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Bio-cool Revolution: Aloe Vera Hydrogel as a Natural Supercooling Medium

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Abstract: *The growing pace of industrialization and the pressing challenges of climate change have accelerated the need for sustainable, energy-efficient, and eco-friendly cooling alternatives. Conventional cooling technologies and chemical refrigerants, while effective, significantly contribute to greenhouse gas emissions, excessive power usage, and environmental harm. Addressing these concerns, the Bio-Cool Revolution presents Aloe vera hydrogel as a natural, sustainable supercooling medium that utilizes the inherent physicochemical properties of bio- derived materials for efficient thermal control.*

Aloe vera, a plant rich in water and polysaccharides with excellent biocompatibility, emerges as a suitable base for developing environmentally benign hydrogels. The hydrogel derived from Aloe vera exhibits superior water retention, heat stability, and controlled phase transition, allowing it to sustain supercooled states without rapid crystallization. This enables prolonged and efficient cooling with minimal energy requirements. Its internal polymeric network, strengthened by hydrogen bonds and natural polysaccharides, further improves its latent heat storage, viscosity, and thermal regulation characteristics.

Experimental findings confirm that Aloe vera hydrogel displays stable supercooling with reduced ice nucleation, maintaining steady temperatures over longer durations. Its renewable, biodegradable, and non-toxic nature makes it a greener alternative to synthetic refrigerants. Potential applications of this bio-cooling medium include pharmaceutical cold-chain storage, food preservation, thermal insulation, and wearable cooling devices.

This research highlights Aloe vera hydrogel's transformative potential in sustainable thermal management through a bio-inspired and eco-conscious framework. By integrating this natural material into supercooling systems, the approach not only minimizes environmental impact but also promotes energy-efficient and carbon-neutral cooling technologies. Thus, the Bio-Cool Revolution signifies a crucial step toward the next generation of smart, sustainable, and nature- driven cooling innovations in materials science and thermal engineering.

Keywords*:* Aloe vera, Hydrogel, Supercooling, Sustainable cooling, Thermal Management.

I. INTRODUCTION

The growing demand for sustainable and energy-efficient cooling technologies is driven by accelerating climate change, urban heat islands, and the environmental consequences of conventional refrigeration systems. Traditional cooling media and chemical refrigerants such as hydrofluorocarbons (HFCs) and chlorofluorocarbons (CFCs) significantly contribute to ozone depletion, high energy consumption, and global warming. As the world transitions toward green and eco-innovative solutions, the exploration of bio-based cooling materials has gained remarkable scientific interest. [1]

Aloe vera, a widely recognized medicinal succulent, is emerging as a promising candidate in next-generation thermal management due to its exceptional physicochemical properties. The inherently high water content, hygroscopic nature, and unique polysaccharide-rich hydrogel matrix enable Aloe vera to exhibit superior cooling and supercooling capabilities compared to conventional natural hydrogels. The structured gel network allows slow heat diffusion,

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prolonged moisture retention, phase-change stability, and evaporative cooling—making it ideal for applications ranging from biomedical temperature regulation to passive cooling systems.[2]

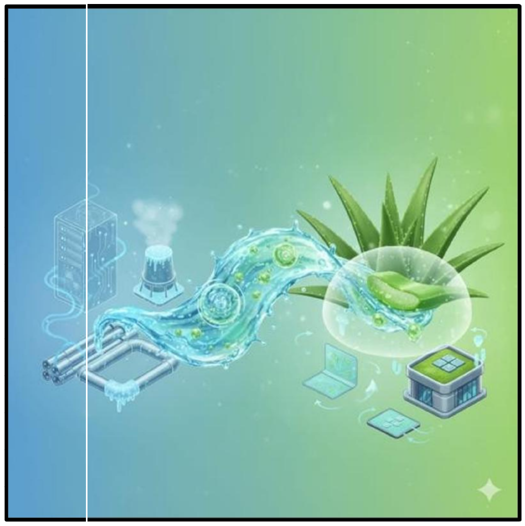

Figure 1: Bio-cooling evolution

The concept of a "Bio-Cooling Revolution" reflects a paradigm shift from synthetic refrigerants to plant-derived supercooling media that are biodegradable, renewable, cost- effective, and safe. Aloe vera hydrogel not only enhances thermal performance but also aligns with circular economy principles and global sustainability goals. Innovative research is now focusing on optimizing its thermal conductivity, durability, and hybrid nanomaterial reinforcement to widen its applicability in transport, food preservation, wearable cooling devices, and future smart materials.[3]

