FUNDAMENTALS AND APPLICATIONS OF PHASE CHANGING MATERIALS IN THE FOOD INDUSTRY

Abstract

Phase-changing materials (PCMs) have become a novel and adaptable component for various industrial applications, especially in the food sector. The principles and uses of PCM are thoroughly covered in this book chapter, emphasizing how they might improve food processing, preservation, and storage. PCMs' unique capacity to absorb, store, and release latent heat during phase transitions is used to solve problems in temperature-sensitive food supply chain operations. The chapter explores the physical and thermodynamic laws that govern phase transitions of PCM, highlighting how PCM changes states to control temperature. Phase-changing materials of both organic and inorganic components are thoroughly examined, with an emphasis on their unique characteristics and applicability for a range of food-related uses. PCMs provide a range of advantages, from enhancing cold chain logistics and lowering energy use in refrigeration to streamlining baking and frying operations. The integration of PCMs is expected to play a crucial role in promoting sustainability, efficiency, and innovation within the food sector as materials science and engineering breakthroughs persist.

Keywords: Applications Of Phase Changing Materials, Food Industry

Authors

H. K. Rohit
Ph.D. Scholar
Dairy Engineering Division,
ICAR-National Dairy Research Institute
Karnal, Haryana, India.
rohithitesh005@gmail.com

Ankit Kumar Deshmukh
Ph.D. Scholar
Dairy Engineering Division
ICAR -National Dairy Research Institute
Karnal, Haryana, India.
deshank96@gmail.com

P. S. Minz
Sr. Scientist
Dairy Engineering Division
ICAR-National Dairy Research Institute
Karnal, Haryana, India.
psminz@gmail.com

Chitranayak
Principal Scientist
Dairy Engineering Division
ICAR - National Dairy Research Institute
Karnal, Haryana, India.
chitranayaksinha@gmail.com

Mukul Sain
Ph.D. Scholar
Dairy Engineering Division
ICAR - National Dairy Research Institute
Karnal, Haryana, India.
sainmukul1995@gmail.com

Arijit Ray
Ph.D. Scholar
Dairy Engineering Division
ICAR - National Dairy Research Institute
Karnal, Haryana, India.
rayarijit300@gmail.com

I. INTRODUCTION

Refrigeration and air conditioning systems are extensive energy-utilizing systems because of their widespread usage and ongoing operation. Increasing the refrigeration system's energy efficiency is thus critical to energy conservation and better performance. Most innovations used to enhance the performance of refrigeration systems fall into four major groups, i.e., improvement of thermal insulation, creation of power-saving compressors, advancement of heat transmission in heat exchangers (Evaporator and condenser), and development of different multi-stage refrigeration cycles. In a refrigeration system, the heat transfer can be accelerated by heat exchangers by utilizing phase change materials (PCM) and micro-fins in the condenser and Evaporator (Khan & Afroz, 2013).

Phase Change Materials (PCMs) can alter their state at a specific temperature range, typically from a solid to a liquid or the opposite (Sain *et al.,* 2019a). This phase change is accompanied by a significant amount of energy absorption or release, known as latent heat, without a significant temperature change (Feng *et al*., 2020). PCMs have been studied and utilized extensively due to their energy storage and temperature regulation capabilities (Sain *et al.,* 2019b). A potential solution based on the latent heat thermal energy storage (LHTES) principle is thermal energy storage with PCM (Oro *et al.,* 2012). Using PCM as LHTES will be an innovative option for performance enhancement by improving evaporator heat transfer and lowering compressor efficiency losses. The most essential requirements for PCM subzero temperature cooling applications are a sufficient temperature for the phase transition and more fusion heat (Rahman *et al*., 2014).

