficiency and overall thermal efficiency of 12.4 % and 22.7 % respectively.
Pragnan Lad et al. [138]	Experimental	Ginger, hot yellow pepper, onion, and tomato	Paraffin Wax-6035	A modified dryer that incorporates PCM within the drying chamber is more efficient compared to other configurations.
S.M. Shalaby et al. [53]	Experimental	*Ocimum Basilicum* and *Thevetia Neriifolia*	Paraffin wax	Solar dryers equipped WPCM can sustain the desired temperature for up to seven consecutive hours after sunset.
Halil Atalay [58]	Experimental	Lemon slices	Pebble stones paraffin wax	The average energy efficiencies and initial investment cost of packed bed (PBTES) were 0.35 % and 10.47 % lower than the PCM thermal energy storage systems respectively.

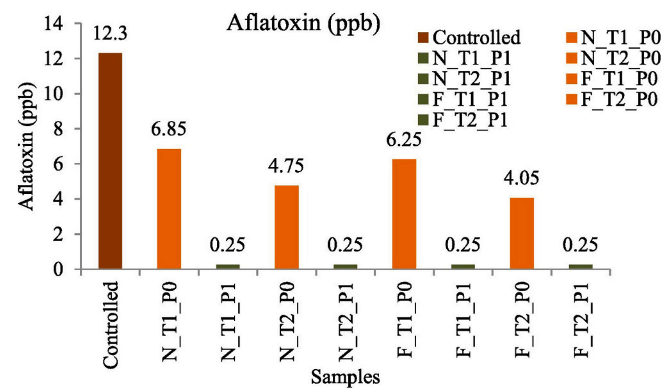

Fig. 9. Effect of Aflatoxin (B1) Levels during Natural and Forced Convection Solar Drying [70].

drying. Experimental results demonstrated that integrating PCM into the GTSD elevated air temperature by approximately 7.5 °C at night, substantially reducing total drying time (Fig. 11). The Midili model was identified as the most accurate for this system. Pankaew et al. [76] researched the impact of PCM integration into GTSD for chili drying, revealing that PCM extended drying time during adverse weather conditions and reduced exergy loss. Similar benefits were observed in GTSD drying processes for gooseberries [102], brown onion [78], and bananas [144]. Complementing GTSD WPCM enhanced both energy and exergy efficiency while improving the quality of the product.

3.6. Brief summary

PCMs are extensively utilised in drying processes, particularly solar drying, with ITSD being the most prevalent method. Incorporating PCMs into solar dryers can effectively prolong drying duration, enhance operational efficiency, and decrease operating costs. Furthermore, PCMs aid in preserving the color, appearance, and nutritional value of products, which is highly significant in the realm of food storage. At present, the most commonly used PCM is paraffin wax. However, due to its limited physical properties, there is still a need to develop new phase change materials for use in drying systems. The search for suitable phase change materials remains an active area of research. Additionally, there is limited research on integrating PCM with electricity-based drying methods for food preservation. Electricity-based drying methods offer fast drying speed and high product quality. Incorporating phase change materials can mitigate high power consumption, warranting further research and attention.

