

Recent Progress of Phase Change Materials and Their Applications in Facility Agriculture and Related-Buildings—A Review

Yijing Cui ¹, Raza Gulfam ^{1,*}, Yousaf Ishrat ², Saqib Iqbal ³ and Feng Yao ⁴ 

¹ College of Electrical, Energy and Power Engineering, Yangzhou University, Yangzhou 225127, China; 19850397678@163.com

² School of Economics and Management, Southeast University, Jiulonghu Campus, Nanjing 211189, China; itexecutiveali@hotmail.com

³ School of Materials Science and Engineering, Southeast University, Jiulonghu Campus, Nanjing 211189, China; saqibiqbal792@gmail.com

⁴ School of Environmental Science and Engineering, Suzhou University of Science and Technology, Suzhou 215009, China; yaofeng@usts.edu.cn

* Correspondence: gulfam@yzu.edu.cn

Abstract: Facility agriculture, which involves agricultural production in controlled environments such as greenhouses, indoor farms, and vertical farms, aims to maximize efficiency, yield, and quality while minimizing resource consumption and environmental impact. Energy-saving technologies are essential to the green and low-carbon development of facility agriculture. Recently, phase change heat storage (PCHS) systems using phase change materials (PCMs) have gained significant attention due to their high thermal storage density and excellent thermal regulation performance. These systems are particularly promising for applications in facility agriculture and related buildings, such as solar thermal utilization, greenhouse walls, and soil insulation. However, the low thermal conductivity of PCMs presents a challenge for applications requiring rapid heat transfer. This study aims to provide a comprehensive review of the types, thermophysical properties, and various forms of PCMs, including macro-encapsulated PCMs, shape-stabilized PCMs, and phase change capsules (PCCs), as well as their preparation methods. The research methodology involves an in-depth analysis of these PCMs and their applications in active and passive PCHS systems within facility agriculture and related buildings. The major conclusion of this study highlights the critical role of PCMs in advancing energy-saving technologies in facility agriculture. By enhancing PCM performance, optimizing latent heat storage systems, and integrating intelligent environmental control, this work provides essential guidelines for designing more efficient and sustainable agricultural structures. The article will serve as the fundamental guideline to design more robust structures for facility agriculture and related buildings.

Keywords: facility agriculture; phase change materials; latent heat storage; buildings



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1. Introduction

Facility agriculture is a modern agricultural production method that uses technical means and artificial facilities to create and optimize the environmental conditions necessary for the growth and development of plants and animals. It allows traditional agriculture to gradually overcome natural limitations, significantly improving land productivity, resource efficiency, and labor effectiveness. This approach is essential for boosting the overall production capacity of agriculture and represents a key initiative for building a strong agricultural nation and advancing agricultural and rural modernization. However, facility agriculture and related buildings pose high demands due to their environmental control capabilities and scalability, resulting in significant energy consumption requirements. For example, large multi-span greenhouses and plant factories can consume up to 10 kWh in the summer, with energy usage intensity reaching industrial-scale levels [1]. According to statistics from the United Nations Food Program, energy costs account for more than 30%

of the total cost of facility agriculture [2]. Consequently, energy stability and consumption costs have become the primary pressures on the upgrading of facility agriculture and the key obstacles to achieving profitability [3,4]. The energy consumption in facility agriculture is widely used for various processes, e.g., winter heating, summer cooling, artificial lighting, irrigation, etc. Temperature regulation, particularly for heating in winter and cooling in summer, constitutes a significant portion of the energy usage in facility agriculture. For example, 35% of the annual energy consumption produced by agriculture globally is used for greenhouse heating [5]. Developing energy-saving and temperature regulation technologies for facility agriculture and related buildings has become crucial for promoting the green and low-carbon transformation and upgrading of facility agriculture.

Phase change heat storage (PCHS) technology, which utilizes phase change materials (PCMs) to absorb or release large amounts of phase change latent heat (PCLH) during the phase change process, allows for heat transfer over space and time. Therefore, this technology can be effectively applied to facility agriculture for temperature regulation [6]. Due to the almost isothermal phase change process and high energy storage density of PCMs, PCHS technology demonstrates superior temperature regulation and heat storage capabilities, rendering it highly promising for applications in facility agriculture and related buildings [7]. Due to this, PCMs have been widely used in facility agriculture and related buildings, e.g., in solar thermal utilization, greenhouse walls, soil insulation, etc. [8].

This review first introduces the main types and corresponding properties of PCMs and analyzes the forms of PCMs suitable for facility agriculture and related buildings, as well as their preparation methods. It then introduces the application of PCMs in facility agriculture and related buildings. Finally, the future development prospects and challenges of PCMs in facility agriculture are summarized and anticipated.

2. Classification of PCMs

PCMs are regarded as excellent heat storage materials as they absorb and release heat energy when a phase transition occurs while keeping the temperature practically constant [6]. Based on the transition of the state of matter, there are four different types of PCMs that can be distinguished from one another: (i) solid–solid, (ii) solid–liquid, (iii) solid–gas, and (iv) liquid–gas. The gas volumes of solid–gas and liquid–gas PCMs are uncontrollable during phase changes, and solid–solid PCMs are difficult to combine with other materials, making their practical applications challenging. Therefore, solid–liquid PCMs are predominantly used in facility agriculture. Additionally, PCMs are classified into low-temperature, medium-temperature, and high-temperature PCMs based on their phase transition temperatures. The range of temperatures required for operations in facility agriculture closely matches the phase transition temperatures of low-temperature PCMs. To sum up, this review primarily introduces low-temperature solid–liquid PCMs widely used in facility agriculture, including inorganic types (crystalline hydrated salts, molten salts, etc.), organic types (hydrocarbons, such as paraffin waxes, and fatty acids), and composite types.

2.1. Inorganic PCMs

Inorganic PCMs are categorized into crystalline hydrated salts, molten salts, metals, and other inorganic substances. Most molten salts and metal alloys belong to the class of high-temperature PCMs. In contrast, crystalline hydrated salts have a phase transition temperature ($<100\text{ }^{\circ}\text{C}$) that aligns with the phase transition temperature range ($10\text{--}30\text{ }^{\circ}\text{C}$) in facility agriculture, and are therefore widely utilized. Crystalline hydrated salts often exist as crystalline solids, including inorganic salts and water. They store and exert heat by releasing and absorbing crystalline water during melting and solidification, respectively. These salts offer numerous advantages, such as high latent heat of melting, high thermal conductivity, compatibility with plastic, minimal toxicity, low volume change, cost-effectiveness, etc. [9,10]. The main inorganic PCMs currently used in facility agriculture, along with their thermophysical properties, are summarized in Table 1, with $\text{CaCl}_2\cdot 6\text{H}_2\text{O}$, $\text{Na}_2\text{SO}_4\cdot 10\text{H}_2\text{O}$, and $\text{Na}_2\text{CO}_3\cdot 10\text{H}_2\text{O}$ being the most widely used.

However, inorganic PCMs have issues like supercooling and phase separation, leading to an irreversible phase change process, material loss, and decreased efficiency of heat storage, largely limiting the practical application in the greenhouse [6,9]. Accordingly, nucleating agents (e.g., borax, $\text{Ba}(\text{OH})_2$, expanded graphite, etc.) and thickening agents (e.g., starch, bentonite, clay, carboxymethyl cellulose, etc.) are typically added to inorganic PCMs.

Berroug et al. [11] incorporated $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ as a PCM and added it to the north wall of a greenhouse, effectively reducing temperature fluctuations and lowering the relative humidity by 10–15%. Benli et al. [12] used $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ with a phase transition temperature of 29 °C as a PCM, combining solar energy collectors for greenhouse heating. Yan et al. [13] utilized sodium acetate hydrate with a phase transition temperature of 58 °C and a PCLH value of 265 J/g in an air heat recovery system for greenhouse heating. This implementation resulted in a reduction in the heating burners' energy consumption.

Table 1. Thermophysical properties of inorganic PCMs.