PCMs are classified based on their phase change temperatures and can include organic compounds (paraffin and non-paraffins), inorganic materials (metals, salt hydrates), and eutectics (Jaglan *et al.,* 2018; Sain *et al.,* 2019a). Each type of PCM has unique characteristics, like melting point, heat storage density, thermal conductivity, and cost, which determine their suitability for different applications. Despite the promising potential of PCMs in the food industry, challenges such as material compatibility, encapsulation, and thermal cycling stability must be addressed. Additionally, selecting the appropriate PCM is crucial and must consider factors such as the desired operating temperature, PCM thermal properties, cost, and environmental impact. With ongoing research and development, the use of PCMs in the food industry is anticipated to grow, contributing to energy efficiency, food quality, and safety (Sain, 2019).

II. PHASE CHANGE MATERIALS (PCM)

In order to store latent heat, phase change materials (PCM) are used. Lane (1983) asserts that Telkes coined latent heat storage in the 1940s, a recent field of study. The chemical bonds within the phase change material break up when the source temperature is raised, resulting in the phase change from solid to liquid.

Because the PCM absorbs thermal energy, the phase change is an endothermic process. The material melts at the phase change temperature, which remains constant throughout the process. Latent heat is the quantity of heat that a substance absorbs when melting.

A large amount of heat is stored within a small temperature change with a high storage density. The phase change process occurs at a constant temperature so that the temperature will be changed at a smooth rate. When compared to sensible storage materials, latent storage materials like water, masonry, or rock have a stored heat per unit volume of 5 to 14 times greater (Heine & Abhat,1978).

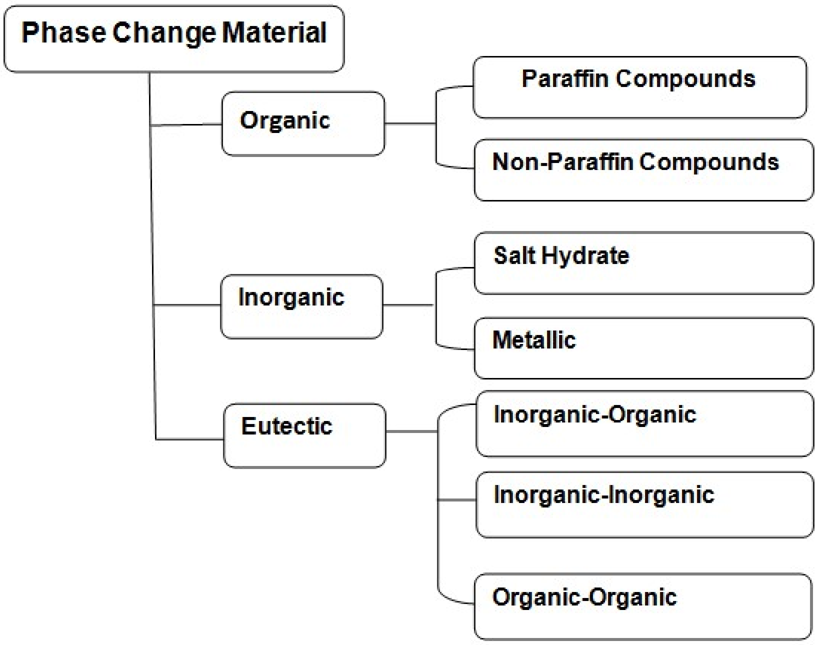

Figure 1: Classification of PCM

III. REQUIREMENTS OF A SUITABLE PCM

1. Physical and Thermal Requirements of PCM According to The Storage and Release of Heat

- The temperature needs to be appropriate.
- Significant phase transition enthalpy.
- Stability of repeatable phase change during cycling.
- High thermal conductivity and low supercooling

2. Technical Requirements According to the Construction of Storage

- Vapor pressure should be low
- Small volume modification
- Chemical resistance of PCM
- The PCM's compatibility with other materials
- Safety restrictions

3. Economic Requirements

- Low price
- Excellent cycling stability

IV. THE WORKING MECHANISM OF PHASE CHANGE MATERIAL (PCM) IN A REFRIGERATION SYSTEM

In a traditional refrigerator or refrigeration system, the compressor operates in an on/off mode. During the compressor off state, heat is removed from the food and the temperature of the evaporator cabinet is increased. When the compressor runs, the refrigerant absorbs heat from the cabinet while circulating through the evaporator coil. If PCM is used inside the cabinet, it will absorb most heat by switching from a solid to a liquid phase. Until the melting of all PCM is not complete, the temperature will not change. Because of this, the product will be heated to the required level while the compressor is off, allowing the material to transition into its next phase properly.