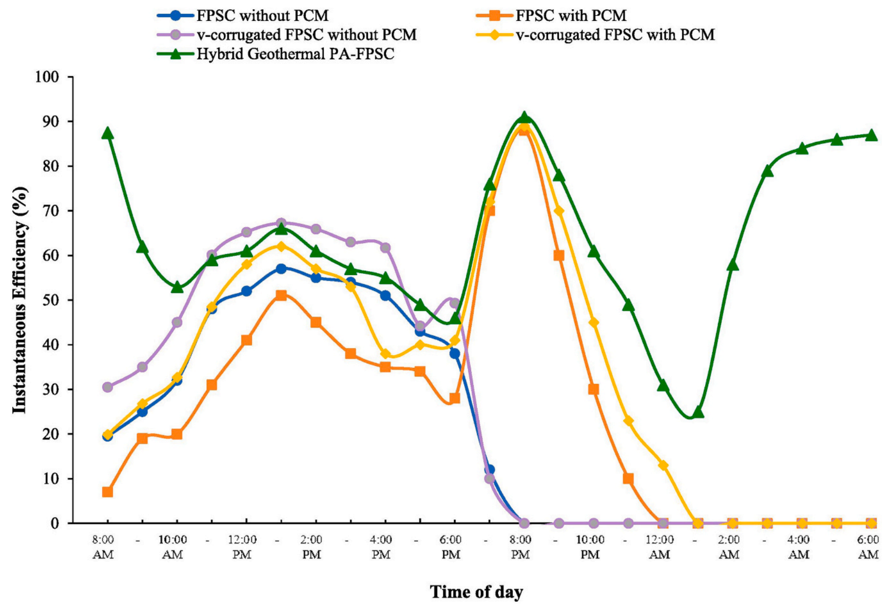

Fig. 10. A comparison of the real-time efficiencies of various types of FPSC with hybrid geothermal PA-FPSC [75].

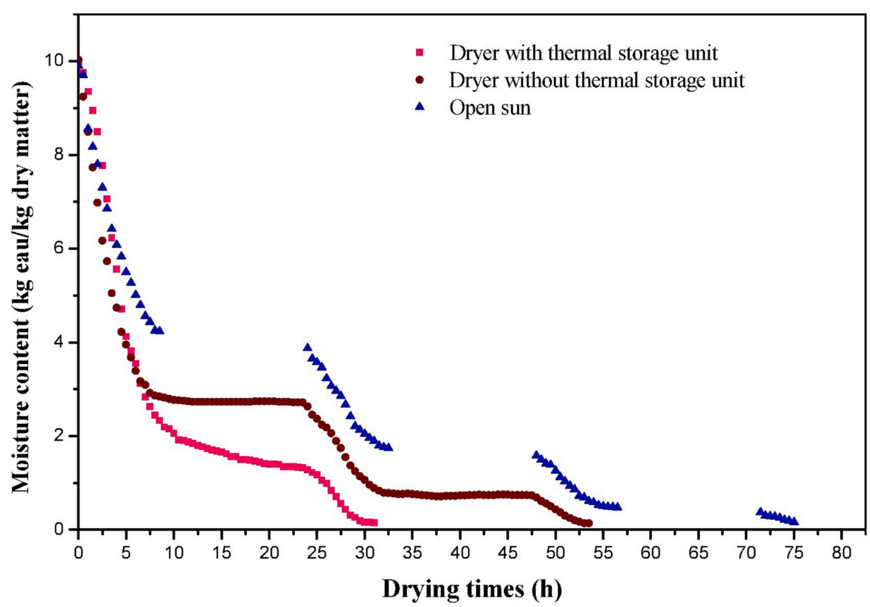

Fig. 11. Evolution of moisture content of red pepper in GTSD WPCM/WOPCM and open sun dryer with drying time [77]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Investigation on the application of adding PCM in refrigeration processes

In contrast to the dehydration process, refrigeration primarily focuses on preserving product quality and moisture content to ensure freshness and desired attributes. With increasing living standards, the demand for high-quality products such as fresh fruits, dairy, vegetables, and meat is rising. Advanced technology for cold chain storage and transportation is crucial; however, current methods face significant challenges.

Firstly, unlike free and abundant solar energy, refrigeration equipment is relatively scarce, especially in developing countries, leading to resource wastage [145,146]. Secondly, temperature fluctuations are common during the cold chain storage and transportation of food, which can negatively impact the quality of fruits, vegetables, and meat products. Frequent temperature changes (over 5 °C) can severely impact their quality. Selvnes et al. [147] reported that approximately 30 % of food stored in display freezers is kept at a temperature two degrees higher than ideal for extended periods, a figure that rises to about 40 % for home refrigerators. Additionally, fresh fruits and vegetables continue to ferment during storage and transportation, generating heat and compromising product quality. High respiration rates contribute significantly to product loss, with different products exhibiting varying respiration rates and sensitivity to storage temperatures [148]. Moreover, as depicted in Fig. 1, the refrigeration process consumes a substantial amount of energy, making up about 16 % of total energy consumption [149].

