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Controllable Supercooling in Phase Change Materials-Advances in Triggering Methods, Lab-Scale Investigations, and Prototype Demonstrations

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Abstract: Supercooled Phase Change Materials (PCMs) offer significant advantages for thermal energy storage by enabling latent heat retention over extended periods with minimal loss. However, controlling crystallization in supercooled states remains a critical challenge for practical applications. This review provides a comprehensive analysis of lab-scale experimental studies on controllable supercooling in PCMs, categorized by triggering methods such as local cooling, mechanical agitation, bubble injection, electric and ultrasonic fields, mechanical shock, and cold crystallisation. Furthermore, the transition of these control techniques into physical prototypes is discussed, highlighting operational challenges and integration issues observed in heat pads, thermal batteries, battery preheating systems, and long-term thermal energy storage units. Despite substantial progress, scaling up supercooled PCM systems introduces new barriers, including premature crystallization, inconsistent triggering, and material degradation. Addressing these challenges through prototype-scale research is critical to achieving reliable, cost-effective thermal energy storage solutions utilising supercooled PCMs as controllable thermal energy storage.

Keywords: supercooled PCMs, controllable, triggering, prototype

1 Introduction

Phase Change Materials (PCMs) have appeared as fundamental components in thermal energy storage, owing to their unique ability to absorb, store, and release thermal energy during phase changes between solid and liquid states. These materials operate on the principle of latent heat or changing in phase allowing them to maintain a nearly constant temperature during energy absorption and release, making them ideal for various applications that require efficient and controlled thermal management (Bien, 2021; Fu *et al.*, 2024). In general, PCMs can be categorized based on their applicability into short to long-term thermal energy storage solutions (Brief, 2013).

In short-term applications, they effectively manage thermal fluctuations, providing instantaneous thermal comfort and optimizing energy usage during peak demand periods which is highly beneficial in addressing the intermittent nature of renewable energy resources. In addition, this is particularly advantageous in buildings where PCMs can enhance the thermal inertia of the structure, reducing reliance on traditional heating and cooling systems in passive cooling strategy (Jha *et al.*, 2024). On the other hand, the use of PCM storage for buffer tank in domestic hot water system is an example how PCM thermal energy storage is applicable in active cooling system. For long term energy storage, PCMs play a crucial role in stabilizing temperature variations over extended periods. PCMs can store excess thermal energy generated during peak sunlight hours for use during the cooler months, thus facilitating energy conservation and enhancing the sustainability of solar thermal systems (Brief, 2013; Song *et al.*, 2023).

The versatility and effectiveness of PCMs in short, mid, and long-term thermal energy storage frameworks underscore their significance in advancing green heating and cooling. As the development of new PCM formulations continues, these materials are expected to perform as key catalyst to play a critical role in future energy systems, promoting efficient thermal energy storage and intermittent renewable energy management across various applications.

1.1 Supercooling for controllable PCMs

Phase Change Materials (PCMs) is the type of materials that store and release thermal energy through phase transitions, typically between solid and liquid states. Although often considered as disadvantage, a notable feature of some PCMs is their ability to remain in a supercooled state, wherein the material exists as a liquid even below its freezing point without spontaneous crystallization (X. Shao *et al.*, 2023) called metastable state. This phenomenon enhances the potential to store latent heat over extended durations; however, it also introduces unpredictability in heat release, which compromises the efficiency and reliability of thermal energy systems that require precise thermal regulation(Xi *et al.*, 2022; Xu *et al.*, 2017).

For application whereby, controlled thermal energy released is favourable, controlling supercooling is therefore crucial, as spontaneous crystallization can cause abrupt phase transitions, leading to energy loss, reduced system efficiency, and potential operational hazards such as crack in the container. Controllable supercooling refers to the intentionally maintaining the supercooled liquid state and its crystallization which is exothermic will happen only when triggered enabling thermal energy storage systems to manage heat release with precision. The underlying mechanism is based on metastability, where the liquid state remains stable until disturbed. This behaviour is governed by thermodynamics and nucleation kinetics (Englmair *et al.*, 2018; Wei & Ohsasa, 2010). The primary advantage of such systems lies in their ability to store latent heat without premature solidification, thereby maximizing thermal energy utilization (X. Li *et al.*, 2023; Zahir *et al.*, 2022). Techniques for achieving controlled crystallization typically involve stabilizing the supercooled state and enabling latent heat release at a desired time or condition. Approaches such as nucleating agents, cavitation or bubble injection, and active triggers including mechanical, thermal, and ultrasonic have been widely reported in the literature (Beaupere *et al.*, 2018).

While theoretical models and simulations as presented by (Kutlu *et al.*, 2020; Kutlu, Zhang, *et al.*, 2023) have contributed significant insight into the behaviour of supercooled PCMs, experimental investigations and prototype testing are essential to validate these findings under real-world conditions. The transition from lab to application often reveals additional challenges, such as non-uniform crystallization, poor heat transfer, and long-term degradation of PCM performance. Despite promising advances, several implementation challenges persist. Key concerns include the repeatability and durability of triggering over many thermal cycles and the energy cost associated with activation methods. Wei & Ohsasa (2010) note that reliable cycling requires both thermal stability and resistance to degradation over time. Furthermore, the energy input required to initiate crystallization must remain minimal to ensure that the system operates efficiently (Kutlu *et al.*, 2020). Materials commonly studied for controllable supercooling include sodium acetate trihydrate, known for its significant supercooling range and use in solar thermal applications(Deng *et al.*, 2023; Xiao *et al.*, 2024) as well as other salt hydrates and organic materials such as erythritol and xylitol. Recent studies have explored methods to enhance performance, such as the integration of boron nitride nanosheets with erythritol to improve both thermal conductivity and supercooling stability (Deng *et al.*, 2023)

Controllable supercooling is promising for high-performance thermal energy storage systems. The combination of long-duration heat storage and on-demand release makes this technology attractive for a range of applications. However, realizing this potential requires effective triggering strategies, reliable cycling performance, and careful material selection.

1.2 Review article contribution

There are many review articles have been published which offer a comprehensive foundation for understanding the development and application of phase change materials (PCMs) across different scales and contexts. A review by Feng *et al.* (2022) summarizes the thermal properties of various PCMs and discusses preparation methods, addressing issues such as thermal conductivity and supercooling. The review article was designed for researchers exploring both academic and practical applications of PCMs in energy storage solutions. A group of researchers review smaller-scale PCMs and discusses strategies to enhance thermal conductivity, an important consideration for both lab-scale experiments and real-world applications (Weiss & Jha, 2023). Focusing on the materials, Thangavel *et al.* (2023) focused his review on different type of phase change materials and their applications and provide key insights into their functional characteristics across different scales of investigation.

Focusing on supercooled PCMs, Shamseddine *et al.* (2022) reviewed the supercooled state of PCMs, as a key factor in energy storage efficiency, making it relevant for understanding both laboratory investigations and full-scale applications. However, their paper focuses more on the supercooling behaviour of non-controllable PCMs which usually considered as a disadvantage in PCMs application. Also, a review article by Kumar & Banerjee (n.d.) discussed on the advantages of additive manufacturing techniques in creating PCM-based systems, bridging the gap between lab-scale prototypes and real-world applications. More on supercooling research, review by W. Li *et al.* (2024) explores sodium acetate trihydrate (SAT) as a promising PCM due to its high latent heat, safety, and cost-effectiveness. Their paper outlines SAT's challenges—most notably, supercooling, phase separation, and cycling stability. It highlights various enhancement strategies such as the use of thickeners, nucleating agents, and encapsulation techniques. The review also discusses recent applications, including SAT-based thermal batteries and seasonal storage units. The authors emphasize the need for further research on triggering mechanisms, container compatibility, and long-term reliability under fluctuating environmental conditions. Hua *et al.* (2023) provides a comprehensive review of seasonal thermal energy storage (STES) systems based on supercooled phase change materials. It highlights the advantages of PCM-based STES, particularly in balancing seasonal energy supply and demand in solar heating applications. The highlight of the review is the supercooling control, heat loss minimization, and material stability over seasons as key areas for ongoing research. Ji *et al.* (2024) reviews the stability and supercooling behaviour of PCMs, with an emphasis on inorganic PCMs such as salt hydrates. It discusses mechanisms of supercooling, such as lack of nucleation sites and surface effects, and reviews mitigation strategies including nucleating agents, ultrasonic stimulation, seeding, and encapsulation. The article also provides insights into how cycling durability, material compatibility, and trigger control affect long-term PCM use. It concludes by recommending standard testing protocols and deeper study into multi-functional PCM composites.