This review provides a comprehensive exploration of Aloe vera hydrogel as a natural supercooling medium, including its composition, mechanisms of thermal regulation, fabrication strategies, recent technological advancements, and its potential integration into commercial cooling systems. By bridging biological science with material engineering, Aloe vera-based hydrogels may redefine the future of green cooling technologies.[2]

Literature Review:

1. Modupeola Dada & Patricia Popoola (2024) — Aloe vera Hydrogel for Supercooling Applications: A review.

Dada and Popoola (2024) explored the potential of Aloe vera–based hydrogels, which are naturally enriched with the polysaccharide acemannan, to enhance supercooling efficiency in preservation and cooling systems. They point out that these hydrogels possess strong water- retention properties and can delay ice nucleation, making them valuable for applications such as refrigeration, thermal energy storage, and biomedical cooling. The authors also emphasize that, while promising, Aloe vera hydrogels still require further refinement to improve their stability, purity, and long-term reliability in supercooling technologies.

2. Sathishkumar A, Sundaram P. (2024) — Aloe Vera–Based Nanofluids for Thermal Energy Storage

Sathishkumar et al. (2024) examined nanofluids formulated from Aloe vera and reinforced with graphene nanoplatelets for application in cool thermal energy storage systems. Their findings show that Aloe vera functions as a sustainable, stable, and efficient base fluid that boosts thermal conductivity, shortens charging time, and delivers improved cooling efficiency compared to traditional fluids. The authors conclude that Aloe vera–derived nanofluids hold strong potential as eco-friendly materials for next-generation thermal energy storage technologies.

3. Khare S, Kumar S, Urmaliya P, & Yadav S. (2024). Recent Advancement and Applications of Green Hydrogels: Revolutionizing Biomedicine and Environmental Sustainability

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In this review, the authors examine eco-friendly, biopolymer-based green hydrogels and outline their latest developments in both biomedical fields—such as drug delivery and tissue engineering—and environmental sectors, including wastewater purification and contaminant removal. They emphasize improvements in fabrication techniques, chemical modification, and stimuli-responsive properties, demonstrating how these sustainable hydrogels are driving innovation in medical and environmental technologies.

4. Alrashidi A, Abdo S. (2025) — Investigating the Effectiveness of Hydrogels for PV Cooling Across Different Operational Conditions: An Experimental Approach

Alrashidi and Abdo (2025) conducted an experimental study to assess hydrogels as a passive cooling solution for photovoltaic panels exposed to diverse environmental and operational settings. Their results demonstrated that hydrogels significantly lowered PV surface temperatures, boosted electrical efficiency, and provided consistent cooling performance even under intense heat and strong solar radiation. The authors conclude that hydrogel-based cooling is a straightforward, energy-efficient, and dependable method for improving PV output, particularly in hot and arid regions.

5. Shamseddine I, Pennec F. (2022) — Supercooling of Phase Change Materials: A Review. Renewable and Sustainable Energy Reviews

Shamseddine and Pennec (2022) analyzed the underlying factors that lead to supercooling in phase change materials and discussed how this phenomenon reduces the efficiency of thermal energy storage systems. Their review outlines the current approaches used to mitigate supercooling—such as incorporating nucleating additives and applying encapsulation techniques—and highlights the ongoing need for more effective and dependable solutions for large-scale PCM deployment.

6. Koley S. (2024) —Electrochemistry of Phase-Change Materials in Thermal Energy Storage Systems: A Critical Review of Green Transitions in Built Environments. Trends in Sciences. Koley S. (2024) examines the role of electrochemical behavior in determining the durability, functionality, and overall efficiency of phase-change materials applied in thermal energy storage. The review emphasizes new eco-friendly PCM innovations for sustainable construction and concludes that enhancing electrochemical resilience is essential for achieving consistent and energy-efficient storage performance.

7. Hadi A, Nawab A. (2023) — Development of sodium alginate–aloe vera hydrogel films enriched with organic fibers: study of the physical, mechanical, and barrier properties for food- packaging applications. Sustain Food Technol.

Hadi A and Nawab A (2023) formulated sodium alginate–Aloe vera hydrogel films incorporating organic fibers and assessed their structural, mechanical, and protective characteristics for eco-friendly food-packaging use. Their findings indicated that the inclusion of Aloe vera and fibers enhanced the film's durability, water-resistance, and overall performance, positioning it as a viable biodegradable substitute for traditional plastic packaging.