The incorporation of PCMs into cold chain storage and transportation presents a practical and effective solution to the a forementioned constraints. PCMs offer high energy storage density, cost-effectiveness, and versatility in application. By mitigating temperature fluctuations, stabilizing temperatures, and reducing costs, PCMs have the potential to enhance the quality and safety of cold chain storage and transportation. Researchers have investigated the refrigeration of various foods in PCM-integrated refrigeration systems, as depicted in Fig. 5(b). The refrigeration process can be categorised into single-function PCM refrigeration and multi-function PCM refrigeration, depending on the utilisation of PCMs. Single-function PCM refrigeration encompasses insulated packages where PCMs solely release cold energy. Multi-function PCM refrigeration includes freezer cabinets, refrigerated vehicles, and cold storage systems [20,150].

4.1. Applications of single-function PCMs in refrigeration processes

Single-function PCM refrigeration systems solely serve to regulate temperatures within a defined range by providing a cold source without the need for additional energy sources. This simplifies system composition by eliminating the requirement for supplementary refrigeration units, such as those reliant on electricity. As a result, system design and deployment are liberated from spatial constraints, enabling the use of adaptable, compact packaging units or structures conducive to passive refrigeration systems. These systems offer cost efficiency and versatility in application scenarios compared to composite-function PCM refrigeration systems. However, their drawback lies in limited temperature control duration, rendering them unsuitable for long-distance transportation.

The combination of PCMs in food packaging presents an efficient method for preserving food quality and extending shelf life. Gin et al. [110] evaluated the effects of PCM installed on refrigerator walls on drip loss in bovine muscle, and ice crystal size in vanilla ice cream, reporting significant reductions in meat dripping losses and smaller ice crystal sizes. As mentioned in Table 5, Zhao et al. [111] introduced a novel integrated cold and modified atmosphere packaging (MAP) system tailored for fruit freshness storage, demonstrating significant enhancements in various quality attributes of strawberries compared to control samples (Fig. 12).

Paquette et al. [114] devised a three-dimensional model to simulate heat transfer in multi-layered boxes for non-refrigerated food transportation. Their findings revealed that positioning a frozen gel pack in the center of the box substantially delayed thawing and prolonged food storage duration. The study identified thermal conductivity of cabinet walls and emissivity of inner surfaces as critical parameters governing temperature. These findings underscore the potential of PCM-based packaging solutions to improve food quality and extend shelf life, both in refrigerated environments and during non-refrigerated transportation. Oró et al. [126] devised and tested PCM packaging for commercial ice cream containers, where 2 cm of PCM (CRISTOPIA, E-21 2% wt) was wrapped around the open ice cream storage container while maintaining the same volume. Simulation studies of the ice cream refrigeration process revealed that utilising PCM-wrapped containers efficiently regulated temperature and enhanced the overall quality of ice cream. Erdinc Tas et al. [86] engineered nanohybrids of PCMs and halogenated nanotubes (HNTs) as nanofillers endowed with thermal buffering properties. Their experiments demonstrated that nanocomposite films embedded in WPCM represented the initial flexible food packaging films showcasing notable thermal buffering capabilities at cold chain temperatures. Compared to neat PE film, the nanocomposite film delayed the temperature rise of frozen samples by 18 min and 20 min, respectively (Fig. 13). Other studies investigating PCMs with single-function applications in storage packaging are summarised in Table 8.