Although there are many review articles published in the recent 5 years on PCM as thermal energy storage, focusing on supercooled PCMs, none of the articles have focused on lab-scale and prototype-level studies of controllable supercooled PCMs. Therefore, setting it apart from the published review articles, this article aims to provide a comprehensive overview of controllable supercooled PCMs triggering method and physical prototypes demonstrating controllable supercooling in managing supercooling behaviour, exploring validated control methods, and identifying challenges in translating laboratory work into real-world applications for controllable supercooled PCMs.

2 Controllable supercooled PCMs triggering method

This section reviews experimental investigations or lab-bench testing focused on the controllable crystallization of supercooled PCMs under laboratory conditions. Studies are categorized based on the triggering method used to release latent heat on demand namely seeding, local cooling triggering, cavitation, and mechanical shocked crystallisation. These lab-scale evaluations provide insights into onset temperatures, crystallization repeatability, and energy efficiency of each technique.

2.1 Seeding

Seeding is one of the most straightforward methods to initiate nucleation in supercooled materials. It involves introducing a stable solid crystal of the same material, around which the surrounding liquid rapidly crystallizes. This structural transformation enhances system stability and releases latent heat. Due to its reproducibility and effective heat release, seeding has been widely explored in experimental studies. A key challenge in seeding is maintaining the presence of solid seed crystals while melting as the bulk PCM. This can be addressed by applying localized high pressure to selectively raise the melting point of a few particles. The relationship between pressure and nucleation temperature is described by the Clausius-Clapeyron equation, shown in Equation (1).

$$\frac{\Delta \mathbf{T_m}|_{\mathbf{p}}}{\mathbf{\Delta P}} = \mathbf{T_m}|_{\mathbf{p=0}}\, \mathbf{\Delta v/L} \tag{1}$$

In Equation (1), $\frac{\Delta \mathrm{T}_m|_p}{\Delta P}$ is the rate of change of the melting temperature with respect to pressure which determines how much the melting point increases or decreases per unit of pressure. Meanwhile, $T_m|_{p=0}$ is the melting temperature at atmospheric pressure which is often takes as 1 atm or 0 Pa in the context of pressure increase in standard conditions. Δv is the change in specific volume (volume per unit mass) between the two phases, and finally L is the latent heat of fusion (typically per unit mass), which is the amount of energy required to convert a unit mass of the material from solid to liquid at constant pressure and temperature.

According to this equation, a significant increase in pressure leads to a corresponding rise in the material's melting point. Therefore, in seeding, the increase in local pressure leads to an increase in the melting temperature in that small zone. So even if the rest of the PCM is at or above the normal melting point, that pressurized crystal won't melt because its local melting point is higher. As a result, solid region is preserved and acts as a seed crystal, allowing controllable and repeatable crystallisation of the supercooled PCMs. Among the earliest study is by Sandnes (2008) who investigated seeding mechanisms in a heat pad device. The device includes a small metal component designed with specific contact points that allow solid crystals to be trapped under high pressure, depending on the material's hardness. Seeding occurs when this metal piece is flexed, releasing the trapped crystal into the supercooled liquid. This method triggers crystallization by relieving the pressure on the solid seed crystal. The study also involved analysing various types of triggering mechanisms for controlled nucleation. Also, X. Shao *et al.* (2023) investigated the combination of seeding and agitation as a mechanism to trigger the crystallisation of eutectic phase change material xylitol/erythritol.

2.2 Local cooling triggering

The fundamental of triggering *via* local cooling is the initiation of nucleation. The initial crystal is created by reducing the temperature of the material down to its crystallisation point to create seeding. As discussed in (Englmair *et al.*, 2018), by local cooling of sodium acetate trihydrate (SAT) in liquid phase down to its crystallization temperature, heterogeneous nucleation can be initiated. Hence, it was concluded that local cooling can be introduced to initiate nucleation as long as the local temperature is reduced down to its crystallisation temperature. Among the researchers who have investigated local cooling in supercooled PCMs are Englmair *et al.* (2018) who demonstrated the potential of thermal triggering using local cooling mechanisms like CO evaporation and Peltier modules to control crystallization in SAT. Their setup as presented in Figure 1 allowed the PCM to remain supercooled until crystallization was initiated by a temperature drop in targeted zones. This localized approach enabled stable and selective triggering, showing promise for solar heating integration. However, scaling this control method, especially regarding thermal contact efficiency, remains a challenge for real-world operation and implementation.

As illustrated in Figure 1, the Peltier module was thermally connected to a steel extension pipe, which featured a hole drilled at its base. This extension pipe, filled with phase change material (PCM), was mounted directly on top of the Peltier device. An airtight seal was ensured using rubber gaskets. A steel plate was placed in contact with the lower Peltier element, serving as the interface with the extension pipe. To enhance heat transfer between the Peltier module and the steel plate, thermal compound was applied. A K-type thermocouple was positioned beneath the lower Peltier element to monitor the temperature at its cold side, which corresponded to the steel plate temperature. Above the upper Peltier element, a heat sink system was implemented, consisting of an air-cooled assembly with aluminium fins and an electrically powered fan to dissipate heat efficiently.

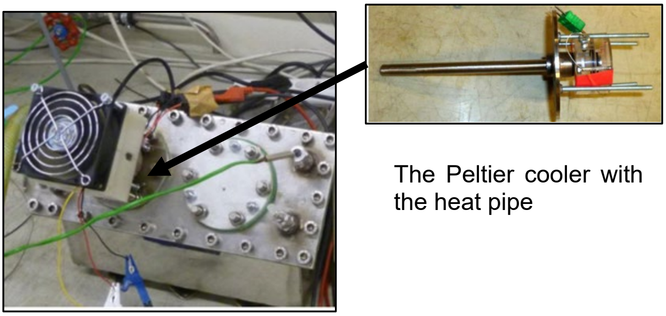


Figure 1: The installed Peltier device on the small-scale heat storage prototype-image taken from (Englmair *et al.*, 2018)

In another related study, Wang & Zhou (2021) investigated the use of local cooling based on Peltier effect to crystallise supercooled sodium acetate trihydrate (SAT, Tm = 55.7 ° C), sodium thiosulfate pentahydrate (STP, Tm = 48.9 ° C), and their binary mixtures. Phase separation, crystallization behaviour, and latent heat discharging characteristics at different mass ratios were compared and analysed. The findings show that SAT has a 2 ° C higher maximum discharging temperature than STP, with a longer induction period (39 s) and discharging time (3 h). However, STP demonstrates better cycling stability and less phase separation after repeated freezing–melting cycles. Although supercooled SAT-STP mixtures are more difficult to trigger than single-component salts, the addition of STP significantly alleviates phase separation on SAT. The eutectic mixture (mSAT:mSTP = 28:72, eutectic temperature 40.8 ° C) successfully triggers crystallization within 4 minutes, reaches a discharging peak of 39 ° C, and maintains temperatures above 30 ° C for 3.3 hours, outperforming single-component hydrates. Moreover, increasing SAT content complicates the crystallization and discharging behaviour. The induction period first increases and then decreases, with the trend in maximum discharging temperature matching the binary phase diagram. The binary mixtures also broaden the effective phase change temperature range to 30–50 ° C, making them attractive for long-term thermal storage and low-temperature heating applications. Tests with pure SAT (100 g) showed that, after full melting at 85 ° C and supercooling to 22.7 ° C, local cooling to 16 ° C triggered rapid crystallization within 111 s, releasing latent heat with a surface temperature rise to about 49 ° C, lower than the melting point due to freezing-melting hysteresis. These results are valuable for optimizing solar energy storage systems using supercooled PCMs.