Concept of bio-cooling:

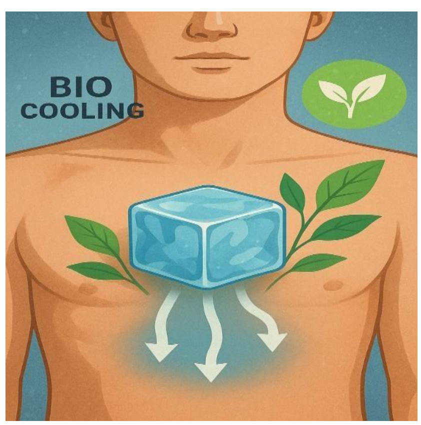

Figure 2: Concept of bio-cooling

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1. Bio-cooling refers to the use of naturally derived biological materials to regulate or reduce temperature without relying on conventional mechanical refrigeration or harmful synthetic coolants.[4]
2. Instead of consuming large amounts of electricity or emitting greenhouse gases, bio-cooling harnesses intrinsic biological properties such as high-water retention, evaporative cooling ability, phase-change behavior, and thermal buffering capacity.[2]
3. These materials—often sourced from plants, microorganisms, or biopolymers—can store and dissipate heat gradually, creating a stable cooling effect.[5]
4. A central idea in bio-cooling is to mimic natural thermal management strategies found in living organisms.[4]
5. Plants maintain internal temperature through processes like transpiration, gel-based tissues, and moisture-regulated structures, and these mechanisms can be translated into engineered materials.[2]
6. By translating these mechanisms into engineered materials, bio-cooling systems can achieve efficient temperature control while remaining safe, biodegradable, and environmentally friendly.[2]
7. Recent innovations focus on bio-polymers formed into hydrogels, films, or coatings that can absorb large quantities of water and slowly release it during heat exposure.[6]
8. This not only prolongs cooling performance but also reduces the need for electricity-driven systems.[4]
9. As climate change increases global energy demand for air-conditioning, bio-cooling offers a sustainable alternative that can be adapted to food preservation, healthcare temperature control, wearable cooling products, and next-generation smart materials.[2]

Aloe vera hydrogel:

Figure 3: Aloe vera hydrogel

1. Aloe vera hydrogels exhibit high hydrophilicity and enhanced water-absorption capacity, which make them effective in moisture retention and thermal buffering.[7]
2. Composite hydrogels incorporating Aloe vera show improved structural and mechanical properties (e.g., tensile strength, homogeneity) when Aloe content is increased and properly formulated.[6]
3. Aloe vera-based hydrogels have been successfully developed as biocompatible, biodegradable platforms (e.g., for wound dressings), indicating their suitability for eco-friendly cooling applications.[8]
4. The gel network of Aloe vera can be used in hybrid systems (e.g., blending with other polymers like alginate or film materials) that retain Aloe's cooling/evaporation potential while adding durability or tailored functionality.[9]
5. Research indicates Aloe vera hydrogels may support "supercooling" behavior (i.e., absorbing and retaining large amounts of water, delaying phase change or heat release) in certain formulation.[2]

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Mechanism of Supercooling:

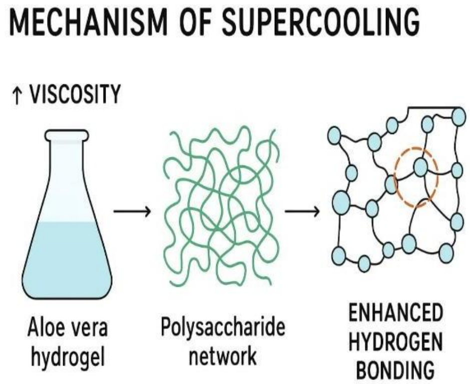

Figure 4: Mechanism of Supercooling

The hydrogel derived from Aloe vera acts as an efficient natural super-cooling medium due to its unique physicochemical structure and high-water content. Its matrix is rich in the bio- polysaccharide acemannan which forms an interconnected porous network, allowing the gel to hold large quantities of water within its structure. During the cooling process, this retained water undergoes super-cooling — that is, it remains in a liquid state below its normal freezing point without immediate ice crystallisation. The hydrogel structure restricts the mobility of water molecules and suppresses nucleation sites, thereby delaying ice formation and maintaining a stable sub-zero or near-zero temperature environment for an extended period. Simultaneously, evaporative cooling plays a synergistic role: as the hydrogel absorbs heat from its surroundings, surface-bound water gradually evaporates, consuming latent heat and further enhancing the cooling effect. The high thermal capacity and reversible swelling behaviour of the hydrogel allow it to repeatedly store and release cooling energy, making it suitable for sustainable cooling applications. Thus, Aloe vera hydrogel exhibits a dual-action cooling behaviour: firstly, a delayed freeze effect via super-cooling through nucleation inhibition; and secondly, a direct heat removal via evaporative mechanisms. This dual mechanism positions Aloe vera hydrogel as a bio-based, eco-friendly alternative to conventional synthetic cooling media in next-generation thermal management systems.[2]