4.2. Applications of multi-function PCMs in refrigeration processes

Compared with single-function refrigeration systems, multi-function refrigeration systems have a more complex structure, equipped with refrigeration modules powered by additional energy to achieve long-term temperature control. PCM is an indispensable component in this kind of system because it is responsible for both energy storage and providing a cold source. Studies [20] have illustrated that applying PCMs in multi-function refrigeration systems can effectively reduce temperature fluctuations and thereby reduce food quality loss during the storage and transportation process [151]. Therefore, PCMs have been widely used in many refrigeration fields including cold rooms, freezer cabinets, refrigerated vehicles, etc.

Cold storage warehouses, refrigerated display cabinets, and refrigeration systems are specialized facilities designed with temperature-controlled environments to accommodate temperature-sensitive products. Their primary function is the storage of perishable goods, including fresh products, frozen foods, pharmaceuticals, and similar items,

Fig. 12. Strawberries stored in various packaging options after being kept at 10 °C for 4 days (Dec 2017) and at 20 °C for 2 days (April 2018). [111].

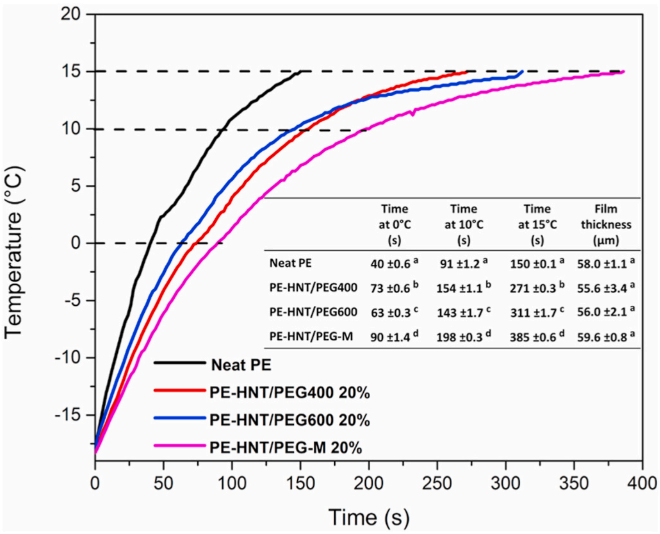

Fig. 13. Time-temperature profiles illustrating the thawing process from −18 °C to room temperature for both neat PE film and PE-HNT/PEG nanocomposite films. Tabulated data indicates the elapsed time for the frozen films to reach 0 °C, 10 °C, and 15 °C, along with the thickness of the films. [86].

thereby safeguarding their quality and prolonging their shelf life. However, these facilities necessitate prolonged maintenance of low temperatures, leading to significant electricity consumption and the need to mitigate unforeseen power supply inadequacies [152]. Integrating PCM with the refrigeration system enables not only backup cooling provision during power shortages but also capitalizes on tiered electricity pricing to mitigate economic expenditures. H.M. Hoang [80] examined the thermal characteristics of an encapsulated PCM substance (Rubitherm RT5) with varying PCL mass fractions. Experiments and numerical calculations revealed that the encapsulated PCM material exhibits superior thermal buffering capabilities, leading to a significant extension of the shelf life of ham.

Yang [99] proposed and examined the integration of a latent heat cold storage system with a refrigerated warehouse. They noted that the upper section maintained a temperature 4 °C higher than the lower section, which was attributed to external convective heat transfer through the roof with a heat transfer coefficient of 5 W/m·K. Schalbart [153] designed a model predictive controller to optimize energy management for a refrigeration system in an ice cream warehouse integrated with a PCM tank. Simulation results showed that even after 90 days of storage, the ice crystal size in the ice cream remained below the specified threshold of 26 mm, illustrating the effectiveness of PCM tanks in supporting efficient energy management. Rivera [97] used numerical simulations to assess the impact of two different PCMs on the energy and thermal performance of a household convection freezer and its central salmon fillet, as illustrated in Fig. 14. The results revealed that PCM-2 led to a higher energy efficiency improvement of 11.4 % compared to PCM-1 (6.2 %). PCM-2 has a narrower phase change temperature range and can fully harness latent heat. In the absence of food, PCM-2 was shown to reduce energy efficiency from 11.5 % to 4.5 % due to an increased heat load. Karthikeyan [115] studied the effects of a PCM-based cold storage system on the physical and chemical properties of mango fruits under periodic (P12) and continuous (P24) storage conditions. It was found that PCM can help maintain the hardness and ascorbic acid of mangoes, effectively reducing energy consumption by 39 % (P12) and 18 % (P24) respectively. Sung et al. [154] found that using a thermoelectric cooling system combining TEM and PCM can better maintain the color, moisture content, and vitamin C content of fresh green peppers.