2.3 Cavitation

The fundamental effects of cavitation on nucleation are not yet fully understood (Beaupère *et al.*, 2018). The collapse of bubbles in PCM may have caused a pressure fluctuation, where high pressure is generated along with temperature changes that can trigger crystal nucleation. This pressure may be sufficient to raise the melting point and, together with evaporation-induced cooling at the bubble surface, create conditions favourable for homogeneous nucleation.

2.3.1 Mechanical Agitation and Bubble injection

X. Shao *et al.* (2023) examined mechanical agitation to initiate bubble which leads to crystallization in erythritol/xylitol eutectics as shown in Figure 2 a. He showed that combining stirring with fine crystalline seeds significantly improved nucleation reliability and shortened crystallization time to as little as 1.8 minutes.

In another similar study, Hou *et al.* (2024) created a low-temperature thermal energy storage module with a bubble injection and seeding system for an erythritol/xylitol eutectic PCM. However, different from (X. F. Shao *et al.*, 2023), the influence of Multi-Walled Carbon Nanotube (MWCNT) nanoparticle additives (Figure 2b) on nucleation was explored. Their system reduced the supercooling gap to 13.7 ° C and demonstrated >90% repeatability across test cycles. Despite the strong lab performance, the prototype's scalability is constrained by challenges in gas flow control, MWCNT dispersion, and sealing durability. These issues must be resolved for deployment in industrial or building-integrated contexts.

Meanwhile, Yang *et al.* (2022) proposed a method involving the injection of gas bubbles into subcooled liquid erythritol. In their research, Nù56ù bubbles as shown in Figure 2c, were injected into erythritol through the 304 stainless steel vent pipes in the whole heating and cooling process at a room temperature of about 25° C. The researchers claimed that the proposed technique was found to successfully reduced the supercooling degree to just 5 ° C, outperforming traditional methods like adding nucleating agents or using ultrasonication. Additionally, it significantly increased the latent heat of crystallization by nearly 50%, from 218.2 kJ/kg to 322.3 kJ/kg. By adjusting the timing of bubble injection, crystallization can be actively and controllably triggered at different points. This bubble injection method offers a highly efficient, scalable, and cost-effective solution for mitigating supercooling in erythritol and potentially in other PCMs for thermal energy storage applications.

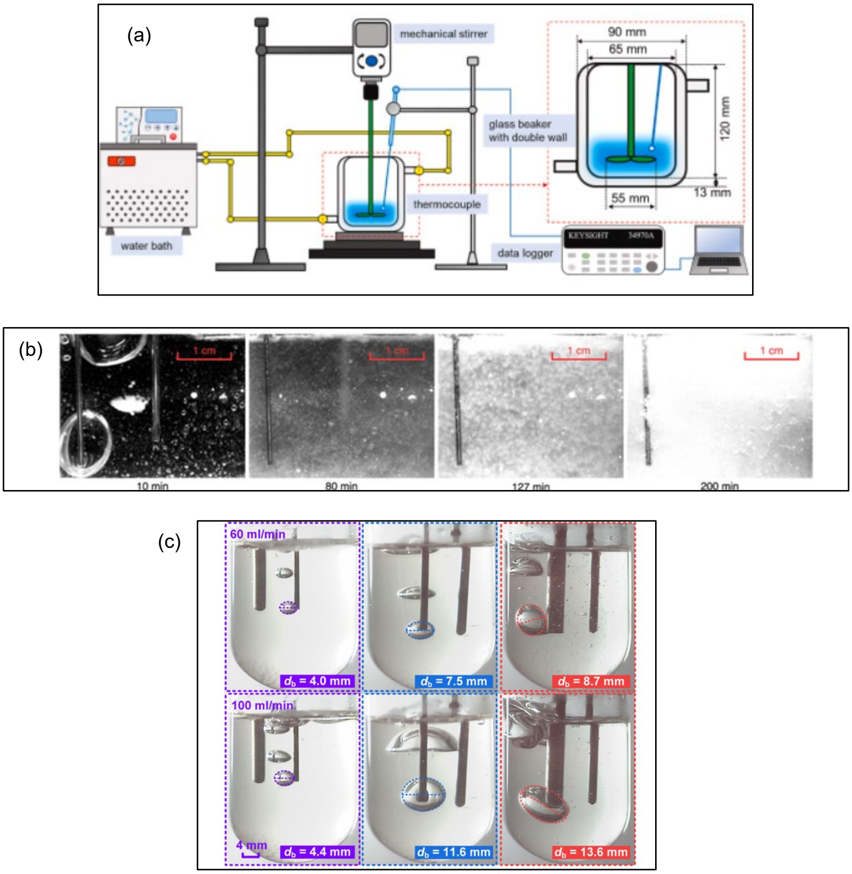
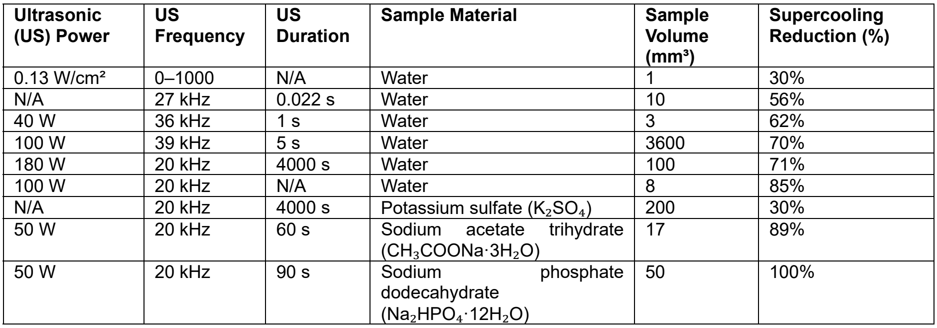


Figure 2: (a) The mechanical agitation technique by (X. Shao *et al.*, 2023) (b) bubble injection technique by Hou *et al.* (2023) and (c)N^{56} injection at different diameters by (Yang *et al.*, 2022)

