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Integration of Phase Change Materials with Solar Energy for Refrigeration

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ABSTRACT

In this review paper we are going to study about the use of latent heat storages (Phase Change materials) in the system of refrigeration which is work through solar energy. In this system we use solar energy for refrigeration for reduce the energy consumption by refrigeration, But in this some problem phase during rainy season & in nights solar energy is not available. So we store solar energy in peak hours and use it when solar energy is not available.

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1. INTRODUCTION

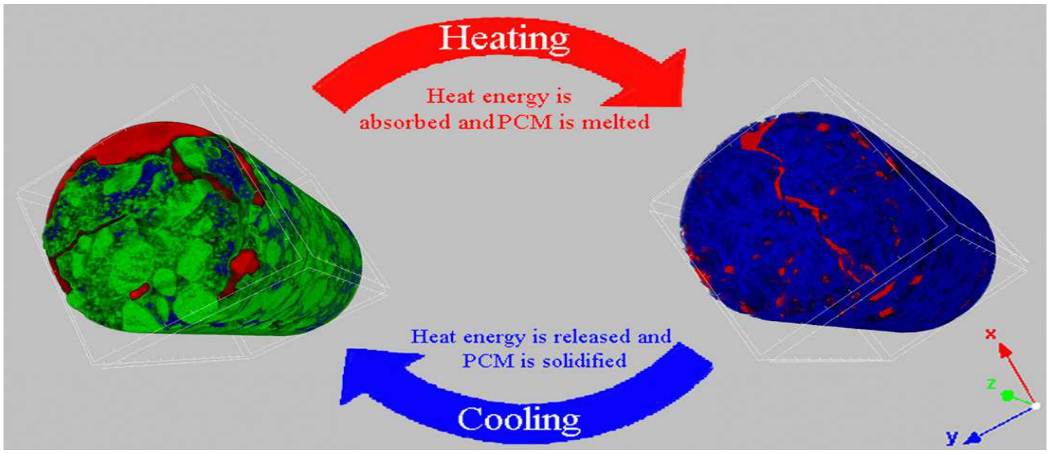
Refrigeration is a significant contributor to energy consumption and greenhouse gas emissions. The demand of refrigeration is increased day by day and accordingly there are limited energy sources are available. So, because of this all problems we use solar energy and reduced energy consumption. In this system we integrate Phase change material with solar energy for 24-48 hours autonomy for critical applications. The combination of solar energy and Phase Change Materials (PCMs) offers an efficient and eco-friendly solution for refrigeration systems.

2. COMBINATION OF PHASE CHANGE MATERIAL AND SOLAR ENERGY FOR REFRIGERATION SYSTEM

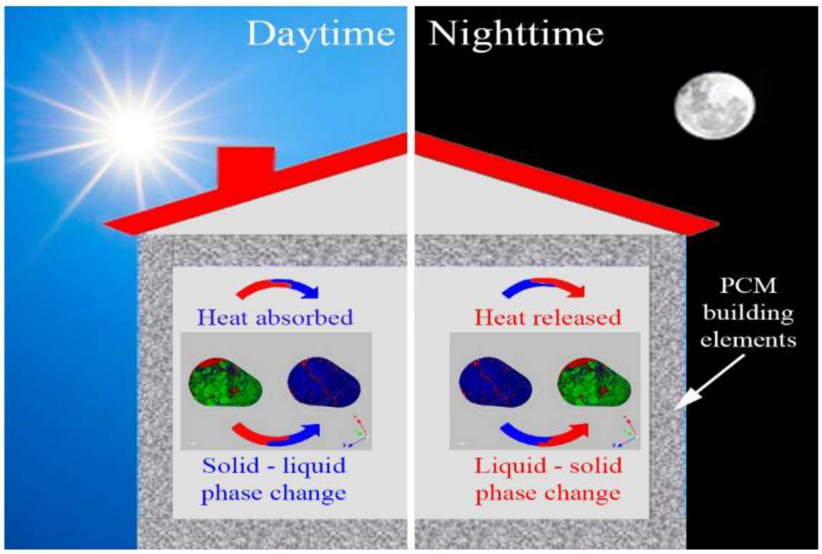
So, Key component of this system are solar collector, PCM storage unit and Refrigeration system.

Solar collector: Capture solar energy to power the refrigeration system or heat the PCM.

PCM Storage Unit: Stores latent heat during phase transition (e.g., melting) and releases it during solidification.



Refrigeration System: Uses the stored thermal energy to maintain cooling, even during cloudy periods or night time.