Due to the latent heat of ice, crystal ice is used as an efficient heat carrier. Ice slurry is an excellent option as a coolant in the conventional refrigeration system because it has a low operating temperature and high heat transportation capacity. Due to synthetic refrigerant use regulation and thermal energy storage, indirect cooling systems are more beneficial.
The rate at which the cooling mediums may absorb heat from the milk determines how quickly the milk will cool. When hot milk is kept in a room where the temperature of the air is at its freezing point, it will take around 12 hours for the milk to cool to 10°C since the air absorbs heat very slowly. As opposed to that, the cooling rate of water is higher 20 times compared to air. According to Davies (2005), the sensible heat of water to raise its temperature from 0°C to 80°C is equal to the latent heat of fusion for 454 g of ice. For increasing the cooling rate, the volume of surrounding ice must be high, and a lower temperature will be required. These methods of ice slurry are exciting and have been employed successfully in many milk cooling systems by Sharma *et al*. (2014).

In developing nations like India, no technique is currently used at the farm level for milk cooling; the reason is that for the refrigeration process, the compressor is used, which requires a higher amount of energy and initial investment. Therefore, a suitable material must be used which is widely accessible and inexpensive. Since water is one of the phase-changing materials (PCMs) with desirable properties, several researchers previously stated they used cold water and ice as a cooling medium in their patented designs.

V. APPLICATION OF PCM AT THE EVAPORATOR

In vapour compression refrigeration systems (VCRS), PCM aims to improve system performance with less fluctuating temperature. Therefore, even a tiny increase in performance from these appliances results in significant energy savings. The majority of the innovative concepts used to enhance the performance of refrigeration systems fall into three broad groups: enhancement of thermal insulation, development of power-saving compressors, and improvement of the heat transfer process from heat exchangers, i.e., Evaporator and condenser (Cheng *et al.,* 2011), because PCM has a high latent heat, applying it to a refrigerator's Evaporator could lengthen the compressor's OFF period. This gives refrigerators two more essential options: to run during off-peak hours and maintain the compartment's temperature even during prolonged power outages.

Because of the use of energy storage by PCM at the Evaporator, the on-time period of the compressor is decreased. As a result, the benefits include reduced total energy consumption, high-quality food, and reduced negative impacts of frequent compressors ON/OFF. In the event of a power outage, phase change materials may be necessary since they impact air and product temperatures and their rate of increment (Gin & Farid, 2010). Furthermore, the presence of PCM can help maintain a more stable temperature in the compartment (Osterman *et al*., 2012).

Direct application of PCM to a naturally cooled evaporator is preferable since it will improve heat transfer from the Evaporator and enable the system's excess cooling capacity to be stored in the PCM (Visek *et al*., 2014). Because phase change materials carry heat more quickly than natural air convection, quicker heat transfer is observed where evaporator coils are submerged in these PCMs. The impact of each parameter, such as PCM thickness, phase change temperature, orientation, shape, and thermal load, is covered independently in the following sections.

1. **Phase Changing Temperature:** Properly selecting phase change temperatures is crucial in cooling systems since it influences the system's functionality but also the consistency of the food material. Food preservation is the primary goal of residential refrigeration systems; furthermore, changes in temperature in phase must be appropriate for this primary purpose. Remember that phase change temperature is the most crucial factor for the effective utilization of phase change material, and the melting point has to fall within the operating range of temperature of the thermostat if added within the compartment.