Refrigerated trucks are meticulously designed for the transportation of perishable goods, including fruits, seafood, meat, vegetables, and pharmaceutical products that necessitate chilled or frozen storage during shipment. [155]. Refrigerated trucks serve as a prevalent refrigeration system frequently employed in transportation processes, thereby assuming a pivotal role in the food supply chain. The large amount of energy required and the existence of temperature fluctuations during transportation are the main problems it faces. Arjenaki et al. [81] developed a prototype packaging utilising PCM to uphold low temperature and quality of meat when exposed to temperature fluctuations in refrigerated vehicles. They found that placing tetradecane at the base of

Table 8
Summary of studies about using single-function PCMs in storage packages.

Authors	Type of study	Drying items	PCM	Findings
Eduard Oró [79]	Numerical	Ice cream, hot tea	Paraffin wax RT-2	- The utilisation of PCM extended the transport time of ice cream and hot tea by 4 and 3.2 times respectively.
D. Leducq [90]	Experimental	Ice cream	Solution of water and chloride	- Using PCM packaging can effectively maintain the temperature of ice cream, reduce temperature fluctuations, and significantly improve the final quality of the product.
Björn Margeirsson [91]	Experimental & numerical	Haddock fillets	Ice pack	- After 6 h, the temperature rose by 8 °C in the and by 14 °C in the EPS box CP box. - Using ice packs reduces the product temperature by approximately 4 °C, resulting in a temperature change of up to 8 °C, compared to a 3 °C increase in product temperature in a box WOPCM.
Björn Margeirsson [95]	Experimental & numerical	Cod fillets	Ice pack	- Fillets in the rounded box exhibited a temperature difference 2 °C lower and extended shelf life by 2 days.
Navaranjan [92]	Experimental	New Zealand terakihi (*Nemadactylus macropterus*)	Ice pack	- The thermal resistance (R) of B2 is double that of B, which exhibits a positive correlation with the thickness of the in-house EPS box. - The quality of fish, as assessed by the time-temperature profile, is correlated with the R value of the insulating material ($\geq$ 0.80).
Laguerre [96]	Experimental & numerical	Sardine	Ice pack	-The 1-D analytical model accurately predicts key parameters such as ice melting time and maximum product temperature. −3-D FEM allows for better prediction of temperature changes.
Laguerre [93]	Experimental & numerical	Horse mackerel (Trachurus)	Ice pack	- The cooling time of the bottom stack exhibited a correlation with the thickness of the fish stack.
Leila Nab [119]	Experimental	Meat	9.96 % tetradecane, 2.3 % SA, and 9.24 % CaCl2	- Samples incorporated WPCM exhibited lower weight loss and higher hardness, gumminess, and chewiness compared to the control. - Meat stored in packages WPCM showed less change in the physicochemical parameters.
R K Sukoco [113]	Experimental	Fish	Potassium Chloride (KCl)	- Fish stored inside the KCl box experience an average loss of 1.39 quality points, whereas those stored in the ice box lose an average of 1.89 after 24 h.