2.3.2 Electric and Ultrasonic Triggering

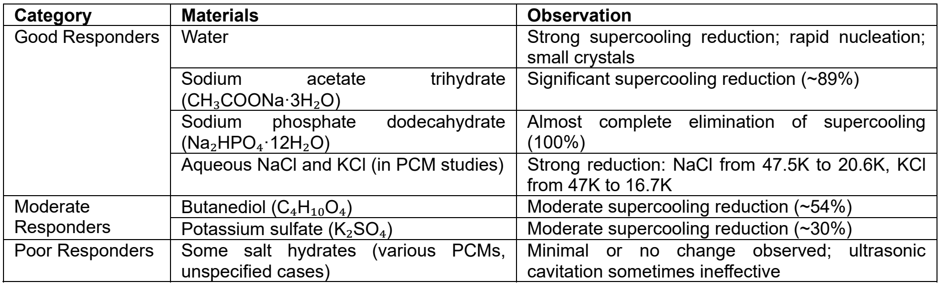
Ultrasonic irradiation is an effective method for triggering crystallization by inducing cavitation of which the formation and collapse of bubbles that generate localized high-pressure and low-pressure zones. Based on the fundamentals of cavitation, when these bubbles collapse, they can initiate nucleation by rapidly changing the pressure around the supercooled material. Studies show that ultrasonic power, sonication duration, solvent type, sample volume, and the number of cavitation bubbles significantly affect the success of nucleation (Beaupere *et al.*, 2018).Higher ultrasonic power and longer exposure reduce the supercooling degree and crystal size, while a standard frequency of 20 kHz often yields the best results. It has been observed that nucleation tends to occur precisely where the cavitation bubble collapses. Using levitating bubbles under ultrasonic fields further enables homogeneous nucleation without interference from container walls, leading to even more controlled and efficient crystallization. Immersed ultrasonic probes were found to be more effective than external transducers because they deliver higher energy directly into the sample. However, not all materials respond equally well; some PCMs show minimal or no supercooling reduction with sonication. Overall, ultrasonic irradiation significantly improves nucleation behaviour by shortening induction time, reducing particle size, and promoting rapid, uniform crystal formation. By referring to (Beaupere *et al.*, 2018) as summarised in Table 1 and Table 2, ultrasonic irradiation has been tested on a variety of materials, mainly focusing on water, salt hydrates, and sugar alcohols.

Figure 3: The performance of ultrasonic triggering samples from (Beaupere *et al.*, 2018)



Ultrasonic (US) Power	**US Frequency**	**US Duration**	**Sample Material**	**Sample Volume (mm³)**	**Supercooling Reduction (%)**
0.13 W/cm²	0–1000	N/A	Water	1	30%
N/A	27 kHz	0.022 s	Water	10	56%
40 W	36 kHz	1 s	Water	3	62%
100 W	39 kHz	5 s	Water	3600	70%
180 W	20 kHz	4000 s	Water	100	71%
100 W	20 kHz	N/A	Water	8	85%
N/A	20 kHz	4000 s	Potassium sulfate (K_2SO_4)	200	30%
50 W	20 kHz	60 s	Sodium acetate trihydrate ($CH_3COONa \cdot 3H_2O$)	17	89%
50 W	20 kHz	90 s	Sodium phosphate dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$)	50	100%

Figure 4: Different types of material and observation from (Beaupere *et al.*, 2018)



Category	**Materials**	**Observation**
Good Responders	Water	Strong supercooling reduction; rapid nucleation; small crystals
	Sodium acetate trihydrate ($CH_3COONa \cdot 3H_2O$)	Significant supercooling reduction (~89%)
	Sodium phosphate dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$)	Almost complete elimination of supercooling (100%)
	Aqueous NaCl and KCl (in PCM studies)	Strong reduction: NaCl from 47.5K to 20.6K, KCl from 47K to 16.7K
Moderate Responders	Butanediol ($C_4H_{10}O_4$)	Moderate supercooling reduction (~54%)
	Potassium sulfate (K_2SO_4)	Moderate supercooling reduction (~30%)
Poor Responders	Some salt hydrates (various PCMs, unspecified cases)	Minimal or no change observed; ultrasonic cavitation sometimes ineffective

Meanwhile, for electrical mechanisms, among the researchers who investigate the triggering mechanism are Dong *et al.* (2024) and Chen *et al.* (2023) who applying low-voltage fields (1.0–1.5 V) to crystallize supercooled SAT composites. Dong *et al.* demonstrated sub-second triggering (0.5 s) with dendritic growth observed, while Chen *et al.* achieved stable control over 100 cycles using structured electrodes. Despite these advances, surface degradation and electrode oxidation over time present challenges to durability. Earlier, Hozumi *et al.* (n.d.) explored ultrasound and electric fields as alternative triggers. These methods hold promise for non-contact, rapid activation, but suffer from limited reproducibility and lack of field validation. Also, Kutlu, Su, *et al.* (2023) investigate the controlled crystallization of supercooled SAT.

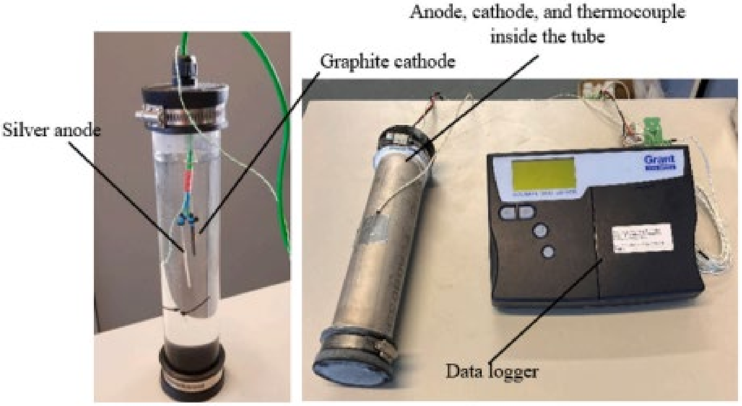


Figure 5: CM triggering tube sample investigated in (Kutlu, Su, *et al.*, 2023)

To conduct the research, electrical triggering device consisting of two electrodes was fabricated. Various electrode materials were considered; however, the combination of a graphite cathode (–) and a silver anode (+) was selected for the triggering experiments. In ensuring successful nucleation, the silver anode required surface preparation to allow the formation of a thin SAT powder layer, which acts as a nucleation site. The surface treatment involved sequential polishing of the anode using grit sandpapers, with SAT powder dusted onto the surface after each polishing step. Following polishing, the silver electrode was immersed in a 75 ° C sodium acetate trihydrate solution for two hours to remove any residual powder. The prepared triggering device as shown in fig. 3, along with a K-type thermocouple, was inserted into a stainless-steel tube filled with molten SAT maintained at 75 ° C. The tube was then sealed at both ends to prevent leakage and allowed to cool naturally to room temperature. Once the PCM temperature reached approximately 30 ° C, a voltage of 9 V was applied across the electrodes. Upon activation, nucleation was successfully triggered, and the PCM temperature rose sharply from 29.5 ° C to 57 ° C.

2.4 Mechanical shocked crystallisation

Young (1911) conducted the first study in 1911 on nucleation induced by mechanical shock, investigating the combined effects of stirring and impact stress, as reported in (Beaupere *et al.*, 2018). Their experiments involved several materials, including water, benzene, and calcium chloride hexahydrate as PCM. After cooling the samples to the target temperature, a hammer was dropped with a specified energy to trigger crystallization, and the minimum degree of supercooling required for nucleation was recorded. It was found that an increase in shock strength corresponded to a decrease in the supercooling temperature.

In a related study, Zhou *et al.* (2018), investigated percussion vibration applied to supercooled SAT within sealed units. In their study, crystallization onset was initiated through mechanical vibration. They found that the crystallisation varied depending on the vibration mass and impact location, with induction times as short as 2–5 seconds. While these techniques highlight the feasibility of mechanically induced triggering, repeatability, energy efficiency, and system integration remain a challenge particularly for larger storage units requiring automated or distributed control.

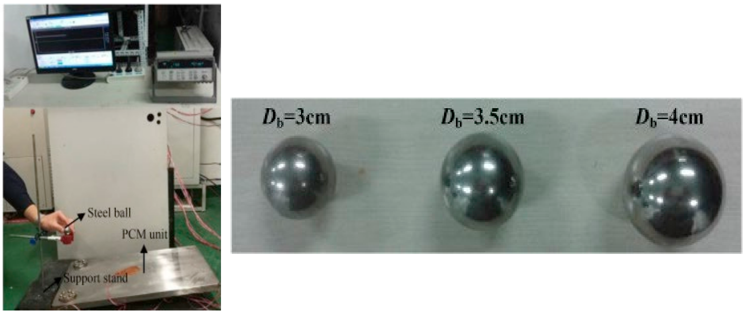


Figure 6: Percussion vibration apparatus used to Click or tap here to enter text.create vibration to agitate the PCM in initiating crystallisation by Zhou *et al.* (2018).