   It was discovered that the vapour compressor refrigeration system's (VCRS) heat transfer improvement was more significant when PCM was applied around evaporator coils if its melting point was higher than the set temperature of the compartment (Chen *et al*., 2020). A higher phase change evaporation temperature results in a lower compressor on/off frequency and a higher system COP. Otherwise, the phase change material does not work efficiently since the phase change temperature is low, limiting the completion of the phase transition process. Due to its low phase change temperature, which restricts its ability to participate in the phase transition process fully, PCM does not function well.

   The supercooling effect is the most important consideration for determining the ideal phase transition temperature (Akeiber *et al*., 2016). Because supercooling has the dual effect of lengthening the phase-change period and reducing the temperature differential between the phase-change material and the Evaporator, it reduces system efficiency (Wang *et al*., 2002). Hence, it slows the heat transfer rate and prolongs the time the compressor is turned on, raising energy consumption. Incorporating nucleating chemicals may inhibit the supercooling effect (Sharma *et al*., 2009).

   The proper phase change temperature and suitable thermo physical characteristics determine which PCM should be used. Water has unique characteristics because of its massive latent heat value, easy availability, and sharp phase change temperature (Marques *et al*., 2014). For subzero temperature applications, it is not used because of its higher freezing point. Therefore, water-salt eutectic solution is usually used because of the desirable melting point and high latent heat (Li *et al*., 2013).

2. **Volume of PCM:** According to Onyejekwe in 1989, the minimal volume of phase change material needed for the energy storage equation can be calculated using the following equation:

$$Q = \rho V \mathrm{h}$$

Where Q is the total stored energy in PCM, h and ρ are the latent heat and density of vaporization of PCM, and V is the volume of phase change material.

The following equation can be used to estimate the total amount of energy held in phase transition material,

$$Q = K \times S(T_{amb} - T_{cold})t$$

T_{amb} is the ambient temperature, T_{cold} is the cool compartment temperature, K is the exchange coefficient, S is the surface fusion, and t is the operating time of PCM (compressor off time). As a result, the formulae above can be used to calculate the volume of PCM needed for a system.

The effectiveness of a heat exchange system is influenced by geometrical factors, factors that can affect thermal resistance and storage temperature. To balance heat gain through the walls during the compressor's OFF time, the volume of PCM should be greater than the volume calculated from the calculation. If PCM thickness is more significant than necessary, not all of the thickness will have the opportunity to undergo phase change (Azzouz *et al*., 2009). As a result, the effectiveness of the phase change material is reduced. The thickness of PCM should be designed for the thermal load because thicker PCM is more expensive and needs a longer compressor duration for cold storage.

3. **Evaporation Temperature**: Integration of phase change materials on evaporation temperature have corresponding effects. During phase change, a PCM's increased latent heat gives it a large thermal capacity and a correspondingly high evaporation temperature (Castell *et al*., 2009). Additionally, compared to a cooling system without a PCM, a higher evaporation temperature results in a more considerable evaporation pressure (Khan & Afroz, 2013), which results in higher COP. PCM freezing time must be extended at lower evaporation temperatures (Waqas & Din, 2013).

4. **Power Outage**: In developing countries like India, the performance of refrigeration systems is highly affected due to the power shortage problem (Hua *et al*., 2021). A traditional refrigeration system's compartment does not stay cold for long because of the rapid heat accumulation from the walls during a power loss. It will impact the compressor's durability, food quality, and energy consumption. Phase change materials can store energy when the system is running and release it in the event of a power outage, which can be used to solve the problem. After two weeks of continuous power outages, it was noticed that PCM maintained the quality of frozen meat and ice cream against drip loss and ice recrystallization, respectively, with encouraging results (Krishna *et al*., 2017).

In the event of blackouts, PCMs can serve as a backup in an emergency in this way. The system's thickness, thermal load, and thermo physical characteristics significantly determine how long a phase change material can maintain a compartment's frigid temperature. Only cold storage in PCMs on the evaporator side is believed to be helpful during power outages.