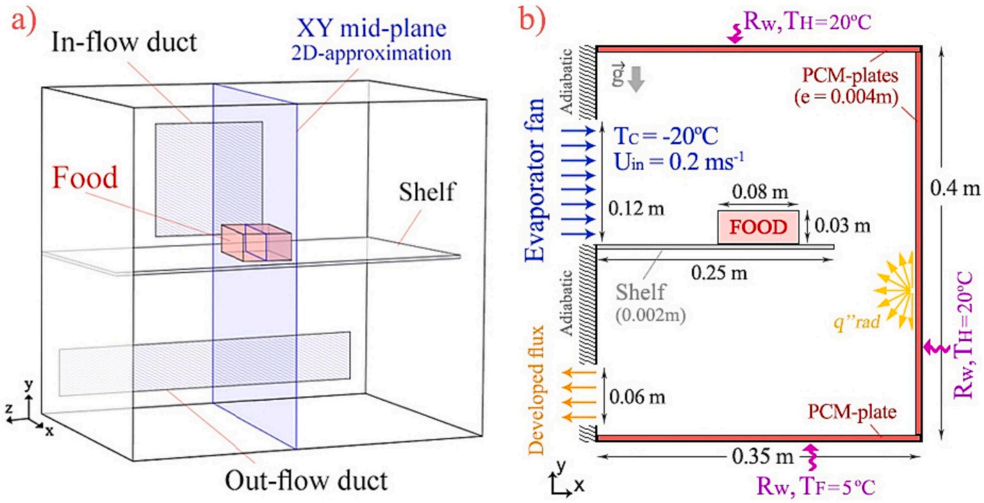

Fig. 14. Physical model of the convective freezer WPCM plates: (a) three-dimensional view; (b) 2D study domain. [97].

the meat significantly reduced weight loss when exposed to room temperature and that designated tetradecane packaging was effective in preventing meat temperatures from rising while maintaining meat quality for about 2 h. Based on the starch graft copolymerization method, Kong et al. [117] developed and designed a biodegradable PCM with high latent heat (super absorbent resin (SAR). Experiments have found that applying SAR during the transportation of shiitake mushrooms can significantly reduce their browning index, relative conductivity, and malondialdehyde content, and extend the shelf life of fresh shiitake mushrooms. In their study, Li and colleagues [118] used sodium carbonate decahydrate (SCD) as a cold energy storage material to develop a composite PCM for preserving fresh fruits during refrigerated transport. Their experiments demonstrated that the PCM-filled refrigeration board could effectively retain cooling energy at a room temperature of 2 °C, thereby substantially prolonging the storage duration of kiwifruit.

4.3. Brief summary

Based on a detailed examination and synthesis of existing research, it has been found that integrating PCMs into refrigeration systems effectively regulates temperature, minimizes temperature fluctuations, and enhances the storage quality of fresh foods. In the case of passive refrigeration systems, current research emphasizes PCM product quality and the extension of refrigeration time. However, practical considerations, including PCM layout parameters (such as location, thickness, and type), performance degradation due to extended PCM usage time, and challenges such as economic benefit analysis of applying PCMs, need to be further studied and addressed. The multi-functional refrigeration system, integrating traditional electric refrigeration with PCM energy storage, effectively reduces temperature fluctuations and enhances energy efficiency. However, the dynamic coordination and optimization of PCM with other refrigeration systems require further investigation. Future research could focus on integrating modular PCM energy storage units into freezers and transport vehicles, enabling them to charge during normal power supply and discharge energy to maintain stable temperatures during power outages or transportation, thereby improving overall system reliability and performance.

5. Conclusion and outlook

Based on a literature review of PCM in the field of food storage, it has been observed that PCM's feasibility for intermittent storage of heat/cold energy has been recognised, leading to widespread use in the food storage industry to reduce reliance on fossil fuels. This article summarises the latest progress in the utilisation of PCMs as energy storage materials in the food storage application, focusing on drying and cooling.