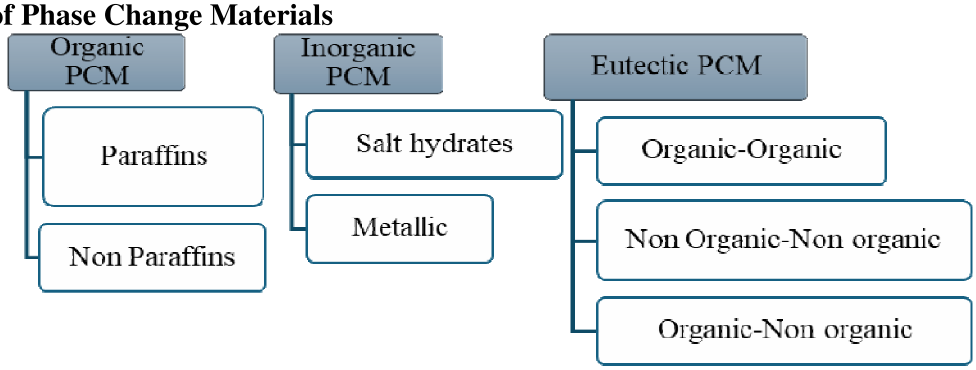
3. Phase Change Material and it´s selection criteria

A Phase Change Material is a substance which releases/absorbs sufficient energy at phase transition to provide useful heat or cooling. By melting and solidifying at the phase-change temperature (PCT), a PCM is capable of storing and releasing large amounts of energy compared to sensible heat storage. Heat is absorbed or released when the material changes from solid to liquid and vice versa or when the internal structure of the material changes. PCMs are accordingly referred to as latent heat storage (LHS) material. (1)

3.1. Characteristics of Phase Change Materials

Latent heat storage can be achieved through changes in the state of matter from liquid → solid, solid → liquid, solid → gas and liquid→ gas. However, only solid → liquid and liquid → solid phase changes are practical for PCMs. Although liquid–gas transitions have a higher heat of transformation than solid–liquid transitions, liquid→ gas phase changes are impractical for thermal storage because large volumes or high pressures are required to store the materials in their gas phase.

3.2. Types of Phase Change Materials



3.3. SELECTION CRITERTIA OF PHASE CHANGE MATERIAL

Based on Properties of Phase Change Material: (1) Based on Thermal Properties: a) Suitable melting point for particular operation. b) High latent heat of fusion per unit volume. c) High thermal conductivity of solid and liquid phases for better heat transfer. d) Higher specific heat for additional sensible heat storage. (3)

Thermodynamic parameters	Organic PCM	Inorganic PCM	Eutectic PCM
Latent heat (KJ/Kg)	120-250	150-400	100-300
Thermal conductivity (W/m·k)	0.1-0.3	0.5-1.5	0.5-8.5
Phase transition temperature (°C)	-20 - 150	20-800	Can be adjusted by changing the ratio of components

(2) Based on Physical Properties a) High density for smaller container volume. b) Small volume change during phase transition. c) Low vapor pressure to reduce the containment problem. (3) Based on Kinetic Properties a) Little or no super cooling during freezing b) High rates of nucleation and growth. c) Effective heat transfer. (4) Based on Chemical Properties: No degradation after no. of freeze/melt cycle. (1)

(5) Based on PCM Thickness: Effect of PCM Thickness on The PCM Melting and Freezing Time: Four PCM thicknesses were considered by the model. The PCM total storage capacity varied between 138 kJ for a 2 mm slab and 345 kJ for a 5 mm slab. The heat load and cooling capacity used to predict the PCM melting and freezing times with different thicknesses correspond to an ambient temperature of 25°C.