PCMs	Phase Transition Temperature (°C)	Phase Change Latent Heat (kJ/kg)	Thermal Conductivity		References
			Solid	Liquid	
$\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	29.6	212	1.08	0.56	[14]
	29	190.8		0.54	[15]
	28	188.34	1.09	0.54	[16]
$\text{CaCl}_2 \cdot 12\text{H}_2\text{O}$	29.8	174	-	-	[15]
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	32	180	1.088	0.54	[14]
$\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$	33	247	-	-	[9]
$\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$	40	279	-	-	[6]
$\text{FeBr}_3 \cdot 6\text{H}_2\text{O}$	21	105	-	-	[6]
$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$	37	223	-	-	[6]
$\text{KFe}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$	33	173	-	-	[6]
$\text{KF} \cdot 4\text{H}_2\text{O}$	19	231	0.584	0.479	[9]
$\text{K}_2\text{HPO}_4 \cdot 6\text{H}_2\text{O}$	14	109	-	-	[6]
$\text{LiNO}_3 \cdot 3\text{H}_2\text{O}$	30	256	1.46	1.425	[9]
$\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	25.8	125.9	-	-	[17]
$\text{Mn}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$	37.1	115	-	-	[6]

2.2. Organic PCMs

The main types of organic PCMs include paraffin waxes, fatty acids, polyols, etc. Among these, paraffin waxes and fatty acids have received widespread attention in facility agriculture due to their low cost, good stability, non-corrosiveness, and suitable melting point range, as well as the absence of phase separation and supercooling issues [18]. Paraffin waxes are divided into two types: one type consists of saturated hydrocarbons with the general formula $\text{C}_n\text{H}_{2n+2}$, which are straight-chain alkanes with carbon atoms ranging from 12 to 40 [19]; the other type is a mixture of alkanes and other hydrocarbons with the form $\text{CH}_3(\text{CH}_2)_n\text{CH}_3$ [16]. Paraffin waxes are heavily researched because of their wide range of phase transition temperature congruent melting, and great nucleation performance. Their melting points and heat of fusion increase with the quantity of carbon atoms. In practical applications, considering the cost, industrial-grade paraffin waxes (paraffin mixtures) are widely used [6]. The melting temperature of fatty acids, ranging from −5 to 71 °C, is considered close to the operating temperature of agricultural facilities. A range of PCLH values from 45 to 210 kJ/kg is offered, and many excellent qualities, including consistent melting, repeatable melting, freezing, high latent heat of fusion, etc., are provided. Their disadvantage, however, lies in their high expense, which is 2–2.5 times higher than that of industrial-grade paraffin waxes [6]. The thermophysical properties of frequently employed organic PCMs are presented in Table 2. Organic PCMs are applied in the scenarios involving agricultural facilities, such as building envelopes, heating (or cooling) units, low-temperature solar storage, etc. [20,21]. Organic PCMs have properties like lower thermal conductivity, PCLH values, and flammability compared to inorganic

PCMs. Consequently, contemporary researchers are primarily focused on improving the thermal conductivity and strengthening the flame retardancy of organic PCMs [22–25].

Beyhan et al. [26] constructed a root zone temperature control system (RZTCS) for soilless agricultural greenhouses based on PCM thermal energy storage. The insulation effects of a 40% oleic acid + 60% capric acid mixture were compared with pure oleic acid as PCMs. The results showed that the substrate using the 40% oleic acid + 60% capric acid mixture as the PCM maintained a nighttime temperature that was consistently 1.2–1.9 °C higher, demonstrating better temperature control. Li et al. [27] used butyl stearate as the PCM, which had a phase transition temperature of around 18 °C and a PCLH value of 140 J/g. It was stored in cylindrical stainless-steel bottles and placed in a growing spinach greenhouse. In a comparative study with a greenhouse without PCM installation, it was verified that butyl stearate as a PCM effectively maintained thermal insulation. This contributed to a reduction in indoor temperature fluctuations of roughly 1–2 °C, a decrease in the top daytime temperature of about 1–2 °C, and a rise in the lowest nighttime temperature of approximately 1–3 °C. Enibe et al. [28] designed a natural convection solar air heater (SAH) with PCM energy storage, which is suitable for use as a solar cabinet crop dryer for aromatic herbs, medicinal plants, and other crops. Azaizia et al. [29] constructed a solar greenhouse dryer using paraffin waxes as the PCM. During tests on the drying of red peppers, it was observed that the solar greenhouse equipped with the PCM maintained a higher air temperature, which was approximately 7.5 °C higher at night. Additionally, the greenhouse’s relative humidity was reduced by 18.6%, which shortened the drying time for the red peppers.

Table 2. Thermophysical properties of organic PCMs.

PCM	Phase Transition Temperature (°C)	Phase Change Latent Heat (kJ/kg)	Density (kg/m ³)	Specific Heat (kJ/kg·K)	Thermal Conductivity (W/m·K)		Reference
					Solid	Liquid	
C ₁₄	5.5	228	760 (liquid, 20 °C)	2.20	-	-	[6]
C ₁₅	10	205	770 (liquid, 20 °C)	2.18	-	-	[6]
C ₁₆	16.7	237.1	760 (liquid, 20 °C)	2.30	-	-	[6,15]
C ₁₇	21.2	213	776 (liquid, 20 °C)	2.35	-	-	[6,15]
C ₁₈	28	244	774 (liquid, 70 °C)	2.40	0.15	-	[6,20]
C ₁₉	32	222	782 (solid)	2.45	-	-	[6,9]
C ₂₀	36.7	246	779	2.50	-	-	[6]
C ₁₆ H ₃₄	18.25	236	770 (solid)	2.30	-	-	[9]
C ₁₇ H ₃₆	22.05	214	775 (solid)	2.35	-	-	[9]
C ₁₈ H ₃₈	20.8–21.7	171–172	760 (liquid)	2.35	-	-	[15]
	28.25	244	779 (solid)	2.40	-	-	[9]
CH ₃ COOH	28	200	774 (liquid)	2.14	0.358	0.148	[15]
	17	192	1049	2.05	-	-	[6]
CH ₃ (CH ₂) ₁₀ COOH	16.7	184	-	-	-	-	[6]
	42–44	178	-	-	-	0.147	[9]
CH ₃ (CH ₂) ₈ COOH	32	152.7	878 (liquid, 45 °C)	1.80	0.153	-	[15]
	36	152	0.88	1.80	-	-	[6]
	30.1	153	878 (solid)	1.79	0.16	0.16	[9]
CH ₃ (CH ₂) ₆ COOH	29.62	139.77	0.89	1.79	-	-	[30]
	16.1	144.2	0.910	2.30	-	-	[30]
	16	148.5	-	-	-	0.149	[9]
CH ₃ (CH ₂) ₁₀ COOH	42.4	186.4	0.871	1.75	-	-	[30,31]
C ₂₁ H ₄₂ O ₂	14–18	140–142	-	-	-	-	[9]
C ₂₂ H ₄₄ O ₂	19	140	760 (liquid)	2.0	-	-	[15]
	18–23	123–200	872 (liquid)	2.25	0.21	-	[15]
C ₂₀ H ₃₈ O ₂	27–29	122	-	-	-	-	[17]
C ₁₂ H ₂₂ O ₄	19	140	-	-	-	-	[9]
C ₂₁ H ₄₂ O ₂ S	21	143	-	-	-	-	[9]
C ₃₆ H ₆₀ O ₂	21.9	201	-	-	-	-	[9]
C ₂₀ H ₄₀ O ₂ S	26	90	-	-	-	-	[9]
C ₂₀ H ₃₈ O ₂	27–29	122	-	-	-	-	[9]
SN ₂₇	27	192.6	1.53 (solid),	1.9–2.2	1.05	0.58	[9]
			1.71 (liquid)				
BioPCM-Q21	21	225.6	235 (s)	2.0–2.3	0.21	0.19	[9]
PEG	22	127	1126 (l)	2.30	-	0.189	[15]
E600H(OC ₂ H ₅) _n -OH	20–25	146	-	-	-	-	[6]

2.3. Composite PCMs

Single inorganic or organic PCMs have their bottlenecks and limitations in facility agriculture applications. To overcome the inherent shortcomings of single PCMs, researchers have been exploring composite PCMs consisting of two or more PCMs combined in a certain proportion [32–34]. The advantages of both are combined in composite PCMs, expanding the application range of PCMs [35]. However, these composite PCMs also face challenges, e.g., material leakage, low latent heat, high cost, a lack of thermophysical data, and limited heat material properties, requiring further explorations by researchers. Table 3 lists the thermophysical properties of some composite materials.