2.5 Synthesis of findings

Seeding remains the most common and practical method for initiating crystallization in supercooled PCMs. As summarized in Table 3, local cooling methods, such as CO injection and Peltier cooling, provide stable control but face challenges in scalability and system integration. Mechanical agitation, including nano-assisted nucleation and seeding, effectively reduces crystallization time, although repeatability and consistency under practical conditions remain concerns. Bubble injection techniques, using MWCNTs or nitrogen, significantly reduce supercooling gaps and improve energy storage stability, but their reliability under varying loads needs further validation. Mechanical shock triggering achieves rapid crystallization but introduces challenges in durability and consistent activation. Electric and ultrasonic methods offer fast, contactless triggering, though electrode degradation and long-term stability must be addressed. Overall, while laboratory successes are encouraging, further work is needed to ensure reliable, energy-efficient, and scalable triggering mechanisms for real-world applications of controllable supercooled PCMs.

Table 1: Lab-Scale Experiments on Supercooled PCMs categorised based on triggering method

Type of triggering	**Supercooled PCMs**	**Trigger Method**	**Key Results**	**Gap Identified**	**The fundamental mechanism**	**Reference**
Local cooling	Sodium acetate trihydrate	CO_2 + Peltier cooling	Stable, localized control of supercooling	Needs scalability and modular validation	Temperature was brought down to crystallisation temperature	Englmair et al. (2018)
	Sodium acetate trihydrate and sodium thiosulfate pentahydrate	Peltier cooling	Tests with pure SAT (100 g) at supercooling of 22.7 °C, local cooling to 16 °C triggered rapid crystallization within 111 s, releasing latent heat with a surface temperature rise to about 49 °C			Wang & Zhou (2021)
Mechanical agitation	Erythritol + nano-Al_2O_3	Nano-assisted nucleation	Improved wetting and crystallization performance	Field applicability not validated	Cavitation - pressure variation effect when the bubble collapsed.	Yuan et al. (2021)
Mechanical agitation	Erythritol/Xylitol	Agitation with seeding	Crystallization time reduced from 43.3 to 1.8 min	Repeatability and consistency still limited		Shao et al. (2023)
Bubble injection	Erythritol/Xylitol	MWCNT + bubble injection	Solidification enthalpy = 203.1 J/g, stable over 100 cycles Supercooling reduced by 39.35 °C; enthalpy increased by 50 J/g	MWCNT loading impact under scaling not fully studied		Hou et al. (2023)
Bubble injection	Erythritol	Nitrogen bubble injection	Reduced supercooling to 5°C; crystallization triggered on demand	Variable load and cooling rate effects need study		Yang et al. (2022)
Mechanical shock	SAT	Percussion vibration in sealed module	Induction time varies with ball size/position; 2–5 s typical	Triggering consistency and vibration placement critical. Repeatability decreases at lower rpm; mechanical wear concerns	Vibrations help to refine crystalline particles.	Zhou et al
Electric and ultrasonic	Water	Ultrasonic waves (45 kHz)	Triggered crystallization observed in controlled conditions	Requires PCM-specific testing	By inducing cavitation.	Hozumi et al. (2002)
	SAT with Copper Foam/EG	Electric (1.5V DC)	Trigger in <5s; enhanced thermal conductivity Triggered crystallization within 5–10 s; stable over 100 cycles	Balance between conductivity and supercooling Surface degradation and potential electrode oxidation	Local crystallization induced at the anode via electric field and surface-seeded nucleation	Dong et al. (2024)
Electrical triggering	Sodium acetate trihydrate SAT/ carboxymethyl cellulose (CMC)/EG	Electric using structured electrodes	Stable over 100 cycles, <10s induction time	Electrode oxidation over cycles		Chen et al. (2023)
	Sodium acetate trihydrate (SAT)	Electrical activation using graphite cathode and silver anode with surface-treated silver electrode to create nucleation site	Successful nucleation triggered at ~30 °C temperature rose from 29.5 °C to 57 °C upon 9V activation	Surface treatment steps are complex; long-term electrode performance and reusability not explored		Kutlu, Su, et al., 2023

3 Physical Prototypes Demonstrating Controllable Supercooled PCMs

While lab-scale experiments have yielded promising control strategies for supercooled PCMs, their transition into real-world devices remains essential for validating practical feasibility. This section highlights physical prototypes and systems that demonstrate on-demand crystallization control in supercooled PCMs. These include heat pads, thermal batteries, energy storage modules, and integrated electronics cooling systems. Each prototype displays unique trigger mechanisms and material combinations, offering insights into performance under operational conditions and exposing challenges in reliability, scale-up, and design integration.

3.1 Heat Pad Systems

The earliest and most widely recognized example of a physical supercooled PCM prototype is the commercial heat pad, typically filled with SAT (Sandnes, 2008). Sandnes (2008) investigated the physics and chemistry behind these pads, where a manual disk flex releases trapped crystalline seeds to trigger instantaneous crystallization. These pads demonstrate fast, repeatable thermal response and user activation, making them ideal for personal heating applications. However, their reliability depends on consistent seed preservation and user handling, limiting their suitability for automated or large-scale systems.

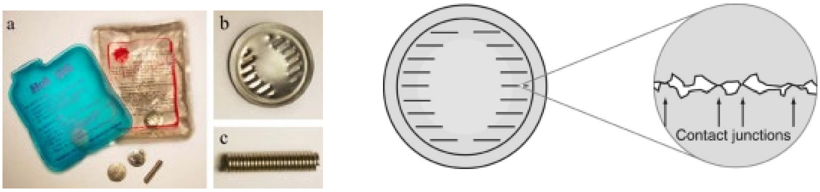
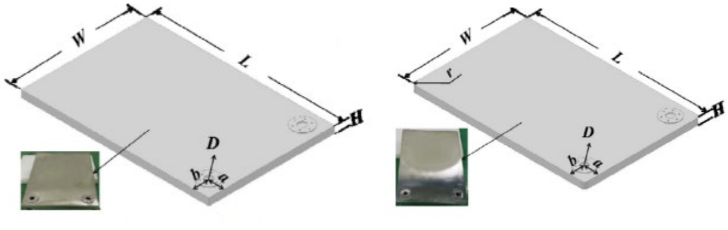


Figure 7: A microscopic view of the opposing slit surfaces of the disk trigger. The local pressure at the contact junctions depends on the plastic yield hardness of the substrate(Sandnes, 2008)

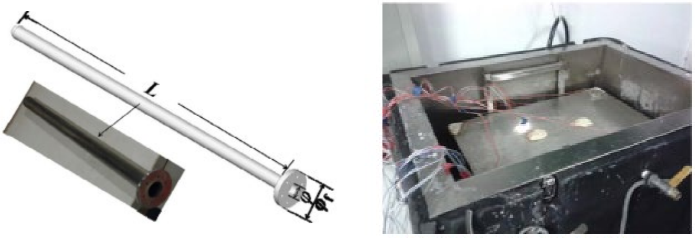
3.2 Thermal Battery Units for Buildings

As previously discussed in 2.2, Englmair *et al.* (2018) developed a segmented flat-panel thermal battery using SAT with controllable supercooling achieved through CO injection and Peltier cooling. Stable supercooling was maintained in up to 220 kg of SAT-based PCM, allowing for selective crystallization to improve energy management in solar heating systems. Each prototype heat storage unit measured 240 × 120 × 5 cm and contained 200–220 kg of SAT composite. In six experimental trials the SAT composites remained in a stable supercooled state at ambient temperatures (20 ° C) until crystallization was initiated. This was done by evaporating CO in a 100 mL chamber positioned adjacent to the supercooled PCM compartment. Liquid CO was supplied from a cylinder with a dip tube, connected *via* rubber tubing to the CO chamber. A pressure-regulating valve with a manometer maintained the CO at around 5.5 bars to keep it in liquid form within the system. They have concluded that, crystallization of SAT composites in heat storage units could be reliably triggered using two controlled local cooling methods. One involved evaporating carbon dioxide in a nearby chamber, while the other used Peltier elements mounted directly on the PCM chamber. Both methods successfully lowered the temperature enough to initiate crystallization once the SAT-water mixtures had supercooled below 30 ° C. In each case, crystallization began quickly—within two to five minutes after cooling started.