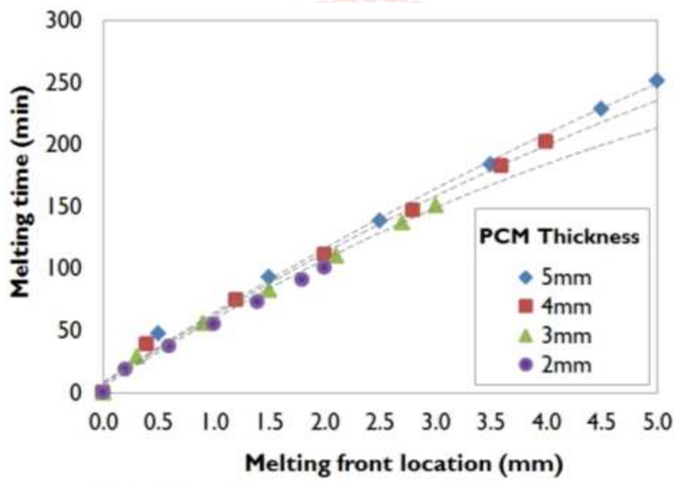
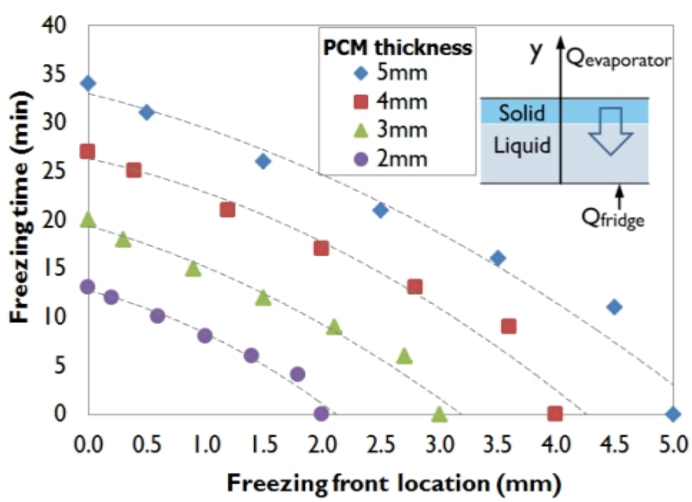
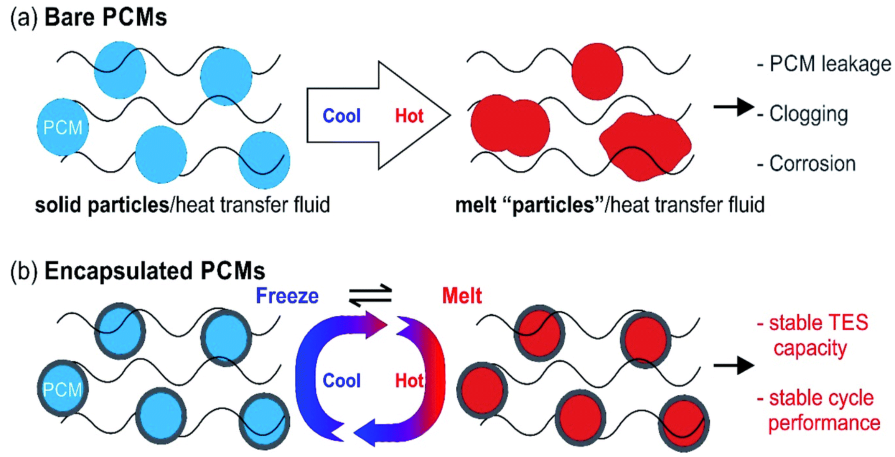


FIG1. Effect of Pcm Thickness on Melting Time



3.4. Encapsulation Methods for Phase Change Material

The successful deployment of PCMs in refrigeration hinges on effective encapsulation techniques. Poorly contained PCMs may leak during phase transitions, contaminate the coolant/loss, or degrade structurally. Encapsulation serves several functions: preventing leakage, enhancing thermal transfer, buffering volumetric changes, and boosting mechanical robustness. (2)



Types of Encapsulation Technology:

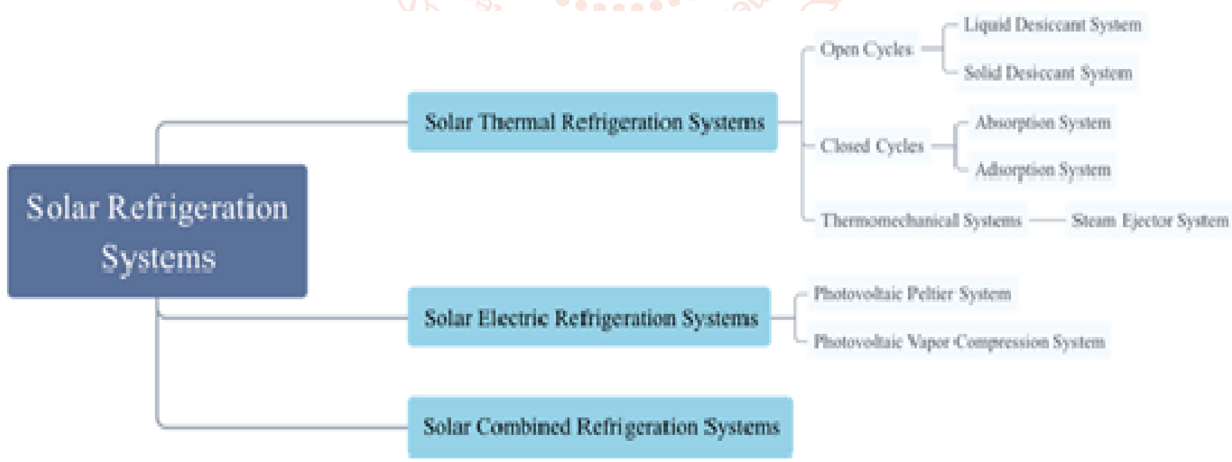
(1) Microencapsulation: The encapsulated PCMs are called micro-encapsulated PCMs (MEPCMs) depending on PCM dimensions MEPCMs: 0.1–1000 µm. Encapsulation refers to the process of embedding PCM cores (can be single-core or multi-core) into a shell or layer (protection structure). This shell thus isolates and protects PCM cores from the external environment. By micro encapsulation, PCMs can be transformed into powder or paste form. By using the porous shell structure the volume expansion of PCMs can be no longer an issue. The materials used for encapsulation vary from organics (such as polystyrene, urea formaldehyde, and polymethyl methacrylate) to inorganic materials (such as calcium carbonate, silica, sodium silicate, and metal oxides). (5)

(2) Form stable Composites: PCM is absorbed into porous matrix (e.g., expanded graphite, silica gel, metal foams). According to one research PCMs were vacuum-impregnated into expanded graphite (EG) and then cold-compacted to form dense, shape-stabilized panels. This encapsulation by expanded graphite is enhanced thermal conductivity of PCM up to 6 W/m·K, significantly higher than pure PCM values. Expanded graphite matrix provided shape stability, leakage prevention, and improved thermal response under cycling conditions. (4)

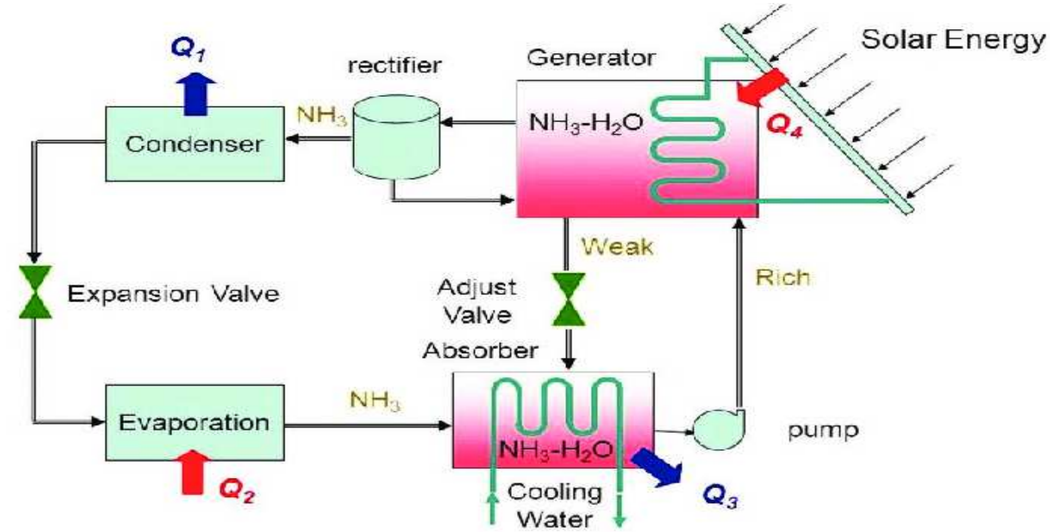
(3) Nano and Composite Encapsulation: This encapsulation method is as same as Micro encapsulation method but in this method PCM dimension size is 1-100 nm. (5)

4. Integration of PCMs in Solar Thermal Refrigeration Systems (3)

The combination of solar energy and Phase Change Materials (PCMs) offers an efficient and eco-friendly solution for refrigeration systems.