VI. ANALYSIS OF PCM AT EVAPORATOR

The use of PCM lengthens the compressor's OFF period and boosts system COP. The enhancement of COP can be obtained to 2-74% with the integration of PCM on the evaporator side. The PCM type, thermal load, and ambient temperature all affect the percentage enhancement of COP.

PCM at the Evaporator has an exciting potential because cold storage helps the refrigeration system. Additionally, it was found that the Evaporator's PCM raises the evaporation temperature, which raises the compressor's input temperature. As a result, the temperature at the condenser side rises, and the system's ability to improve performance at the evaporator side is restricted. However, evaporation temperature significantly impacts compressor efficiency (Behi *et al.*, 2017). PCM is a viable solution for the refrigeration cycle since it is less expensive than changing the insulation or compressor, which is needed for improving the refrigeration system. Furthermore, it is also applicable to the existing refrigeration system. PCM was used as a backup in case of power outages in addition to improving the system's performance.

VII. ADVANTAGES OF PCM

Table 1: Advantages of Phase Change Material (PCM)

Advantage	**Details**	**Reference**
More controlled temp at the compressor inlet	minimize compressor workload Uniform distribution of temperature	Wang *et al.*, 2007
more stable under changing thermal loads	more efficient system operation Lower sensitivity to changes in the surrounding temperature	Khan *et al.*, 2013
Refrigerant density is higher at the compressor inlet	Higher capacity of refrigeration	Rahman *et al.*, 2014
Help in the event of a power outage	serving as a fallback position kept food cold for longer while there was no power supply	Oró *et al.*, 2012
Higher COP	improved cooling capacity of the system	Khan *et al.*, 2013
Slower storage temperature changes	Better food quality	Visek et al., 2014

VIII. EUTECTIC SALT-WATER SOLUTIONS AS PCM

A solution is said to be a eutectic solution if one or more solutes and solvents are mixed in a way that results in the mixture's lowest freezing point. The eutectic point is the lowest possible freezing temperature (Hussain *et al*., 2017). Recently, there has been an upsurge in energy demand. The need to create new renewable energy sources is relatively high due to the limited availability of nonrenewable energy sources. A novel method for storing energy that can subsequently be retrieved, known as thermal energy storage (TES), may be effective (Mehling & Cabeza, 2008). In TES, the PCM's latent heat provides a renewable energy source.

In terms of volume, PCM offers a high energy storage density. Therefore, it has more potential efficiency for heat and cold storage. Additionally, phase change materials enable isothermal operation at a particular temperature (Ge *et al*., 2013). Using PCM in cooling applications, such as preserving products that require a specific temperature, such as beverages, food, pharmaceuticals, blood derivatives, air-conditioning, and many more, has proved very beneficial (Pichandi *et al*., 2020). Salt-water eutectic mixes are utilized instead of alkane mixtures for cold storage because they are more readily available and less expensive. Water, aqueous solutions of organic salts, ice, eutectic mixes and salt combinations are further options (Yilmaz *et al*., 2010). PCM melts at temperatures below 0 °C and creates eutectic salt-water solutions. These solutions are often inexpensive and have good storage density. For the subzero cooling application, the phase change temperature range for PCM should be between -24 °C and -10 °C. The eutectic mixture of 22.4% NaCl-H_2O revealed a melting point at -21.2 °C, according to Gawron and Schöder (1977).

Figures 3 and 4 depict the heating-cooling tests of KCl-H_2O and NaCl-H_2O solutions. The sub-cooling effect can be detected in both Figures 3 and 4. The sub-cooling and melting temperature ranges are consistent for every solution cycle. This indicates that similar solutions might be applied to different cooling applications. The results for the NaCl and KCl solutions' freezing point depression, corresponding degree of sub-cooling, and freezing-melting temperature range, determined from the heating-cooling curves, are shown in Table 2. Freezing point depression (FPD) lowers a solvent's freezing point when another component is mixed; thus, a solution's freezing point is lower than that of a pure solvent, such as water.
Due to the thermal conductivity of these liquids being comparable to water and their ability to sub-cool like water by several degrees centigrade or more, sub-cooling of eutectic salt-water solutions is a prevalent issue. Many PCMs do not instantly crystallize when cooled below the melting point; crystallization begins after a temperature much below the melting point is achieved. This phenomenon is known as sub-cooling. Although sub-cooling does not significantly affect heat storage, it does stop latent heat from being released when the melting temperature is reached during heat extraction.