Zhou *et al.* (2017) developed and tested three types of stainless-steel thermal storage prototypes using SAT as the phase change material: sharp rectangular, rounded rectangular, and cylindrical units. Each sharp and rounded rectangular unit was filled with about 5.5 kg of SAT, while the cylindrical unit contained about 0.5 kg. All units were placed horizontally to minimize phase separation. Among them, the rounded rectangular unit, with smooth inner surfaces and curved edges, showed the best balance between stable supercooling, heat transfer efficiency, and practical manufacturability. Experiments showed that stable supercooling was achieved more easily in rounded rectangular and cylindrical units with longer charging times (up to 11 hours). Lower cooling rates, smoother surfaces, and small additions of carboxymethyl cellulose (CMC, 1.5%) further improved stability, while higher CMC content (3%) caused spontaneous crystallization. SAT-water mixtures with mass ratios of 3:2, 1:1, and 2:3 also maintained stable supercooling, although a higher water content slightly reduced storage capacity. Their findings provide useful guidance for designing reliable supercooled PCM-based solar thermal storage systems, underscoring the need for precise material control and geometry design. However, sensor-based automation and multi-unit modularity remain challenges for wide-scale adoption in a large-scale building-integrated application.



(b) Sharp rectangular unit (a) Rounded rectangular unit



(d) Cylindrical unit (c) In the framework tank

Figure 8: The prototype in three different configurations and installed in the tank (Zhou & Xiang, 2017)

3.3 Electrically Triggered Preheating in Batteries

Lu *et al.* (2024) developed a novel electrically controlled crystallization electrode (ECE-CCH) using calcium chloride hexahydrate (CCH) to achieve smart thermal management for lithium-ion batteries (LIBs) at low temperatures. A melting-solidification method was used to embed CCH crystals into a silver electrode, creating a device that can trigger the crystallization of supercooled CCH using a low DC voltage (1.0–1.5 V) within just 5 seconds, releasing latent heat on demand. A 48 wt% CaCl solution was selected as the phase change material (PCM), offering a melting point of 31.5° C and a latent heat of 153.0 J/g, with stable supercooling properties. The electrically controlled PCM preheating system (EPS-CCH) was designed and demonstrated to significantly improve battery performance at low temperatures. LIBs with EPS-CCH showed an increase in discharge capacity by 14.27% at 0.5° C, 11.35% at 1.0° C, and 7.04% at 1.5° C at 5° C compared to batteries without preheating. The system offers safe, rapid, and efficient preheating without damaging the battery, making it a promising technology for cold-weather battery management. Future work will aim to extend this method to environments below 0° C.

3.4 3D printing

Brillinger (2023) introduced a novel 3D printing platform that directly extrudes supercooled SAT (55%) into printed structures. The geometry of the nozzle was designed to induce controlled crystallization during printing, demonstrating real-time latent heat management in additive manufacturing contexts. The experiments confirmed the theoretical model for balling and line formation during 3D printing with supercooled liquid salt hydrates. A major advantage of this 3D printing method is the ability to create different geometric shapes by adjusting process parameters in real-time. Additionally, because salt hydrates are water-soluble, the printed forms can be easily dissolved, making the process highly suitable for producing moulds for gypsum or concrete components, with quick and efficient demoulding.

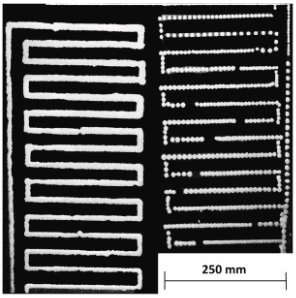


Figure 9: Applied layer (white) of Sodium Acetate Trihydrate at aluminium platform (black) using a digital filter: line formation (left) and balling (right) (Brillinger, 2023)

The method also shows potential for creating artistic or restoration pieces through customized surface structures. Ongoing research by the researcher focuses on expanding the range of usable salt hydrates, such as aluminium potassium sulphate dodecahydrate and magnesium chloride hexahydrate, for which material data is still being collected. A key challenge remains the reliable control of starting, stopping, and preventing back-crystallization in the 3D printhead, which will require further work before industrial application can be achieved.

3.5 Bubble-Assisted shell-and-tube latent heat thermal energy storage

Piquard *et al.* (2023) developed and tested a 42-kWh shell-and-tube latent heat thermal energy storage (LHTES) system filled with 400 kg of Xylitol, a sugar alcohol with high volumetric energy density (115 kWh/m^3) but strong and persistent supercooling. The prototype, known as MASTIN, integrated a bubbling and seeding mechanism to actively trigger crystallization. The system used a gas injection needle and a seeding circuit that introduced crystalline Xylitol powder into the supercooled melt during discharge. Four triggering strategies were evaluated: (1) no triggering (2) bubbling only (3) bubbling with single-point seeding, and (4) bubbling with optimized multi-step seeding. The results showed that without triggering, Xylitol remained liquid throughout the discharge, confirming that spontaneous nucleation is virtually non-existent. Bubbling alone initiated crystallization but lacked repeatability. Coupling bubbling with seeding significantly improved consistency and reduced crystallization delay, while the optimized seeding protocol—split into 10 timed injections eliminated temperature fluctuations caused by supercooling. Additionally, the study observed that while bubbling promoted homogeneous nucleation and reduced vertical temperature gradients in the liquid phase, it also created an “intermediate temperature zone” that lowered outlet water temperatures early in the discharge. The authors suggest that this side effect should be optimized by tuning bubbling parameters (gas flow, velocity, injection strategy) to balance crystallization control with thermal efficiency.

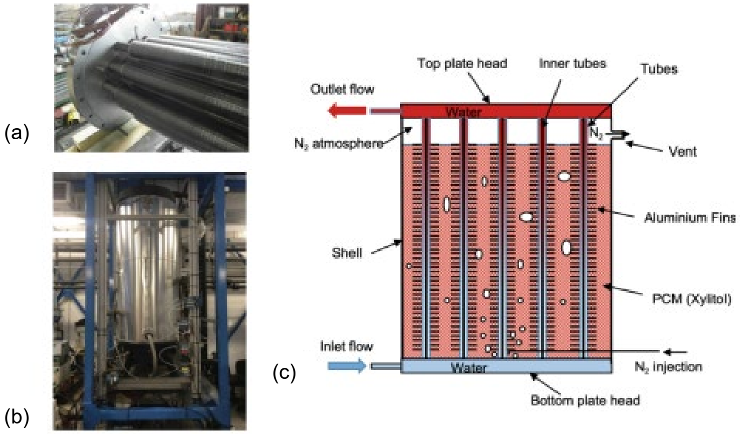


Figure 10: Pictures and schematic representation of the MASTIN storage facility. a) Picture of the embedded tubes of the heat exchanger. b) Picture of the thermally insulated prototype. c) Schematic representation of a discharge of the MASTIN storage (Piquard *et al.*, 2023)

3.6 Space Heating Systems Using Supercooled PCM Tanks

Among early research includes the work of Dannemand *et al.* (2016) who experimentally investigated two 1.5-meter-high cylindrical latent heat storage units filled with SAT composites that utilize supercooling for efficient thermal energy storage. One unit contained SAT with 6.4% extra water, while the other contained SAT with 0.5% Xanthan rubber and 4.4% graphite powder to improve stability and thermal conductivity. Results showed that the SAT composite with Xanthan and graphite maintained stable heat content (205–210 kJ/kg) over 40 cycles, while the SAT with extra water suffered a 21% reduction after 17 cycles due to phase separation. Although thickening SAT reduced the heat exchange capacity rate (HXCR) due to decreased convection, it prevented phase separation, improved supercooling stability, and led to higher latent heat release. Minor improvements in HXCR were observed with the addition of paraffin oil. Despite successful demonstration of supercooled, partly loss-free heat storage, challenges such as spontaneous crystallization, phase separation in tall tanks, and managing PCM expansion still need further optimization for reliable real-world application.