Zou et al. [36] prepared a shape-stabilized composite PCM (SSCPCM) by utilizing $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ as the PCM, titanium-dioxide-modified expanded graphite as the supporting material, and strontium chloride hexahydrate as the nucleating agent. This composite PCM, designed for root temperature control in low-temperature plants, exhibited a phase transition temperature of 10.67 °C, an enthalpy value of 88.39 J/g, good thermal stability, and a thermal conductivity of 8.831 W/(m·K). Dong et al. [37] prepared a composite PCM by adding NH_4Cl and KCl into CaCl_2 . This composite PCM had a PCLH value of 149.6 kJ/kg and a melting point of 24.2 °C, approximately 5 °C lower than that of pure CaCl_2 . Praveen et al. [38] added 0.5%, 1%, and 3% graphene nanosheets to paraffin-based phase change capsules (PCCs), increasing the thermal conductivity from 0.192 W/(m·K) to 0.211 W/(m·K) and 0.37 W/(m·K), respectively. Karaman et al. [39] developed a new shape-stabilized PCM by combining polyethylene glycol (PEG) with diatomite. This composite PCM exhibited a melting point of 27.70 °C and a PCLH value of 87.09 J/g. The test showed that the composite PCM possessed excellent thermal reliability and chemical stability, making it a good prospect for application as a thermal storage material in the outside walls of greenhouses.

Table 3. Thermophysical properties of composite PCMs.

Composite PCM	Phase Transition Temperature (°C)	Phase Change Latent Heat (kJ/kg)	Density (kg/m ³)	Specific Heat (kJ/kg·K)	Thermal Conductivity (W/m·K)	Reference
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} + 80\% \text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O} + 6\% \text{KCl}$	23.89	183.25	1900	2.10	0.143	[40]
$\text{CaCl}_2 \cdot 6\text{H}_2\text{O} + \text{NH}_4\text{Cl} + \text{KCl}$	24.2	149.6	1500–1700	1.5–2.5	0.5–0.6	[37]
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} + \text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O} + \text{NaCl}$	23	156.7	-	-	-	[41]
40% $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O} + 60\% \text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$	27.3	220.2	-	-	-	[16]
70% $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O} + \text{CH}_3(\text{CH}_2)_8\text{COOH}$	33	168.8	-	-	0.468 (15 °C)	[33]
$\text{CaCl}_2 \cdot 6\text{H}_2\text{O} + \text{SrCl}_2 \cdot 6\text{H}_2\text{O} + \text{TiO}_2 + \text{EG}$	10.67	88.39	-	-	8.831	[36]
$\text{C}_{18} + \text{C}_{21}$	25.8–26	173.93	-	-	-	[15]
$\text{C}_{18} + \text{C}_{22}$	25.5–27	203.80	-	-	-	[15]
$\text{CH}_3(\text{CH}_2)_8\text{COOH} + \text{C}_{12}\text{H}_{24}\text{O}_2$	18	120	-	-	0.143	[15]
	21	143	-	-	-	[15]
75.2% $\text{CH}_3(\text{CH}_2)_8\text{COOH} + 24.8\% \text{C}_{16}\text{H}_{32}\text{O}_2$	22.1	153	-	-	-	[15]
$\text{CaCl}_2 \cdot 6\text{H}_2\text{O} + \text{CaBr}_2 \cdot 6\text{H}_2\text{O}$	14.7	140	-	-	-	[15]
$\text{C}_{14}\text{H}_{28}\text{O}_2 + \text{C}_{10}\text{H}_{20}\text{O}_2$	24	147.7	-	-	-	[15]
$\text{CaCl}_2 + \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$	25	95	-	-	-	[15]
75% $\text{CaCl}_2 \cdot 6\text{H}_2\text{O} + 25\% \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$	21.4	102.3	1590	-	-	[16]
66% $\text{CaCl}_2 \cdot 6\text{H}_2\text{O} + 33\% \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$	25	127	-	-	-	[16]
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} - \text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O} + \text{EV}$	23.98	110.3	-	-	0.192	[35]
67% $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O} + 33\% \text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	30	136	-	-	-	[16]
$\text{CH}_3\text{CONH}_2 + \text{NH}_2\text{CONH}_2$	27	163	-	-	-	[15]
RT25-RT30	26.6	232	785	2.2	0.19 (solid) 0.18 (liquid)	[9]
Triethylolethane + urea	29.8	218	-	-	-	[16]
Triethylolethane + water + urea	13.4	160	-	-	-	[9]
$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O} + \text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	30	136	-	-	-	[16]
45% $\text{Ca}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O} + 55\% \text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	25	130	-	-	-	[16]
$\text{CH}_3\text{COONa} \cdot 3\text{H}_2\text{O} + \text{NH}_2\text{CONH}_2$	30	200.5	-	-	-	[15]

3. Encapsulation and Utilization Methods for PCMs

Due to some issues, like leakage and corrosion, PCMs are often encapsulated before being used in certain application scenarios in facility agriculture. According to the encapsulation methods and usage forms of PCMs, they can be mainly divided into three types: (i) macro-encapsulated PCMs, (ii) shape-stabilized PCMs, and (iii) phase change capsules (PCCs).

3.1. Macro-Encapsulated PCMs

Macro-encapsulated PCMs involve enclosing PCMs in containers of specific shapes (panels, bags, tubes, barrels, etc.). Containers are mainly used to engage in active and passive heat exchange with the external environment, to store and release heat energy. This approach possesses benefits like straightforward construction and easy usability, making it the most widely utilized encapsulation form for PCMs at present, as shown in Figure 1. Lorach-Massana et al. [42,43] used RT18 with a phase transition temperature of 17 °C as a PCM. They chose a PCM in low-density polyethylene bags with a circumference of 200 mm and a thickness of 150 µm, as illustrated in Figure 2a. They analyzed how the PCM's position within the bag influenced the heat storage performance, validating the observation that PCMs have good application prospects in facility agriculture. Chen et al. [44] sealed a PCM in black aluminum foil bags, as displayed in Figure 2b. In the daytime, solar energy was stored in heat collectors with these bags, and in the nighttime, the thermal storage units were placed in the greenhouse to maintain the temperature by releasing heat. Arkar et al. [45] designed spherical thermal storage containers using RT20 as a PCM combined with a mechanical ventilation system. Through experimental research and numerical simulations, they analyzed and compared the thermal comfort of the greenhouse under mechanical ventilation, nighttime cooling, and natural cooling modes. Kong et al. [46] created PCM panels by encapsulating a capric acid and dodecanol (CADE) mixture between two aluminum plates, as shown in Figure 2c. These PCM panels were used on the outer and inner faces of greenhouse walls/roofs. The results revealed that using PCM panels on the inner surfaces significantly reduced the peak temperatures inside the greenhouses. Beyhan et al. [26] utilized a mixture of 40% oleic acid and 60% capric acid as the PCM, encapsulating it in plastic containers measuring 0.16 m × 0.10 m × 0.03 m. They developed an RZTCS for plants using PCMs and tested the growth conditions of zucchini and peppers. The results indicated that the PCM-based temperature control system created better growth conditions, enhancing the quality and yield of the plants. Benli et al. [47] employed $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ as a PCM with a melting temperature range of 32–45 °C and a melting latent heat value of 190 kJ/kg. They encapsulated the PCM in a cylindrical plastic can for use as a seasonal thermal storage unit for greenhouse heating. Table 4 lists the direct use of PCMs.

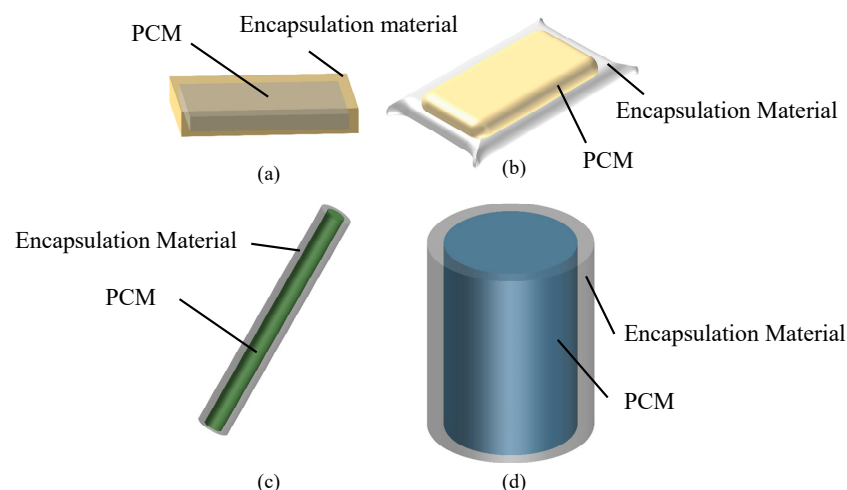


Figure 1. (a) Panel; (b) Bag; (c) Tube; (d) Cylindrical container.