1. According to the researches, incorporating PCM within various solar drying systems can significantly elevate the internal temperature of the drying chamber by up to 7.5 °C during the night, thereby leading to a reduction in drying time of up to 48.3 %, an enhancement in drying efficiency by 43.42 %, and a substantial energy savings of 33 %. PCMs can also effectively maintain the physical and chemical properties (color difference, rehydration ratio, volume shrinkage) as well as the nutritional components (TFC, TPC, Aflatoxin B1, etc.) of dried products.
2. Paraffin wax is the most used PCM. The majority of studies (92.9 %) analyse fruits and vegetables as research objects, with ITSD being the most popular solar dryer type. It is worth noting that the temperature of the applied phase change material is primarily between 40 and 60 °C (46.57 %). Phase change temperature is not the only factor to be considered in the selection of PCM, but also the change in energy consumption brought about by different phase change temperatures.
3. There are only 29 articles that study the effects of phase change materials on food in the field of food refrigeration, with 46.1 % studying its impact on meat. Only 35.6 % of the papers incorporated PCM phase transition temperatures below 20 °C, with 16.3 % utilising temperatures below 0 °C.
4. The application of phase change materials in food refrigeration can extend cold chain transportation time by 4 times, reduce ambient temperature by 8 °C, and decrease energy consumption by 39 %. It can also effectively maintain the product's appearance, browning index, physical and chemical properties, relative conductivity, and malondialdehyde content, etc.

PCM indeed holds significant promise for enhancing food storage processes, and researchers have made considerable strides in advancing its application in the food industry. However, there are notable challenges that warrant attention:

1. Limited Variety of PCM: Existing research predominantly utilises paraffin wax as the PCM for drying processes, with limited exploration of eutectics and salt hydrates, as depicted in Fig. 4. To improve drying efficiency and achieve better control of product quality, researchers should explore a wider variety of PCMs and minimize dependence on paraffin-based materials. Bio-based PCMs, characterized by their renewable nature, biodegradability, and environmental friendliness, offer a promising alternative to conventional

materials. Future studies could assess the environmental impact of bio-based PCMs across the entire cold chain lifecycle and examine their commercial viability, including cost-effectiveness and scalability.

2. Narrow Temperature Range: PCMs used in drying processes often exhibit a narrow temperature range, typically between 40 °C and 60 °C, which may not align with the optimal drying temperatures of certain foods that require temperatures above 60 °C [156]. Similarly, PCMs with phase change temperatures below 0 °C are less explored, despite their potential utility in cooling processes. Researchers should diversify PCM selection to include materials with higher phase change temperatures for controlled experiments, ensuring the production of high-quality dry products across a broader range of temperature requirements.
3. Design Considerations for PCMs in refrigerators: Addressing design issues related to the application of PCMs in refrigerators requires careful consideration of factors such as PCM location and dosage. Comparative calculations are essential to optimize configuration and usage efficiency under specific application conditions. Researchers should conduct thorough analyses to determine the most effective placement and quantity of PCM within refrigerators, ensuring efficient heat transfer and optimal cooling performance.
4. The influence of PCM temperature control effect in Single-Function PCM Refrigeration Systems: It is valuable to conduct an exploration into the duration for which low temperatures can be sustained and food freshness can be ensured solely using PCM as a cooling source. This analysis will involve a comparative assessment of the economic advantages between passive (PCM charging at night and discharging during the day) and active cooling systems, considering the impact of tiered electricity prices.
5. With the continuous development of cold chain logistics technology, food preservation demands higher precision in temperature control and real-time monitoring. In future research, integrating PCMs with Internet of Things (IoT) technology is a promising direction worth exploring. By embedding sensor networks and wireless communication modules, real-time monitoring and feedback on the cold chain transportation environment can be achieved.

CRediT authorship contribution statement

Lucong Han: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shuai Zhang:** Writing – review & editing. **Edward Wright:** Writing – review & editing. **Xiaofeng Zheng:** Writing – review & editing. **Yuying Yan:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors have confirmed that they do not have any competing financial interests or personal relationships that could have affected the work presented in this paper.

Acknowledgements

This work was supported by H2020-MSCA-RISE-778104–ThermaSMART, and Royal Society (IEC\NSFC\211210).

Data availability

No data was used for the research described in the article.

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