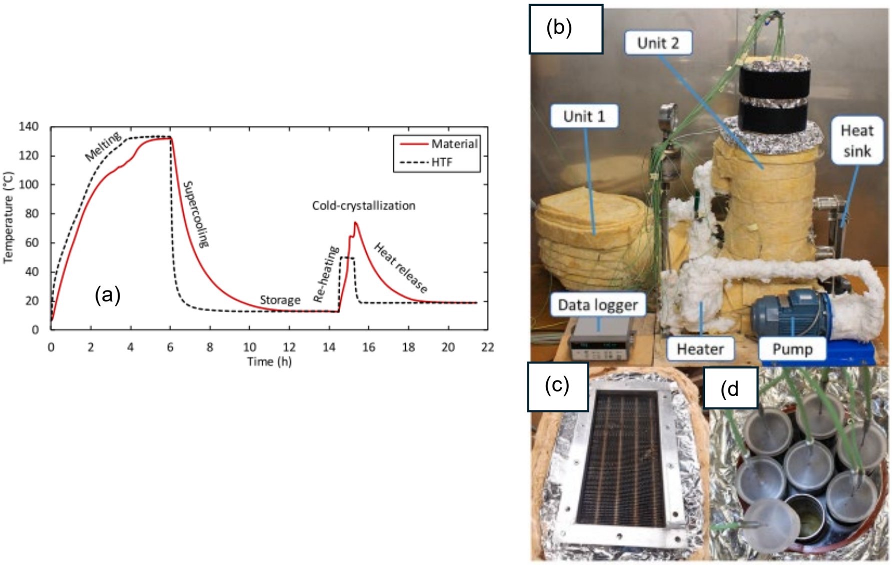


Figure 11: (a) The concept of cold crystallization (HTF is the heat transfer fluid) and (b-d) the prototype by Turunen *et al.* (2023)

More recently, Turunen *et al.* (2023) has developed 6.5 kg of an erythritol-polyelectrolyte mixture for long-term TES prototype. From their research, the prototype was found yielded an average melting enthalpy of 166 J/g for the mixture which was corroborated with calorimetric measurements. Unlike other researchers, Turunen *et al.* (2023) employed cold crystallisation method as illustrated in Figure 9 a- to discharge the thermal energy storage. From their investigation, results confirmed operational feasibility of the prototype TES with an overall storage efficiency of 0.50–0.80 when the latent heat of melting is used for long-term storage and the sensible heat of supercooling for short-term storage. The prototype enabled determination of previously undefined critical cooling rate, above which premature crystallization during supercooling was not observed despite the stochastic nature of supercooling and crystallization. Furthermore, momentary heat release rate of 1000 W was employed by allowing complete cold crystallization before discharging the heat. The operational parameters defined in this work confirm reliable use of cold-crystallization in long-term TES at kilogram scale with realistic operational values which forwards the implementation of advanced cold-crystallizing materials in long-term TES applications.

3.7 Portable solar box cooker

An interesting application of supercooled PCMs was investigated by Coccia *et al.* (2021). The researchers investigated a portable solar box cooker integrated with a thermal energy storage (TES) unit containing 2.5 kg of xylitol as a heat storage material (HSM). Xylitol, though promising due to its high latent heat (227 J/g) suffers from severe supercooling, which impairs its ability to release stored heat upon cooling. To address this, the authors incorporated a manual mechanical mixing device into the TES chamber to trigger crystallization during the cooling phase. Outdoor experiments were conducted comparing three configurations: (1) silicone oil only (2) silicone oil + xylitol without triggering, and (3) silicone oil + xylitol with manual triggering. Without triggering, xylitol remained in a supercooled state and contributed no phase change heat during discharge. However, with manual agitation, crystallization was successfully initiated, allowing xylitol to behave like a true PCM. The cooling duration of the cooking load was extended by an average of 346% compared to tests without TES and by 80% compared to TES without triggering, enabling better thermal stability during off-sunshine periods. While the mixing device proved effective, the study also identified limitations such as non-uniform triggering, slight supercooling persistence, and manual dependence. The authors recommended exploring automated or bubbling-based triggering methods to further enhance usability and performance in real-world settings. This prototype shows the viability of low-cost supercooled PCM integration in decentralized cooking systems for off-grid or developing regions. Click or tap here to enter text.

3.8 Synthesis of Findings

At milligram to gram scale, sugar alcohol-based materials have demonstrated highly promising thermal storage performance. However, as summarized in Table 4, scaling up to kilogram-scale systems has key challenges: larger material volumes increase the probability of premature crystallization and unstable supercooling due to the stochastic nature of nucleation, while materials that supercool reliably often exhibit slow crystallization kinetics, resulting in insufficient heat release rates for practical use. Additionally, thermal properties such as melting enthalpy and crystallization temperature observed at small scale do not consistently carry over to larger systems, with issues like polymorphism, incongruent melting, and increased thermal mass reducing storage efficiency. As a result, managing critical cooling rates becomes increasingly complex, and reliable, automated initiation of crystallization at large scale remains difficult to achieve. Furthermore, the physical chemistry governing metastable states, including supercooling, nucleation, and cold crystallization, in large material volumes is still not fully understood. Research at prototype scale is therefore considered crucial and essential to bridge the gap between small-scale observations and the development of reliable, predictable system designs.

However, important to emphasize here that, despite these challenges, large-scale cold crystallizing supercooled TES remains a promising approach for compact, high-density heat storage over periods of weeks to months with minimal thermal loss. It offers a cost-effective alternative to electrochemical batteries in applications such as district heating, localized waste heat recovery, and stationary solar thermal storage, where long-duration thermal energy storage is critical.

Table 2: Summary Table: Physical Prototypes with Supercooled PCMs

Prototype Type	**PCM**	**Trigger Method**	**Key Results**	**Challenge/Gap**	**Reference**
Heat pad	Sodium acetate trihydrate	Manual disk flex (seed release)	Fast crystallization on trigger; reusable device	Trigger consistency, seed retention over time	Sandnes (2008)
Flat thermal battery	SAT composite	CO injection and Peltier cooling - local cooling method	Stable supercooling in 200–220 kg PCM; selective crystallization	Thermal sensor integration, modular scaling	(Englmair et al., 2018)
Sharp Rectangular Unit Thermal Battery	Sodium acetate trihydrate (5.5 kg)	Natural cooling (no active trigger)	Difficult to maintain stable supercooling even after 10 h charging; sharp corners promote spontaneous crystallization.	Sharp inner corners cause crystal nucleation; difficult to achieve stable supercooling without very long charging times.	(Zhou & Xiang, 2017)
Rounded Rectangular Unit Thermal Battery	Sodium acetate trihydrate (5.5 kg)	Natural cooling (no active trigger)	Best balance of stable supercooling, manufacturability, and heat transfer efficiency; stable after 10–11 h charging.	Requires careful control of cooling rate and surface smoothness to avoid nucleation; slight difficulty with high CMC content (above 1.5%).	
Cylindrical Unit Thermal Battery	Sodium acetate trihydrate (0.5 kg)	Natural cooling (no active trigger)	Easy to achieve stable supercooling with smooth surfaces and sufficient charging (10–11 h).	Very small PCM volume (only 0.5 kg), difficult to scale up cost-effectively; manufacturing is more complex and expensive compared to rectangular designs.	