Latent heat is the amount of energy that is absorbed or released during the freezing or thawing process. It has been found that latent heat is more closely related to the amount of water involved in the phase transition process than to the actual amount of water present. To prevent sub-cooling, it is necessary to drop the temperature substantially below the phase transition temperature. Nucleation must happen to start solidification. However, no latent heat is produced if no nucleation happens, and the material retains sensible heat. Sub-cooling might be a significant issue for technological applications. Although sub-cooling has a melting-freezing point lower than 0 °C, it can be viewed as a drawback compared to these alternatives. To create the proper eutectic behavior of specific salt slurry for a particular milk cold chain application, it is necessary to ascertain the freezing characteristics of ice and salt slurries and to track their ability to store cooling at various concentrations at temperatures. (Yilmaz *et al*., 2010).

Table 2: Freezing Point Depression of Eutectic Salt-Water Solutions (adapted from Yilmaz *et al*., 2010)

Solutions	**Subcooling [ºC]**	**Freezing Temperature [ºC]**	**Melting Temperature [ºc]**	**(Freezing Point Depression)**
5.0% KCl	1.59	-3.38/-3.58	-11.79/-6.00	2.32
10.0% KCl	7.48	-6.60/-7.10	-11.40/-9.60	4.80
15.0% KCl	4.40	-12.80/-13.20	-10.23/-9.43	-
20.0% KCl	5.59	-12.93/-13.13	-10.15/-9.15	-
21.0% KCl	4.80	-10.35/-10.65	-10.15/-9.65	-
22.0% KCl	6.90	-10.45/-11.25	-10.95/-9.15	-
23.0% KCl	7.48	-12.12/-12.82	-12.32/-9.83	-
24.0% KCl	5.10	-10.80/-11.10	-11.10/-9.10	-
5.0% NaCl	3.87	-3.87/-4.27	-4.8/-3.18	3.04
10.0% NaCl	6.28	-7.60/-7.70	-7.80/6.10	6.56
15.0% NaCl	5.30	-15.19/-15.29	-10.40/-9.20	10.88
20.0% NaCl	2.79	-18.22/-17.92	-18.92/-14.62	16.45
21.0% NaCl	2.20	-18.46/-18.26	-18.86/-14.62	17.77
22.0% NaCl	1.60	-21.95/-21.39	-20.15/-19.65	19.17
23.0% NaCl	0.20	-20.89/-21.85	-22.15/-19.65	20.66
24.0% NaCl	0.30	-20.19/-19.9	-3.28/-2.08	-

According to Granryd and Melinder (2005), when ice crystals form and mix with the liquid, the aqueous solutions typically do not consolidate to ice. When the mixture's temperature reaches the eutectic point, total freezing begins. For every 1% increase in $CaCl_2$ concentration, the heat transfer value typically decreases by roughly 2.5%. This occurs because the eutectic solution's specific heat value decreases as salt concentrations rise. According to one theory, brines made of calcium chloride or potassium carbonate have good thermo physical characteristics, are cheap and non-toxic, and effectively lower freezing points (the freezing point is lowered to -55 °C by 29.9% w/w $CaCl_2$). Nevertheless, corrosion occurs at temperatures below 0 °C is a drawback of using their application to cooling systems (Feng *et al*., 2020).