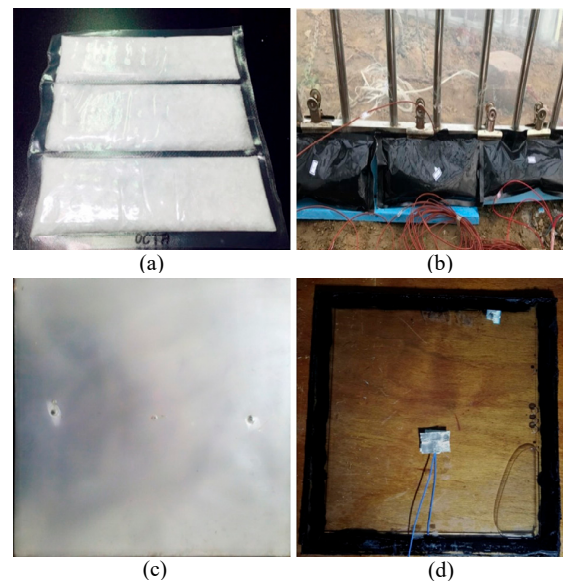


Figure 2. (a) Nylon packaging bags, reprinted with permission from Ref. [48], 2016, Energy and Buildings; (b) Black aluminum foil bags, reprinted with permission from Ref. [44], 2020, Applied Energy; (c) PCM panels, reprinted with permission from Ref. [46], 2013, Energy and Buildings; (d) PCM glass, reprinted with permission from Ref. [49], 2018, Energy and Buildings.

Table 4. Direct utilization of PCMs.

PCM	Encapsulation Form	Size and Appearance	Reference
N-octadecane (C18)	Nylon packing tape encapsulation	The nylon bag is divided into three compartments, each containing 60 g of PCMs	[48]
Paraffin waxes (RT18HC)	Tubular low-density polyethylene (LDPE) bag	Tubular LDPE bags with a circumference of 200 mm and a thickness of 150 μ m	[42]
Eutectic PCMs consisting of 70% paraffin waxes, 22% fatty acid, and 8% tetradecanol	Black aluminum foil bag	88 cm $\times$ 60 cm $\times$ 10 cm	[44]
A mixture of CADE	PCM panel	Size 10 cm $\times$ 10 cm $\times$ 0.1 cm	[46]
A mixture of 40% oleic acid and 60% capric acid	Rectangular container	0.16 m $\times$ 0.10 m $\times$ 0.03 m	[26]
CaCl ₂ ·6H ₂ O	Cylindrical plastic cans	Diameter of 800 mm, length of 1500 mm	[47]
PCM 1, PCM 2 and PCM 3	PCM-filled glass units	500 mm $\times$ 450 mm $\times$ 4 mm	[49]
Paraffin waxes (RT18)	Hong capsule construction steel	30 cm $\times$ 17 cm $\times$ 2.8 mm Thickness of 0.75 mm	[50]

3.2. Shape-Stabilized PCMs

PCMs need to be encapsulated in practical use to avoid leakage and the corrosion of other components in energy storage systems, which increases the thermal resistance between the heat source and the PCMs, reduces the heat transfer rate, and increases the preparation cost [51]. Shape-stabilized PCMs consist of PCMs and supporting substances. When PCMs undergo a transition from a solid to a liquid state, supporting substances can prevent the leakage of liquid PCMs, allowing composite materials to keep their solid shapes. Therefore, they are called shape-stabilized PCMs. Shape-stabilized PCMs offer several benefits, including a high specific surface area, no need for encapsulation, and the ability to be molded into any shape [52]. Hence, in recent years, shape-stabilized PCMs have seen substantial development for applications in building energy efficiency, air conditioning systems, solar thermal technology, and thermal regulation. The complete preparation of SSCPCMs typically involves two main steps: First, the PCMs are mixed with supporting materials to obtain a preliminary SSCPCM. Second, the SSCPCM is

compacted and surface-coated to enhance its stability. There are many methods for preparing shape-stabilized PCMs, with adsorption, blending, and sol-gel methods commonly used for facility agriculture applications.

The adsorption method involves adsorbing liquid PCMs into porous carriers with high specific surface areas and rich pore structures, depending on the high adsorption rate of porous carriers to achieve a high general heat storage capacity for shape-stabilized PCM. Common porous carriers mainly include inorganic non-metallic minerals and porous carbon materials. Vacuum impregnation is frequently used in the adsorption method. Compared to natural impregnation, vacuum impregnation can adsorb more PCMs, thereby increasing the impregnation rate. Zhong et al. [53] incorporated liquid C18 into expanded vermiculite and expanded perlite to prepare SSCPCMs with vacuum impregnation, maintaining a high PCLH value (142 J/g, 132.2 J/g) and original phase transition temperature (26.2 °C, 26.1 °C). Xu et al. [54] employed vacuum impregnation to impregnate molten paraffin waxes into expanded vermiculite. The paraffin wax/expanded vermiculite SSCPCM had a melting phase transition temperature of 27.0 °C and a PCLH value of 77.6 J/g. Karaman et al. [39] prepared an SSCPCM by integrating PEG into the pores of diatomaceous earth via vacuum impregnation. The SSCPCM had a phase transition temperature of 27.70 °C and a PCLH value of 87.09 J/g. Scanning electron microscopy revealed that the PEG was fully dispersed into the pores of the diatomaceous earth, serving as the supporting material. Karaipekli et al. [55,56] chose a eutectic mixture of capric acid and myristic acid as the PCM and utilized silica and expanded perlite as supporting materials, using vacuum impregnation to prepare an SSCPCM. They determined that the SSCPCM with expanded perlite as the supporting material demonstrated superior heat storage capability by comparison.

There are two types of blending: solution blending and melt blending. Melt blending involves using high-melting-point materials such as high-density polyethylene, low-density polyethylene, polypropylene, and polyurethane as the supporting materials for composite PCM systems. Under high-temperature conditions, low-melting-point PCMs and high-melting-point supporting materials are heated to a molten state. Next, the two materials are mixed uniformly to form a thick liquid. Finally, the mixture is cooled into a shape-stabilized PCM. Wang et al. [57] used PEG as the PCM and expanded graphite, activated carbon, and ordered mesoporous carbon as supporting materials. They prepared three types of shape-stabilized PCMs possessing different pore structures with physical blending and impregnation methods. The results indicated that micron-scale pores provided the same shape stability as nano-scale pores while minimizing the phase change enthalpy loss caused by interactions between the pores and the PEG chains.

In the sol-gel method for producing shape-stabilized PCMs, a chemically active substance is first selected as a precursor to be dissolved in a solvent to create a homogeneous solution, and the pH value of this solution is modified using the corresponding acid and alkaline solution according to the need. Next, the PCMs are adequately mixed with the homogeneous solution, allowing the substances in the mixture to undergo hydrolysis and condensation reactions to create a sol system. Next, the sol system is washed with distilled water or ethanol, followed by evaporation and drying. The aggregation between colloidal particles forms a shape-stabilized colloidal network filled with PCM. Wang et al. [58] utilized the sol-gel method to develop an innovative ternary shape-stabilized material consisting of paraffin wax, epoxy resin, and expanded graphite. First, pure paraffin wax was heated to a liquid state. Next, 6% expanded graphite was added to the liquid paraffin wax. The mixture was stirred with a homogenizer for 0.5 h before adding epoxy resin to form a stable epoxy resin-paraffin-expanded graphite emulsion. Finally, the emulsion was left in a high-temperature environment for 24 h to form a shape-stabilized PCM.

3.3. Phase Change Capsules (PCCs)

Microencapsulation is a technology that involves coating or surrounding polymer materials on the surfaces of PCMs to create capsules ranging from micrometers to millimeters

in size [59]. These capsules can be divided into nano-capsules ($<1\ \mu\text{m}$), micro-capsules ($1\text{--}1000\ \mu\text{m}$), and macro-capsules ($>1000\ \mu\text{m}$), according to the particle size. PCCs consist of two primary components: the PCM as the core material and a polymer or inorganic material as the shell material, as shown in Figure 3. These manufactured PCCs can vary in shape (e.g., spherical, tubular, elliptical, irregular, etc.) [60] and exhibit diverse structures (e.g., single-core, multi-core, multilayer, etc.), as shown in Figure 4. PCCs are extensively employed in latent heat storage systems because of their ability to prevent reactions between PCMs and the external environment, avoid PCM leakage, and regulate the volume changes of PCMs during phase transition [60–62]. However, the main issue of PCCs is the limited rate of heat transfer caused by the low thermal conductivity of the phase change core material [63]. The methods for preparing PCCs are categorized into three primary groups: physical, chemical, and physical–chemical methods [59]. The chemical techniques include in situ polymerization, interfacial polymerization, suspension polymerization, emulsion polymerization, etc. The physical techniques include spray drying and solvent evaporation, while the physical–chemical techniques contain sol–gel and coacervation [64]. When choosing a method for preparing PCCs, the characteristics of the core material, cost, and desired capsule performance should be comprehensively considered. Table 5 lists the applicable preparation methods for organic and inorganic PCMs. Table 6 summarizes the preparation methods, particle morphology, and thermal properties of various PCMs.