1.Solar Thermal Refrigeration System: Solar thermal refrigeration systems—particularly those based on absorption, adsorption, or ejector cycles—utilize solar thermal collectors such as flat-plate or evacuated tube designs to generate hot water or steam. This thermal energy drives either chemical absorption cycles (typically using lithium bromide–water mixtures) or physical adsorption cycles (often employing ammonia–water pairs), enabling cooling without conventional electricity. These systems are especially valuable in off-grid or energy-scarce regions. To enhance stability and performance, Phase Change Materials (PCMs) are strategically integrated into components like the solar collector, generator, or cold storage chamber. By absorbing excess thermal energy during peak sunlight and releasing it during low irradiance periods, PCMs buffer fluctuations in solar input, extend cooling autonomy, and improve overall system reliability.



2. Solar Electrical Refrigeration System: Solar electric refrigeration systems utilize photovoltaic (PV) panels to generate electricity that powers conventional vapor compression refrigeration cycles. These systems may operate with or without battery backup, depending on the application and energy storage strategy. To enhance reliability and maintain consistent cooling during periods of low solar irradiance or nighttime, Phase Change Materials (PCMs) are integrated into key thermal zones such as evaporator panels, cold storage walls, or as ice-based thermal banks. The PCMs absorb excess cooling during peak solar hours and release it gradually, stabilizing internal temperatures and ensuring uninterrupted refrigeration even in battery-less configurations. This approach is particularly effective in off-grid or rural settings where grid access is limited or unreliable.

4.1. A CASE STUDY: PERFORMANCE IMPROVEMENT OF A DOMESTIC REFRIGERATOR BY USING PCM (PHASE CHANGE MATERIAL) (1)

Experiments were carried out under certain thermal loads with water as PCM. Here the effect PCM in certain quantities in this case 5 litres at certain thermal loads on the performance parameter of house hold refrigerator. The number of compressors on-off cycle within a certain period of time for different PCMs and without PCM can be pointed up. Use of water as PCM imposes a great impact on COP improvement at certain thermal loads. Using water as PCM and certain thermal load it is found that the 55- 60% COP improvement

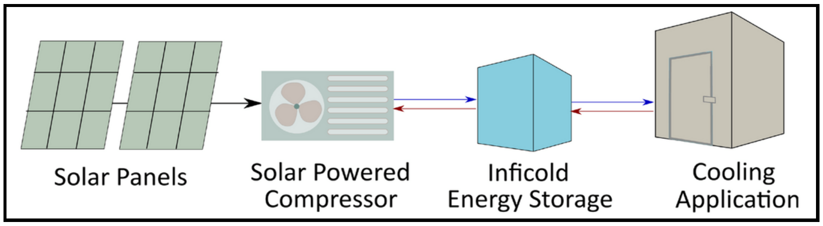
has been achieved by the PCM in respect without PCM in conventional refrigerator. During the compressor running the refrigerant takes the chamber heat by free convection in case of without PCM, which is slower heat transfer process in respect to conduction process. But PCM most of the heat in the cabinet is stored in the PCM during compressor running time. Since the conduction heat transfer process is faster than the free convection processes the cooling coil temperature does not require dropping very low to maintain desired cabinet temperature. As result the evaporator work sat high temperature and pressure with PCM. Moreover, due to high operating pressure and temperature of the evaporator the density of the refrigerant vapor increases, as a result the heat extracted from the evaporator by the fixed volumetric rate compressor is higher than without PCM. The experiments were carried on for calculating the C.O.P of the refrigeration system with and without PCM the results of which are given below table:

Number of Observations	C.O.P found in vapor compression refrigeration system without PCM	C.O.P found in vapor compression refrigeration system with PCM
1	6.12	9.85
2	5.55	9.42
3	6.12	9.45
4	5.5	9.04
5	5.13	9
6	6.78	9
7	5.1	9
8	5.11	8.91
9	5.02	8.82
10	5.02	8.91

4.2. Case Studies of Solar-PCM Refrigeration in High-Irradiance Regions (with Focus on India)

Case Study – 1

Inficold's milk coolers and cold storage systems in India represent a breakthrough in decentralized dairy refrigeration. These units utilize bulk milk coolers embedded with phase change materials (typically water or ice banks) and are powered by solar photovoltaic compressors, eliminating the need for grid electricity or backup generators. The technology enables rapid cooling and provides up to one-day thermal autonomy, ensuring consistent performance even during power outages. Outcomes include significant improvements in milk quality, reduction in spoilage, and long-term durability—thanks to stainless steel tanks designed for a lifespan exceeding 20 years. With the ability to rapidly down temperatures to 4 °C, these systems are ideally suited for rural and decentralized dairy collection centers. In recognition of its innovation and impact, Inficold received the National Technology Award in 2019, and its solutions have been successfully deployed across states like Uttar Pradesh and Rajasthan.