IX. APPLICATIONS OF PCM IN THE FOOD INDUSTRY

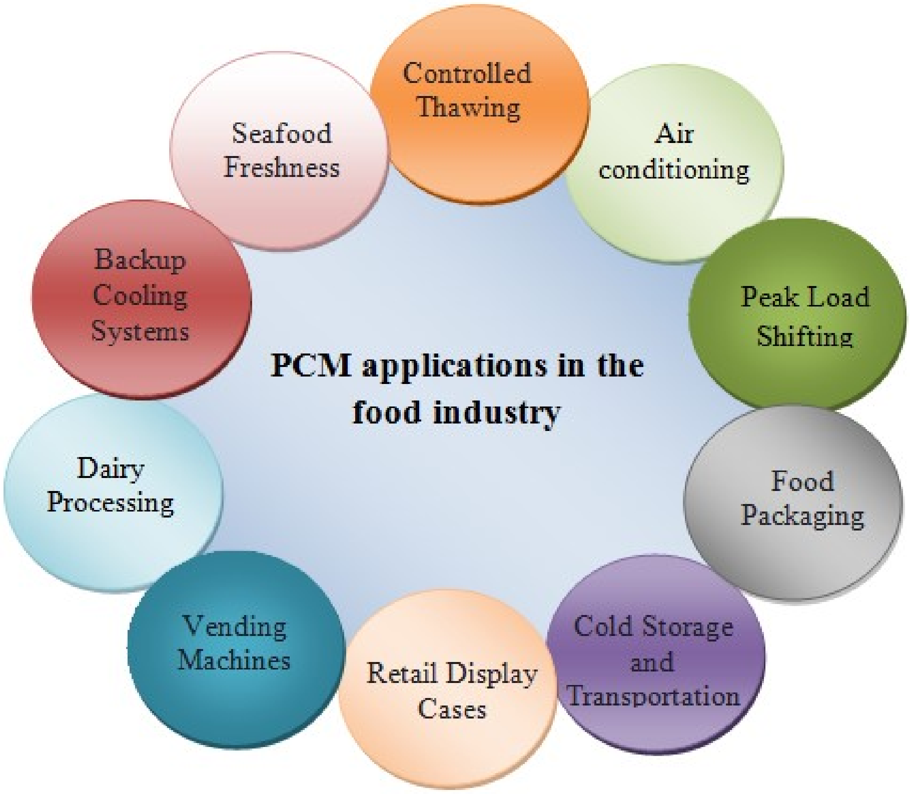

Figure 2: Applications of PCM in the Food Industry

In recent years, there has been much attention to the fantastic ability of Phase Change Materials (PCMs) to store and release thermal energy during phase changes, such as from solid to liquid or vice versa. These materials can potentially revolutionize industries, particularly those where maintaining and controlling temperature is essential. Due to its innate requirement for efficient temperature control for safety, quality, and shelf life, the food industry stands out among these sectors as a prominent benefit of PCMs.

1. **Cold Storage and Transportation:** The domain of cold storage and transportation is one of the food industry's most basic applications of PCMs. Foods, particularly perishables like fruits, vegetables, meat, and dairy, require a specific temperature to be stored properly (Oro *et al.*, 2012). Maintaining these temperatures throughout transportation is critical to prevent food deterioration or quality degradation when the food is delivered to its final location. Cooling systems used in conventional refrigerated vehicles and containers consume much electricity. Particularly during transit times when opening doors or during brief power outages, adding PCMs to these containers may provide more constant temperature management (Zhang *et al.*, 2016). The appropriate PCM selection can lower energy usage while preserving food product quality for extended periods. Many catering applications need the transportation of prepared meals or frozen goods that are

manufactured in one location. PCM containers might also transport milk derivatives, precooked meals, ice cream and many other items without tampering with the cold chain.

2. **Food Packaging for Temperature-Sensitive Food:** The food sector has changed due to the development of online shopping. Nowadays, many shoppers get groceries—including perishable items—online. This shift calls for inventive packaging solutions to ensure the food maintains a safe temperature during its journey from the warehouse to the consumer's doorstep (Nazir *et al*., 2019). When used in insulated packaging, PCMs can maintain the desired temperature for longer, maintaining the freshness and safety of frozen and chilled items (Singh *et al*., 2018).