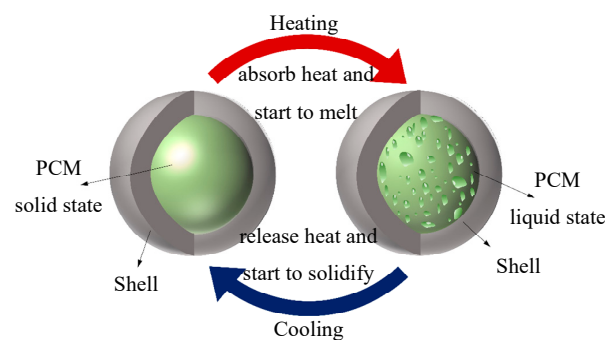


Figure 3. Principle diagram of phase change microcapsules.



Figure 4. Schematic diagram of phase change microcapsules.

Table 5. Unsuitable cases in the classification of microcapsule preparation methods.

	Method	Organic	Inorganic
Chemical	Suspension polymerization	Suitable	Unsuitable
Physical–chemical	Coacervation	Suitable	Unsuitable
Physical	Spray drying	Suitable	Unsuitable

In situ polymerization uses the phase change core material as the dispersed phase. All the monomers and initiators are added to the continuous phase or dissolved in the dispersed phase along with PCMs. First, the monomers are pre-polymerized under appropriate conditions, and once the pre-polymer reaches a specific size, it is deposited on the core material's surface, forming a durable microcapsule system [65,66], as shown in Figure 5a. In situ polymerization has advantages such as good chemical and thermal stability, uniform morphology and coating, and the ability to produce at nano/micro scales. However, it requires high costs and technical expertise. Fang et al. [67] prepared a nano-PCC using n-tetradecane as the core material through in situ polymerization. The

shells were formed by the polymerization of urea and formaldehyde. Sodium dodecyl sulfate was utilized as the emulsifier, while resorcinol served as the system modifier. The nano-PCC had a diameter of approximately 100 nm and displayed regular spherical shapes in scanning electron microscope (SEM) images. The core material was effectively encapsulated, with an n-tetradecane mass fraction of up to 60% and a melting PCLH value of 134.16 kJ/kg. Zhang et al. [68] created PCMs with paraffin waxes and C18 as PCMs, using cellulose-nanocrystal-stabilized Pickering emulsions as templates. In order to produce materials, using in situ polymerization, PCCs with melamine formaldehyde resin shells were prepared. These capsules had an adjustable thickness and a diameter of 4 μm .

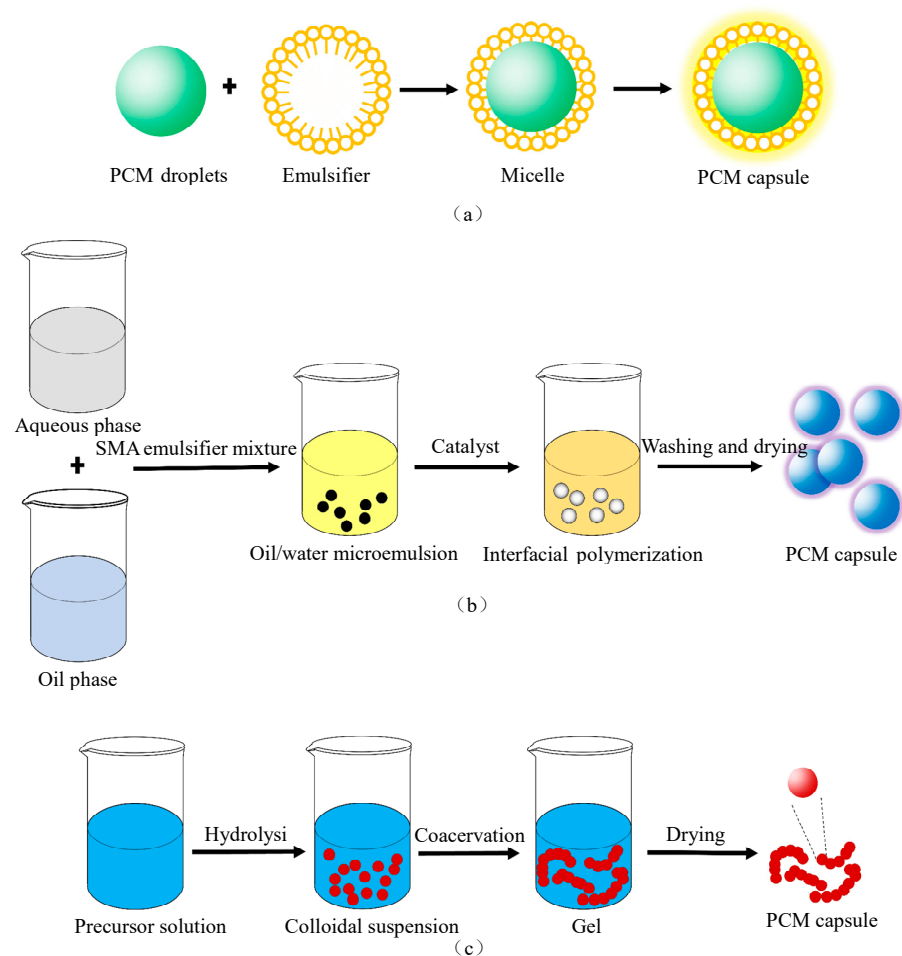


Figure 5. Schematic diagram of phase change capsule (PCC) preparation methods: (a) In situ polymerization method; (b) Interfacial polymerization method; (c) Sol-gel method.

Interfacial polymerization should feature the selection of an appropriate emulsifier to emulsify PCMs first, forming an oil/water emulsion. Monomers are then polymerized to form a polymer film on the core material's surface, thus creating capsules. Finally, the capsules are separated, as shown in Figure 5b. This method can be performed at room temperature and offers advantages like simplicity and effectiveness. However, it requires high-quality wall materials, and the prepared microcapsules may contain small amounts of unreacted monomers. Additionally, the polymer film formed by interfacial polymerization has high permeability, which is unsuitable for encapsulating core materials with strict requirements. Yan et al. [69] used n-eicosane as the PCM, polyurea as the shell, Pickering emulsion as the template, and sulfonated lignin as the emulsifier. They used the interfacial polymerization method to prepare a PCC, and this capsule displayed a regular spherical shape, high phase change enthalpy (209.8 J/g), a high encapsulation rate (82.9%), and excellent thermal cycle stability.

The sol–gel method involves uniformly dispersing a precursor in a solvent and mixing it evenly with catalysts and binders. Subsequently, hydrolysis and condensation reactions occur, leading to the creation of a stable and clear sol system. Next, the sol ages to form a gel with a continuous three-dimensional network structure. Finally, the gel is dried and sintered to produce micro/nano-scale capsule materials [65,70], as shown in Figure 5c. Fang et al. [71] utilized the sol–gel technique to create PCCs encased in a SiO₂ shell. With an encapsulation efficiency of 87.5%, these capsules exhibited a solidification PCLH value of 107.05 kJ/kg and a melting latent heat of 165.68 kJ/kg. Additionally, it was observed that the SiO₂ shell improved the thermal stability of the capsules, which was attributed to the synergistic interaction between the paraffin waxes and SiO₂. Chen et al. [72] employed the sol–gel method to prepare phase change microcapsules using stearic acid as the PCM and SiO₂ as the shell material. The SiO₂ shell not only improved thermal stability, but also reduced the flammability of the stearic acid PCCs.

The coacervation method can be simple or complex. Simple coacervation is achieved through the interaction between the dissolved polymers and low molecular substances. Complex coacervation involves first dispersing phase change core materials into an aqueous polymer solution to create an emulsion, and then depositing shell materials onto the phase change core material by adding a second aqueous polymer solution and adding salt, or by changing the pH value, temperature, or dilution medium. Finally, PCCs are stabilized through the processes of cross-linking, desolvation, or heat treatment [60]. Hawlader et al. [62] employed the complex coacervation method to prepare a PCC with paraffin wax as the core material and gelatin/arabic gum as the shell material. The PCC they prepared could store and release high levels of energy (145–240 J/g).

Table 6. Preparation of microcapsules.