Case Study – 2

The Government of India, through the Ministry of New and Renewable Energy (MNRE), has established comprehensive design and performance standards for solar cold storage systems integrated with Phase Change Material (PCM) thermal energy storage. These guidelines mandate that PCMs used in such systems must be food-safe, non-toxic, and capable of maintaining their thermal properties for over ten years. Additionally, they must ensure strict temperature control and undergo detailed testing protocols to validate performance and safety. Typical deployments range from 2 to 20 metric tons, operating within a temperature band of 0 to −5 °C. Common PCM choices include water, ice, and salt-based eutectics. These systems are specifically tailored for rural, agricultural, and fishery applications, aiming to enhance cold chain infrastructure in off-grid and underserved regions.

5. Practical Implementations and Commercial Systems

Several leading Indian and global providers have successfully commercialized solar-PCM hybrid refrigeration systems, addressing critical cooling needs in off-grid and rural environments. SunDanzer, a U.S.-based company with global reach, offers off-grid refrigerators and freezers powered by solar photovoltaic panels and proprietary PCM packs. These systems operate without batteries, making them ideal for rural health posts and agricultural applications where maintenance and reliability are key. Another prominent initiative is SolarChill, a global partnership involving organizations such as Greenpeace, UNICEF, WHO, and Indian government agencies. SolarChill has developed solar-powered medical refrigerators that utilize PCM for thermal storage, eliminating the need for batteries while meeting the stringent WHO Performance, Quality, and Safety (PQS) standards. These innovations demonstrate the viability and scalability of solar-PCM technologies in both healthcare and agricultural sectors. Ecozen and Inficold, two leading Indian innovators, have developed field-proven solar cold rooms, milk chillers, and portable PCM packs tailored for agricultural markets. Their solutions feature robust IoT-based control systems and are optimized for rural deployment. Meanwhile, PureTemp, operating across the US and India, offers a diverse portfolio of bio-based PCMs that serve critical cold chain applications in vaccines, food preservation, and temperature-sensitive transport.

6. Recent Innovations and Emerging Research Trends

(1) Nano-enhanced and composite PCMs incorporate advanced materials such as graphene, carbon nanotubes (CNTs), metal oxides, and expanded graphite to significantly improve thermal conductivity and cycling stability, making them ideal for high-performance solar refrigeration. (2) Complementing these are porous ceramic and metal foam heat exchangers—often made from materials like silicon carbide—which serve as passive, finned structures filled with PCM. These exchangers maximize surface contact and accelerate thermal charge/discharge rates, enhancing both photovoltaic panel cooling and cold storage efficiency.

6.1. Benefits of PCM based solar refrigeration system

PCM-based solar refrigeration offers significant economic advantages by minimizing dependence on expensive batteries and fuel generators. In most agricultural and off-grid deployments, these systems achieve a payback period of just 3 to 5 years. Additionally, they enhance the shelf life of food and medical products, leading to reduced spoilage, improved farm-gate prices, and more reliable health service delivery in remote areas. Solar-PCM refrigeration systems reduce greenhouse gas and particulate emissions by replacing diesel generators. They Favor recyclable, bio-based, and non-toxic PCMs, aligning with circular economy principles. Compared to batteries, these systems offer lower maintenance, longer lifespans, and improved safety with reduced fire risk.

6.2. Challenges of PCM based refrigeration system

PCM-based refrigeration systems face several technical challenges. The inherently low thermal conductivity of most PCMs limits heat transfer efficiency, affecting cooling rates. Additionally, issues like phase segregation and subcooling can impair thermal reliability and reduce energy storage effectiveness over repeated cycles. Integrating PCM modules into existing refrigeration systems also requires careful design and control strategies, making retrofitting and system optimization more complex.

6.3. Conclusion

PCM-based solar refrigeration systems offer a transformative solution for sustainable cooling in agriculture, healthcare, and rural infrastructure. By leveraging solar energy and phase change materials, these systems reduce dependence on batteries and diesel generators, enhance temperature stability, and extend product shelf life. Their economic viability, environmental benefits, and adaptability to off-grid conditions make them especially valuable in regions like India. Despite challenges such as low thermal conductivity and integration complexity, ongoing innovations in nano-enhanced PCMs and advanced heat exchangers continue to improve performance. With strong government support, proven field deployments, and growing commercial interest, PCM-solar hybrid refrigeration is poised to play a pivotal role in building resilient, low-carbon cold chains.

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