3. **Retail Display Cases:** Display cases serve as more than just a product showcase for retailers; they play a significant role in maintaining the quality of products. PCMs can be a game-changer, particularly in areas where the ambient temperature can alter or power interruptions are frequent. To keep products within the correct temperature range, lengthen shelf life, and guarantee quality even during unplanned disruptions, they can be incorporated into the design of display cases.

4. **Backup Cooling Systems:** Even a brief power outage can cause substantial monetary losses for critical storage facilities, such as those that contain enormous supplies of vaccinations or specialty food products. Until power is restored or alternative measures are taken, PCMs can be a reliable backup, providing cooling.

5. **Thermal Cookers:** Modern kitchen appliances integrate PCMs to guarantee that food stays hot or cold for extended periods without a continual power or heat supply. For example, thermal cookers can control temperature using PCMs, perfect for picnics or places with unstable power supplies.

6. **Controlled Thawing:** To maintain the quality and safety of frozen products, careful thawing is required. Quick or uneven thawing might compromise the food's texture, flavour, and safety. A consistent and secure defrosting process can be offered by a regulated defrosting environment made possible by PCMs (Xu *et al*., 2015).

7. **Seafood Freshness:** Seafood has a very high sensitivity to temperature changes. Incorporated PCMs in seafood packaging help maintain cooler temperatures, preserve freshness, and avoid decomposition. As a result, fishermen and seafood vendors may have a longer selling window and experience less waste.

8. **Warehouse and Cold Storage Facilities:** Even slight temperature changes in big storage facilities can cause huge losses from food spoiling. Uneven cooling results from traditional cooling systems' inability to handle peak demand periods. These storage units' infrastructure can have PCMs, which can release or absorb heat to maintain temperatures (Fan and Khodadadi, 2011). This guarantees a constant temperature and saves energy, improving the effectiveness and environmental friendliness of the overall system.

9. **Vending Machines:** In hotter climates, particularly throughout the summer, vending machines may have problems keeping products at temperatures that are safe for consumption. These machines can maintain appropriate temperatures for prolonged

periods without routine cooling because of the incorporation of PCMs, which results in energy savings and maintains the safety of the finished product.

10. **Dairy Processing:** Temperature is the most critical factor in numerous phases of the processing of dairy products. Consistent temperatures are essential for the safety and quality of products during operations like pasteurization and fermentation. PCMs can help to keep these temperatures stable, ensuring the production of dairy products of the highest standard.

11. **Air Conditioning:** Thermal energy storage (TES) is one of the principal uses of PCMs in air conditioning. By including PCMs in the system, extra cool energy generated off-peak (during the night, for example) can be stored and used later, lessening the burden on the air conditioner. Walls, ceilings, and floor panels are architectural materials that can include PCMs. The PCMs absorb the heat when the structure warms, melting. As they solidify at lower temperatures, they release the heat trapped there, lowering the requirement for ongoing cooling and enhancing indoor comfort (Pasupathy *et al*., 2008). PCMs can provide prolonged cooling periods in portable or small-scale air conditioning equipment without constant energy use. This is especially useful when there may not be a reliable power source.

X. CONCLUSION

In the food industry, phase change materials (PCMs) have become a promising solution for various temperature regulation problems. They are beneficial for thermal management and energy storage because they can collect and release large amounts of energy during phase transitions with little change in their temperature. The properties of various PCM types, including inorganic, organic, and eutectic or bio-based PCMs, can be tuned to particular purposes. These uses demonstrate the adaptability and promise of these materials and cover every aspect of the food supply chain, from temperature-controlled packaging and food processing to cold chain logistics and refrigeration systems. Although the basics of PCMs are widely established, their actual application in the food business is still in its infancy. It is essential to carefully analyze cost-effectiveness, environmental impact, stability through numerous heat cycles, and containment or encapsulation solutions. Additional research and development are required to realize their potential and overcome current obstacles fully. Despite these difficulties, PCMs have enormous potential for boosting energy efficiency, ensuring food safety, and raising the quality of food items.

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