PCM	Preparation Method	Size and Appearance	Heat Property	Reference
N-tetradecane–urea and formaldehyde polymerization	In situ polymerization	Particle size is about 100 nm	Melting latent heat of 134.16 kJ/kg, with a high mass fraction of 60%	[67]
Paraffin wax and C18–melamine formaldehyde resin	In situ polymerization	Diameter is 4 µm	Phase change enthalpies of paraffin wax and C18 microcapsules are as high as 164.8 and 185.1 J/g, respectively, corresponding to core material contents of 87.0% and 84.3%	[68]
63% capric acid and 37% palmitic acid–melamine formaldehyde	In situ polymerization	Spherical, smooth, and evenly distributed	Encapsulation efficiency is approximately 75.2%; the melting point is 36.1 °C, the melting latent heat is 106.2 kJ/kg	[66]
N-eicosane–polyurea	Interfacial polymerization	Good and intact spherical shape	The encapsulation ratio is 82.9%; the melting latent heat is 209.8 kJ/kg The encapsulation rate of paraffin wax is 87.5%; microencapsulated paraffin	[69]
Paraffin wax–SiO ₂ dioxide	Sol–gel	ME PCM size is about 8–15 µm	composite material solidifies at 58.27 °C with a PCLH value of 107.05 kJ/kg, and melts at 58.37 °C, with a PCLH value of 165.68 kJ/kg	[71]
Stearic acid–SiO ₂ dioxide	Sol–gel	PCM size is 20–30 µm	The encapsulation rate is 90.7%; microencapsulated SA melts at 53.5 °C, with a PCLH value of 171.0 kJ/kg, and solidifies at 52.6 °C, with a PCLH value of 162.0 kJ/kg	[72]
Eutectic mixture of capric acid and stearic acid–silica	Self-templating method	Regular spherical particles with dense surfaces	The phase transition temperature and PCLH values are 21.4 °C and 91.48 J/g, respectively	[70]
Paraffin wax–gelatin/gum arabic	Coacervation and spray drying	Microcapsules are spherical with a relatively uniform structure	Microcapsules have high energy storage and release capabilities (145–240 J/g)	[62]

4. Applications of PCMs

Using PCMs has achieved some progress in facility agriculture. The forms of application can be divided into the passive PCHS system and the active PCHS system, depending on whether the process for utilizing PCMs is carried out with or without the aid of external equipment. The passive PCHS system directly absorbs heat by melting PCMs and releases heat during the cooling process to regulate the temperature of facilities, operating independently of external drives. In the active PCHS system, heat energy is transferred from the heat source to the application facility through pipework, using air or water as the intermediate medium. This system offers greater flexibility in storing excess or waste heat energy. Figure 6 shows two application examples of PCM storage in agriculture.

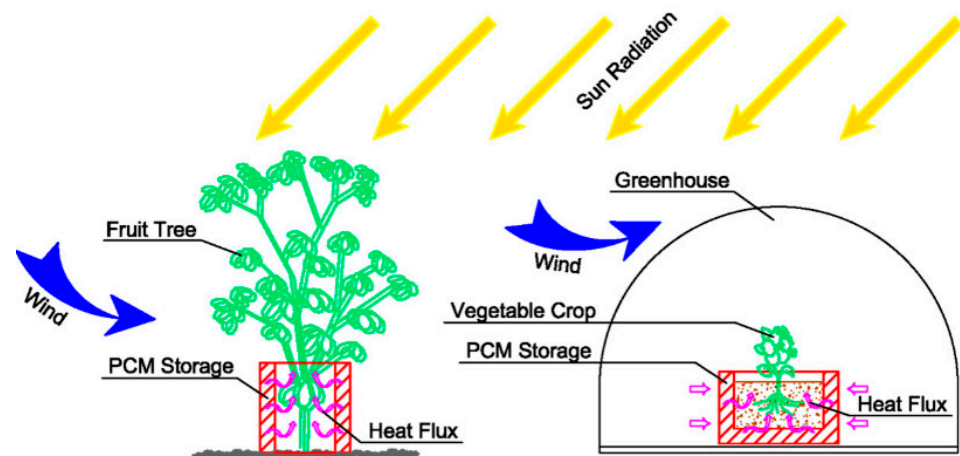


Figure 6. PCM-based concept for the protection of free-standing fruit trees (left) and potted plants in greenhouses (right) [73].

4.1. Passive PCHS System

In the passive PCHS system, PCMs are combined with enclosure structures and soils or placed in agricultural facilities, utilizing the heat storage/release properties of PCMs to achieve facility temperature control, which includes two main forms: phase change walls (PCWs) and phase change heat storage (PCHS) units.

4.1.1. Phase Change Walls (PCWs)

A PCW is a composite wall made by adding PCMs into wall materials, using the heat storage capacity of PCMs to collect solar radiation in the daytime and release heat energy in the nighttime. The PCW transfers heat energy to agricultural facilities through natural convection and radiation [11,74–77]. Berroug et al. [11] employed $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ as a PCM incorporated into the north wall of a greenhouse. This setup increased the temperature of plants and internal air by 2–4 °C and the nighttime covering temperature by 4–5 °C using a 6 cm thick PCM north wall. Additionally, compared to a traditional greenhouse, the greenhouse with PCWs experienced a reduction in relative humidity of 10–15%. Wang et al. [78] investigated the insertion of paraffin waxes into greenhouse walls for passive heating and conducted dynamic simulations of the greenhouse's indoor temperature self-regulation throughout the day. The results indicated that the insertion of PCM layers into enclosure structures decreased the high temperature during the day and increased the indoor temperature by about 1–2 °C at night by releasing heat energy into the room. Ling et al. [79] prepared prefabricated wall panels made from a mixture of paraffin waxes, graphite, high-density polyethylene, and cement mortar. Numerical simulation studies revealed that the thermophysical properties of the PCMs during the heat storage/release phases significantly impacted the thermal performance of the PCM walls. Kalbasi et al. [80] found that incorporating PCM into building walls significantly

reduced electricity demand and natural gas consumption, with the electricity demand decreasing by 62.6%, the natural gas consumption by 34.7%, and the annual energy consumption of the HVAC system by 39.1%.

4.1.2. Phase Change Heat Storage Units

In a passive PCHS system, PCHS units serve as containers encapsulating PCMs and are suspended or directly placed in agricultural facilities. Due to their flexibility, convenience, and low cost, PCHS units are widely used in greenhouses and other agricultural facilities [42,81,82]. Chen et al. [44] sealed a eutectic PCM composed of 70% paraffin waxes, 22% fatty acids, and 8% tetradecanol in aluminum bags and suspended it inside a greenhouse. This PCM used solar heat energy absorbed in the daytime to heat the greenhouse in the nighttime. Beyhan et al. [26] developed a passive RZTCS based on PCHS units for soil-less agriculture greenhouses. They added either 100% oleic acid or a 40% oleic acid + 60% capric acid mixture to plastic containers. The nighttime root zone temperature increased by up to approximately 2.4 °C with the use of PCHS units. Jiang et al. [83] used $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ as a PCM, which was encapsulated in PVC plastic bags. Compared with a reference greenhouse, they found that adding 45 kg of PCM could reduce the highest greenhouse temperature by 3 °C and increase the morning temperature by 4 °C. Bao Lingling et al. [84] used $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ - $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ as a composite PCM, encapsulated it in polyethylene plastic bags, and attached it to the inner side of the greenhouse's rear wall. With sufficient sunshine, the indoor maximum temperature decreased by 1.6–3.1 °C, the indoor minimum temperature increased by 1.7–2.7 °C, and the soil temperature increased by 0.3–1.4 °C.

4.1.3. Challenges and Future Works

While passive PCHS systems have shown promise, key challenges remain. The low thermal conductivity of PCMs limits heat transfer rates, resulting in delayed temperature regulation and, consequently, impacts the overall system performance [85–87]. Additionally, repeated phase change cycles can degrade the long-term stability of PCMs, reducing performance over time. Integrating PCMs into walls or storage units also presents engineering hurdles, including material compatibility, insulation efficiency, and potential leakage during phase transitions. The high costs of advanced PCMs and encapsulation techniques further restrict their broader use [88], especially in resource-constrained agricultural settings.

Future work should focus on incorporating high-thermal-conductivity materials, such as graphene [38,89] and copper nanoparticles [90], into PCMs, while also exploring the use of metal foams [91,92], and fin structures in heat storage units [93–95] to enhance heat transfer. Elsihy et al. [96] demonstrated that fin optimization in a vertical double-tube latent heat storage system significantly enhances melting and solidification efficiency. Furthermore, adjusting the inner tube eccentricity in a double-tube system offers another approach to increasing thermal energy storage efficiency [89]. Advances in encapsulation are also necessary to ensure long-term durability and prevent leakage. Developing hybrid systems that combine PCMs with other heating solutions could improve flexibility and efficiency. Reducing costs through more affordable PCM composites will be crucial for wider adoption. Finally, field trials are needed to assess the real-world performance of passive PCHS systems under various climatic conditions.