Electrically Controlled PCM Preheating System (EPS-CCH)	Calcium chloride hexahydrate (CCH, 48 wt% CaCl solution)	Electrically-triggered crystallization using low DC voltage (1.0–1.5 V)	- Crystallization and heat release triggered within <5 seconds. - Increased LIB discharge capacity by 14.27% (0.5C), 11.35% (1.0C), and 7.04% (1.5C) at 5 °C. - Stable supercooling and latent heat release (153.0 J/g).	Limited stability of CCH below 0 °C (system currently suitable only for 0 °C). - Passivation of silver electrode after long-term cycling needs addressing.	(Lu et al., 2024)
Cylindrical latent heat storage tank (1.5 m tall)	SAT + 6.4 wt% water - SAT + 0.5% Xanthan rubber + 4.4% graphite powder	Natural supercooling (no active external trigger)	SAT + Xanthan/graphite composite maintained stable heat content (~205–210 kJ/kg) over 40 cycles. - SAT + water suffered 21% latent heat loss after 17 cycles. - Thickened SAT improved stability and reduced phase separation.	Reduced convection and lower heat exchange capacity rate (HXCR) in thickened PCM. - Risk of spontaneous crystallization. - Phase separation issues in tall tanks.	(Dannemand et al., 2016)
Compact LHTES	Erythritol/Xylitol	Nitrogen gas + seeding powder	reduced to 13.7 ° C; repeatable crystallization (>90%)	Limited data on heat charging phase	(Hou et al., 2023)
Bench-scale crystallization unit	SAT with copper foam or EG	Electrically triggered (1.5V DC)	Crystallization in <5s; enhanced thermal conductivity	Balance between conductivity and supercooling	(Dong et al., 2024)
3D printing platform	Supercooled SAT (55%)	Geometry-induced crystallization	Real-time extrusion and crystallization of PCM	Repeatability under cycling not evaluated	(Brillinger, 2023))
Shell-and-tube LHTES system (42 kWh)	Xylitol	Gas bubbling and multi-step seeding	Bubbling alone initiated crystallization but lacked repeatability. Coupling bubbling with seeding significantly improved consistency and reduced crystallization delay,	Early discharge temperature drops due to intermediate cooling zone; bubbling parameters require further tuning	(Piquard et al., 2023)

Portable solar box cooker with TES	Xylitol	Manual mechanical mixing	Crystallization enabled real PCM behavior; extended thermal retention by 80â€“346%	Manual triggering limits automation: alternative seeding methods suggested	(Coccia et al., 2021)

4 Critical discussion and conclusions

4.1 Critical Evaluation of Triggering Methods in Prototypes

The reviewed prototypes illustrate that controllable supercooling is no longer confined to theoretical studies or bench-scale setups; it is now being progressively integrated into real-world systems across personal heating, building thermal storage, and battery thermal management. However, a critical analysis reveals that while the concept is promising, several technical, operational, and scalability issues remain unresolved.

Manual triggering, such as in SAT-based heat pads (Sandnes, 2008) remains limited to consumer-level applications due to its reliance on physical activation and non-automatable nature. Despite its reliability, it is not scalable for industrial or automated use cases. Thermal triggering, exemplified by (Englmair *et al.*, 2018; Zhou & Xiang, 2017) provide precise control when paired with sensors and heat exchangers, but requires extensive integration with external thermal control systems. This adds cost, complexity, and spatial requirements, which may deter adoption in retrofitted buildings or compact systems.

Electrical triggering, as seen in Lu *et al.* (2024) represents an exciting direction, particularly for integration with battery systems and other electromechanical modules. However, material compatibility, safety, and electrode durability are critical factors Electrical control systems often operate under variable voltages, making it difficult to sustain consistent triggering thresholds over prolonged cycling. Studies such as (Chen *et al.*, 2023; Dong *et al.*, 2024) show early promise in this regard, but field validation is still lacking. Bubble-assisted and seeding-based methods, including those by (Hou *et al.*, 2024; X. F. Shao *et al.*, 2018) show excellent laboratory performance in reducing the supercooling gap and enhancing repeatability. However, bubble injection systems require precise control of gas flow, pressure, and seed particle distribution. These systems are often difficult to maintain under fluctuating environmental conditions or when embedded in closed-loop systems such as HVAC modules. Additionally, MWCNT or nanoparticle-enhanced PCMs raise concerns about material safety, long-term chemical stability, and manufacturing complexity.

4.2 Integration Challenges and System-Level Considerations

Moving from laboratory prototypes to practical field applications introduces several integration challenges which may hinder the transition of controllable supercooled PCM systems from laboratory demonstrations to fully operational, real-world technologies. First, sensor and control architecture play a critical role. Real-time triggering demands the integration of embedded sensors and actuators capable of detecting supercooling states and initiating crystallization on demand. This adds complexity in terms of control logic, power consumption, and data communication—particularly in large-scale or distributed systems where precision is essential. Second, heat transfer efficiency remains an under-addressed aspect in many prototypes. While triggering mechanisms have improved, the efficiency of thermal exchange between the crystallizing PCM and the application medium—such as air, water, or building elements—is often overlooked. Enhancements like foam fillers or metallic fins (as demonstrated by Dong *et al.* (2024)) can improve conductivity but must be carefully designed to avoid triggering premature crystallization or destabilizing the supercooled state. Third, energy and cost efficiency are an ongoing concern.

Many control methods, including thermal regulation *via* Peltier devices, electrical activation, mechanical vibration, and pre-heating in cold crystallisation, consume energy during standby or activation phases. These parasitic loads can reduce the overall efficiency of the system, particularly in long-term thermal storage. Hence, renewable resources are seen as a promising approach to reducing net-zero emissions from auxiliary components. In addition, further analysis of the key crystallisation triggering mechanisms reveals that cold crystallisation is the most promising approach for large-scale prototypes due to the following reasons:

1. The pre-heating process is more straightforward. It eliminates the need for additional equipment or tools such as stirrers, mechanical agitators, electrodes, and ultrasonic devices.
2. It utilises the same setup to supply pre-heating during cold crystallisation, helping to reach the required crystallisation temperature.

Nevertheless, the question of how to ensure the availability of pre-heating sources remains, with the potential use of electrical battery storage or supercapacitors to provide momentary power supply for initiating cold crystallisation. Lastly, the circularity of supercooled phase change materials (PCMs) is crucial for their long-term sustainability in larger applications. However, many prototypes have yet to undergo rigorous fatigue testing to determine whether PCM behaviour, encapsulation integrity, and crystallization reliability can be maintained over hundreds or thousands of cycles.

5 Conclusion

In this review article, we have focused on comprehensive analysis of lab-scale experimental studies on controllable supercooling in PCMs, categorized by triggering methods such as local cooling, mechanical agitation, bubble injection, electric and ultrasonic fields, mechanical shock, and cold crystallisation. Controllable supercooling of PCMs has transitioned from conceptual studies to real-world demonstrations, highlighting the technology's viability for compact, long-duration thermal energy storage. While various triggering mechanisms thermal, mechanical, electrical, and cavitation-based have been successfully applied at laboratory scale, significant challenges remain in scaling these systems for practical use. Triggering consistency, material stability, integration with sensors and controls, and minimizing auxiliary energy inputs are key technical barriers that must be addressed. Research at prototype scale is crucial to bridging the gap between laboratory feasibility and full system deployment, offering pathways to optimize system efficiency, reliability, and manufacturability. In particular, further research into understanding metastable behaviours in large volumes and in developing a simple and low-energy triggering methods will be central to enabling the widespread adoption of controllable supercooled PCMs.

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