4.2. Active PCHS Systems

The active PCHS system relies on external equipment, such as pumps [97] and fans to drive its operation. It typically uses working fluids for heat exchange and transfer, making it more complex than a passive PCHS system. However, it offers greater flexibility and can be used for multiple purposes, including drying and heating. Common active PCHS systems include shell-and-tube heat exchangers and packed-bed heat exchangers. In shell-and-tube heat exchangers, PCMs are directly filled into the containers, and the heat transfer fluid exchanges heat with the PCMs of heat storage units by flowing

through pipes that penetrate the container to store and release heat energy [12,27,29,98]. However, in packed-bed heat exchangers, PCMs are first encapsulated in the form of PCCs and then placed in the heat storage unit in a packed bed form [99–102]. Based on the heat source, active PCHS systems can be divided into solar-heated, geothermal-heated, and other-source-heated systems. Figure 7 shows the application of PCM in active PCHS systems.

4.2.1. Solar Heat Source Active PCHS Systems

Among the active PCHS systems utilized in agricultural facilities, those with solar heat sources are the most extensively used and researched [12,103]. When solar energy is captured by the collector, it can be either directly transferred to agricultural facilities for use or stored in PCHS modules as thermal energy. The stored heat energy can then be released and utilized when solar radiation is insufficient [98,104–106]. Azaizia et al. [29] designed a heat storage solar greenhouse dryer consisting of two solar air heaters (SAH) and a PCHS unit filled with paraffin waxes in cylindrical aluminum cans. During the day, hot air from the SAHs flew through the heat storage unit, storing some of the heat, which was then transferred to the greenhouse air at night through natural convection. The results indicated that the greenhouse air temperature with the PCHS unit was about 7.5 °C higher than that of the common greenhouse at night, reducing the drying time of peppers from 4 days to 2 days. Kooli et al. [99] designed an SAH with a packed PCHS system, maintaining the greenhouse temperature at 15 °C when the external temperature was as low as 8 °C. Baddadi et al. [100] built an SAH with a packed-bed PCHS system using $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ as the PCC. This system maintained daytime and nighttime temperatures in the greenhouse above 32 °C and 15 °C, respectively. Bouadila et al. [101] studied the heat energy recovery efficiency of an SAH coupled with a packed-bed PCHS system, showing that it could store 56% of excess daytime heat and provide 30% of nighttime heating energy for the greenhouse. Khadraoui et al. [107] designed a solar dryer equipped with a packed-bed PCHS system, which successfully kept the drying chamber temperature 4–6 °C higher and the relative humidity 17–34.5% lower than that of the external environment at night.

4.2.2. Geothermal Heat Source Active PCHS Systems

In addition to solar energy, geothermal energy can also serve as a heat source in agricultural facilities. Ground source heat pump (GSHP) systems are the primary means of geothermal energy extraction. Benli and Durmus [47] designed a GSHP greenhouse heating system that includes PCHS and compared it with an air source heat pump system. Benli [108] tested the energy efficiency parameters of a GSHP greenhouse heating system incorporating PCHS, and the coefficients of the performance of the GSHP ranged from 2.3 to 3.8. When the GSHP increased the greenhouse temperature by 5–10 °C, the auxiliary heat energy provided by the PCMs could further increase the temperature by 1–3 °C.

4.2.3. Other Heat Source Active PCHS Systems

In addition to solar and geothermal energy, other waste heat resources can serve as heat sources for active PCHS systems. Andrews et al. [109] investigated the technical and economic feasibility of using industrial waste heat for greenhouse heating, presenting a case study that combined flat glass manufacturing with commercial greenhouses. Yan et al. [13] proposed a waste heat recovery system based on PCMs for greenhouses using fossil fuels, which improved energy efficiency by 33% and reduced fossil fuel consumption by 48%. Furthermore, Yan et al. [110] applied this system to greenhouse auxiliary heating and burner air preheating, demonstrating that burner air preheating with this system resulted in higher overall system efficiency compared to direct greenhouse heating. Table 7 lists the applications of various PCMs.

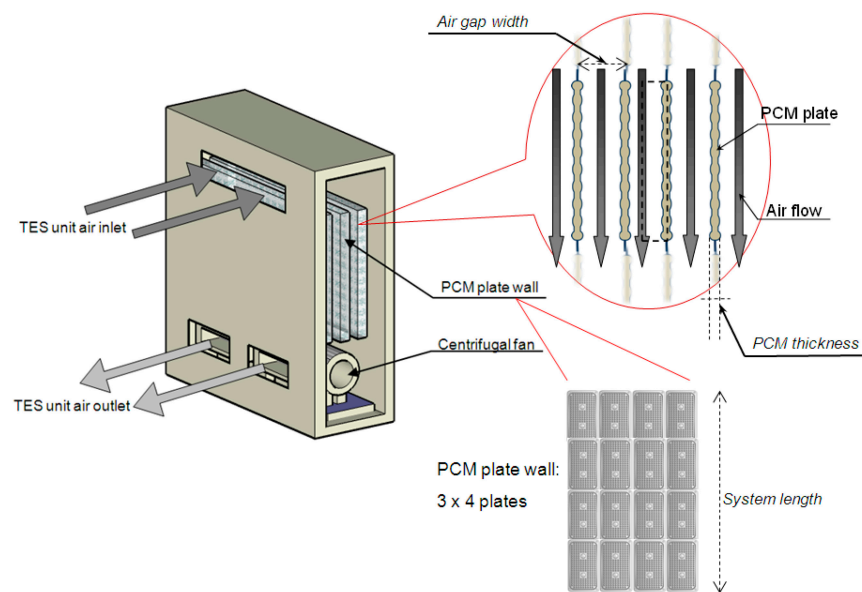


Figure 7. Thermal energy system unit schematic view and PCM plate layout detail (air flowing through the plates) [111].

Table 7. Applications of PCMs.

PCM	Encapsulation and Utilization Method	Application	Crop	Method	Reference
CaCl ₂ ·6H ₂ O	Macro-encapsulated PCM	PCW	Plant	Numerical simulation	[11]
Paraffin wax, graphite, high-density polyethylene, cement mortar	Shape-stabilized PCM	PCW	Vegetable	Physical experiment; numerical model; matrix laboratory	[79]
Paraffin wax	Macro-encapsulated PCM	PCW	Plant	Physical experiment and numerical simulation	[78]
Paraffin wax (RT18H)	Macro-encapsulated PCM	PCHS unit	Tomato	Physical experiment	[42]
A mixture of 40% oleic acid and 60% capric acid	Macro-encapsulated PCM	PCHS unit	Zucchini and pepper	Field measurement	[26]
Cobalt chloride automatic regulation for sunshade protection to prevent overheating	Macro-encapsulated PCM	PCHS unit	Shade-loving plant	DSC measurement	[112]
CaCl ₂ ·6H ₂ O	Macro-encapsulated PCM	PCHS unit	Plant	Physical experiment	[12]
TH29, PCM 21, PCM 17		PCW	None	Mathematical model, Java code program	[113]
Butyl stearate	Macro-encapsulated PCM	PCW	Spinach	Model and physical experiment	[27]
Sodium acetate hydrate	Macro-encapsulated PCM	Active PCHS systems with other heat sources	Cucumber	Model and physical experiment	[13]
Commercial salt hydrate PCM (S19)	Macro-encapsulated PCM	Active PCHS systems with geothermal energy sources	Tomato	Theoretical model	[114]
Capsule (AC27)	PCC	Active PCHS systems with solar energy sources	Tomato	Physical experiment	[99]
CaCl ₂ ·6H ₂ O	PCC	Active PCHS systems with solar energy sources	Plant	Physical experiment	[100]
Paraffin wax	Macro-encapsulated PCM	Active PCHS systems with solar energy sources	Pepper	Physical experiment	[29]

4.2.4. Challenges and Future Works

Active PCHS systems face unique challenges due to their dependence on external equipment like pumps and fans, which increase complexity, energy use, and maintenance needs. Ensuring the reliable operation of these mechanical components over time is crucial, as failures can disrupt agricultural processes. Achieving efficient heat transfer and uniform distribution within PCMs, especially in large-scale systems, remains difficult. Additionally, high initial costs, particularly for systems integrating renewable energy sources, limit the broader adoption of these systems.

Future work should focus on improving control strategies for the more efficient operation of external equipment and enhancing heat distribution within PCMs. Simplifying system design to reduce mechanical complexity without sacrificing efficiency can lower costs and improve reliability. Research into cost-effective integration with renewable energy and field testing across various climates will help optimize these systems for agricultural use.

4.3. Applications of PCMs in Buildings

By absorbing and releasing latent heat to regulate temperature, PCMs play a crucial role in reducing energy consumption in the buildings related to facility agriculture while ensuring a comfortable indoor climate [92]. Consequently, their application in the building sector has attracted significant research interest [115]. Much like their use in facility agriculture, PCHS systems in buildings can be classified into two primary types: passive and active.

4.3.1. Passive PCHS Systems in Buildings

Passive PCHS systems primarily rely on the natural temperature fluctuations of PCMs to store and release heat and are typically integrated into the walls, roofs, or floors of buildings [116]. These systems require no additional mechanical equipment or energy input, making them simple to operate and cost-effective. Figure 8 shows the integration of PCM with building envelope structure. In one study, Figueiredo et al. [117] added PCMs to the floor mortar of one test unit and used another as a control. The results showed that the application of PCMs reduced the temperature amplitude by an average of 21%. Additionally, Jia et al. [118] demonstrated that incorporating PCMs into recycled aggregate concrete not only improved workability, but also reduced water absorption. The research by Mano et al. [119] illustrated that integrating PCMs containing 10% graphite into roof structures could effectively enhance the thermal efficiency of buildings and reduce cooling demands. Through numerical simulations, Mahdaoui et al. [120] confirmed that integrating PCMs into hollow bricks can improve thermal performance, reduce temperature fluctuations, and stabilize temperatures within the thermal comfort range. Iqbal et al. [121] investigated a form-stable thermal storage brick composed of C18, phosphogypsum, kaolin clay, and cement. The results demonstrated that the novel brick significantly extended the thermal lag time and provided superior temperature control. Finally, Mourida et al. [122] conducted experiments with wallboard-type PCMs in residential buildings in Casablanca, and the results showed a significant increase in indoor nighttime temperatures and a reduction in heating energy consumption by approximately 20%. Similarly positive results were observed in studies involving gypsum boards modified with microencapsulated PCMs [123], and in studies on the optimization of walls and roofs with integrated PCMs [124].

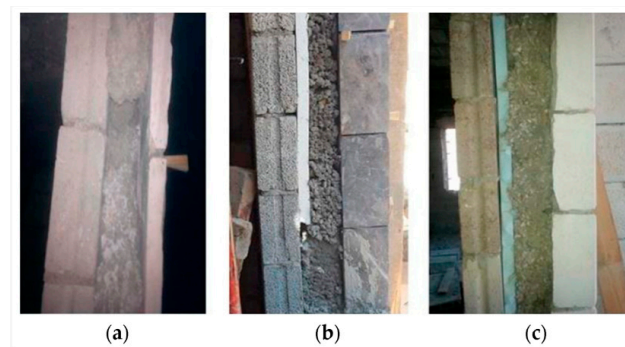


Figure 8. Real examples of constructed walls in residential buildings in Amman, Jordan. (a) Uninsulated wall; (b) Poorly insulated wall; (c) Fully insulated wall [125].

4.3.2. Active PCHS System in Buildings

Active PCHS systems are utilized by integrating mechanical equipment, with air or water serving as the medium to transfer heat from PCMs to different areas of the building. These systems offer more precise temperature regulation and can be adapted to diverse building requirements and external environments. PCMs are widely applied in various active PCHS systems within buildings, such as heating, ventilation, and air conditioning [80,126–128], solar collection systems [129–132], and floor heating and cooling [133]. Their use effectively maintains indoor temperature stability and significantly reduces energy consumption. Manirathnam et al. [131] performed a comparative analysis on an all-glass vacuum-tube solar water heater with and without PCMs, finding that the energy efficiency increased by 13% when PCMs were included. Jiao et al. [134] studied a novel scheme that combines air source heat pumps with passive heating systems to improve heating efficiency in cold regions. The scheme, which integrates a passive solar room and PCMs for heat storage and release, resulted in a system power consumption of 36.96 kWh, which is 66.88% lower than with traditional heat pump heating. Pathak et al. [132] developed a novel U-type vacuum-tube solar collector filled with PCMs (stearic acid) and compared its performance with a collector without energy storage materials. Prakash et al. [135], designed a novel hybrid photovoltaic evaporator using aluminum-foil-encapsulated hydrated salts (HS36) as the PCM, showing potential for realizing zero-energy buildings. Table 8 provides recommended PCM applications for passive and active PCHS systems in agricultural facilities and buildings.

Table 8. Recommended PCMs for passive and active PCHS systems in agricultural facilities and buildings.

PCM	Application	Type	Recommendation
$\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	PCWs	Passive PCHS (Buildings)	Effective for greenhouse walls and temperature regulation [11]
Paraffin wax	PCWs	Passive PCHS (Buildings)	Widely used for moderate thermal performance and compatibility with building materials [78,79]
Paraffin wax + fatty acids	PCHS units	Passive PCHS (Agriculture)	Suitable for greenhouses and improving indoor temperature control [44]
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	PCHS units	Passive PCHS (Agriculture)	High latent heat for consistent temperature regulation in greenhouses [83,84]
Paraffin wax + graphite	Solar heat source	Active PCHS (Buildings, Agriculture)	Enhanced thermal conductivity for heat storage in solar systems [79]
S19	Geothermal heat source PCHS	Active PCHS (Agriculture)	Effective for geothermal systems with high heat storage capacity [114]
Stearic acid	Solar collection systems	Active PCHS (Buildings)	Reliable for solar-based heating systems, especially in agricultural facilities [132]
HS36	Hybrid photovoltaic evaporator	Active PCHS (Buildings)	Ideal for zero-energy buildings with advanced integration [135]

4.3.3. Challenges and Future Works

A key challenge in using PCMs in construction is their limited effectiveness in varying climates. Many PCMs are optimized for narrow temperature ranges, making them less effective in regions with significant temperature fluctuations. Additionally, the lack of standardized guidelines for PCM integration in building materials complicates their adoption, as builders lack clear benchmarks for performance and safety. Design constraints also pose challenges, as incorporating PCMs without compromising the aesthetic and structural integrity of buildings can be difficult.

Future work should focus on developing adaptive PCMs that can perform across a broader range of temperatures, ensuring consistent efficiency in diverse climates. Establishing industry standards for PCM use in construction is essential to streamline adoption. Research into thin, flexible PCM materials that can be seamlessly integrated with modern building designs, as well as 3D-printed PCM composites, could offer innovative solutions. Long-term performance monitoring of PCM-integrated structures will also be crucial to assess durability and real-world effectiveness.

5. Conclusions and Outlook

Energy-saving and consumption-reduction technologies in facility agriculture and related buildings are crucial for promoting a green and low-carbon transformation and upgrade. PCHS technology shows promising application prospects in solar energy utilization, greenhouse walls, soil insulation, and other areas of facility agriculture, with its high heat storage density and excellent temperature regulation capability. This review first introduced the main types and thermophysical properties of PCMs and analyzed forms of PCMs suitable for facility agriculture and related buildings, as well as their preparation methods. From the perspectives of active and passive PCHS systems, it then introduced the application of PCMs in facility agriculture and related buildings. Although significant progress has been made in the research into PCMs in agricultural facilities, there is still considerable room for improvement due to the inherent shortcomings of PCMs and the current development level of PCHS technology.

Future development efforts should focus on several key areas. First, the development of PCMs that are more suited to facility agriculture and related buildings, considering factors such as phase transition temperature, biocompatibility, etc. Additionally, improving the heat storage density and thermal conductivity of PCMs should be a priority. The development of composite PCMs with enhanced mechanical and heat transfer properties will also be crucial, as will expanding the application of shape-stabilized PCMs and phase change microcapsules in facility agriculture and related buildings. Second, optimizing PCHS systems specifically for facility agriculture and related buildings is necessary. This includes exploring the integration of active and passive PCHS systems, strengthening research on energy conversion and efficiency improvement technologies, and further expanding the application scope of PCHS systems in these settings. Finally, the integration of information technology into PCHS systems within facility agriculture should be enhanced. Advanced technologies, such as artificial intelligence and active disturbance rejection control, can be employed to enable precise forecasting and rapid adjustment of PCHS systems. These developments would raise the intelligence level of indoor environmental control systems in facility agriculture and related buildings.

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