Hydrogel Composition & Structure:

The hydrogel derived from Aloe vera is rich in the polysaccharide acemannan, along with other mannose-rich polymers.[10]

Within the gel, these polysaccharide chains form an interconnected porous network that traps water molecules in the matrix.[5]

This high water-content network is crucial because the amount, distribution, and mobility of water determine how effective the hydrogel can be at absorbing and transferring heat.[2]

Water Retention and Cooling Potential:

Because the gel network retains large volumes of water, when the hydrogel is exposed to heat (from the environment or a heated object), the absorbed water begins to absorb heat energy. Some of the retained water remains below the typical freezing point (i.e., super-cooled), and the slow mobility of the water within the gel network delays ice nucleation or crystallisation. The hydrogel thereby acts as a thermal buffer, absorbing heat without immediately transforming into ice, which means the temperature drop can be sustained for longer periods.[2]

Supercooling & Nucleation Delay:
Supercooling occurs when a liquid remains in liquid form below its normal freezing point without crystallising. In Aloe vera hydrogel, the restricted mobility of water molecules, the constrained micro-pores, and possibly the interaction with the polymer chains reduce the number of effective nucleation sites. Therefore, ice formation is delayed, the liquid state persists, and the gel continues to absorb heat without the energy penalty of immediate phase change.[2]

Evaporative Cooling Synergy:
Simultaneously, the gel's considerable surface-bound water content can evaporate when exposed to ambient conditions. Evaporation is an endothermic process: it consumes latent heat from the surroundings, thereby lowering the temperature of the hydrogel and its immediate environment. This evaporative cooling works in synergy with the supercooled state—while the gel remains in the liquid supercooled phase and not frozen, evaporation can proceed more effectively, enabling a sustained cooling effect.[2]

Dual Mode Cooling Action:
Thus, the hydrogel achieves a dual-action cooling mechanism:
First, by heat absorption and storage in retained water while postponing ice formation (via supercooling). Second, by latent heat removal through evaporation of surface water into the ambient environment. Together, these two mechanisms allow the Aloe vera hydrogel to function as a natural super-cooling medium, with longer cooling durations and lower energy input requirements compared to conventional cooling media.[2]

Implications for Thermal Management:
Because the system operates without conventional refrigerants and often without significant mechanical energy input (depending on integration), it offers a more sustainable, environmentally friendly path for thermal management. In systems such as passive cooling coatings, wearable cooling pads, food-cold chain pouches, or building insulation layers, the Aloe vera hydrogel could reduce active cooling load, delay temperature rise, and maintain lower temperatures for longer. Optimising parameters such as gel thickness, water retention ratio, pore size distribution, and ambient exposure conditions are key to maximising performance in real-world applications. [2]

Experimental studies and finding:
Experimental Study 1:
A study titled Alginate Hydrogels with Aloe vera: The Effects of Reaction Temperature on Morphology and Thermal Properties investigated hydrogels that incorporated 20% (v/v) Aloe vera solution in a sodium-alginate/poly(vinyl alcohol) matrix. It found that a higher reaction temperature (65 °C vs 75 °C) promoted greater cross-linking, as observed via gel fraction, differential scanning calorimetry (DSC) and FTIR measurements. The enhanced cross-linking correlated with better thermal properties—specifically a higher thermal transition temperature and improved stability of the hydrogel structure.[5]
Experimental Study 2:
In another work, researchers developed a bio-based hydrogel using Aloe polysaccharides as the matrix reinforced by degradable polyvinyl alcohol to achieve an anti-freeze, supercooling- capable hydrogel (Highly Stretchable Anti‑freeze Hydrogel Based on Aloe Polysaccharides). The hydrogel exhibited remarkable mechanical stretchability and retained water without freezing at sub-zero temperatures, thereby demonstrating potential for supercooling applications.[11]
Experimental Study 3:
A broader review titled Aloe vera Hydrogel for Supercooling Applications: A Review summarized multiple experimental results showing that acemannan-rich Aloe vera hydrogels can absorb and retain up to ~99% of their weight in water—a trait that supports extended super- cooled liquid states in hydrogels.[2]

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Experimental Study 4:

An investigation of the moisture-holding capacity of Aloe vera cuticle (agro-industrial residue) found that the residue achieved a water-holding capacity (WHC) of up to 18 g g^{-1} (i.e., 18 times its weight) under optimized conditions (particle size ~250 µm at pH 6.0, 20 °C). Importantly, this water retention remained stable even when salts (KNO_3 or $Ca(NO_3)_2$) were present, unlike a synthetic polyacrylamide gel whose WHC decreased significantly with increasing salt concentration.[12]

Table 6.1:Experimental studies and findings

Study	Material	Key finding	Relevance to bio- cooling
Study 1	Alginate/PVA + Aloe Vera	Better cross-linking & thermal stability at higher temp	Show aloe vera improves hydrogel thermal performance
Study 2	Aloe polysaccharide + PVA	Anti-freeze, supercooling water retention	Directly about supercooling potential
Study 3	Acemannan hydrogel	~90% water retention	High water content support cooling capacity
Study 4	Aloe vera cuticle	WHC up to 18 g/g, salt stable	Storage water-holding for thermal storage

Environmental & energy implications:

Figure 5: Environmental & energy implications

The adoption of natural hydrogel-based cooling media such as a hydrogel derived from Aloe vera has significant potential to reduce energy consumption in cooling applications. Conventional cooling systems (air-conditioning, refrigeration) are highly energy-intensive, and account for a large portion of global electricity demand and associated greenhouse-gas emissions. Thus replacing or supplementing these with passive or semi-passive bio-cooling systems could substantially lower electricity usage, peak demand and carbon footprints. For example, hydrogel coatings applied to building surfaces have been shown to enhance heat dissipation via evaporative cooling, thereby reducing surface temperatures and the load on active cooling systems.[13]

From an environmental materials standpoint, Aloe vera hydrogels present several sustainability advantages. Being derived from a renewable plant source, the hydrogel matrix is inherently more biodegradable and less reliant on synthetic polymers or harmful refrigerants than conventional cooling media. Green hydrogel technologies aim to minimize environmental impact through non‑toxic composition, biodegradability, and low-energy manufacturing processes.[14]

Furthermore, by reducing reliance on traditional refrigerants (which often have high global warming potential) and lowering cooling-system electricity consumption ,the lifecycle environmental footprint of cooling system can be reduced. For instance, hydrogel-based passive to yield substantial greenhouse-gas emission reductions when scaled appropriately.[15]

Potential Applications:

Figure 6: Potential Applications

1. Passive Thermal Control for Building Envelopes:

Aloe vera hydrogel can be incorporated into wall panels or façade coatings to absorb ambient heat and gradually release it via evaporation or supercooling, thereby lowering the surface temperature and reducing the cooling load on HVAC systems. Such integration into building envelopes can help mitigate the urban heat island effect and improve building energy efficiency.[16]

2. Cold-Chain and Food Preservation Packaging:

By placing Aloe vera hydrogel inserts or sheets within containers or cold-chain systems, the material can act as a natural thermal buffer—absorbing heat ingress, delaying temperature rise, and maintaining lower temperatures for longer durations without the need for active refrigeration. This offers a bio-based alternative to traditional gel packs or synthetic phase- change materials in packaging and logistics.[17]

3. Wearable Cooling and Personal Thermal Management:

Aloe vera hydrogel can be integrated into wearable products—such as vests, textile inserts, cooling patches, or headgear—to provide passive cooling for athletes, outdoor workers, or medical‑use scenarios. Its high water retention and latent heat absorption capabilities allow it to reduce skin or ambient temperature without needing bulky refrigeration. Hydrogels are already being explored in advanced wearable cooling technologies to enhance user comfort and reduce heat stress.[18]

Challenges and Limitation:

1. Limited depth and stability of supercooling:

One of the major hurdles in using Aloe vera-based hydrogels for supercooling is the limited achievable supercooling depth and the difficulty in maintaining that state over time. For example, even in dedicated phase-change material (PCM) research, supercooling is constrained by nucleation events and material heterogeneity.[19]

In the specific case of Aloe vera hydrogels (acetmannan-rich), the literature points out that although they can absorb and retain up to ~99 % of their weight in water, their supercooling performance (i.e., how far below the freezing point they can remain unfrozen and for how long) is still relatively un-explored and may suffer from spontaneous crystallization, structural change or loss of cooling capacity.[2]

2. Mechanical and structural integrity under cooling/ thawing cycles:

Another key limitation concerns the mechanical robustness and repeatability of the hydrogel network when subject to repeated cooling and thawing or supercooling cycles. Hydrogels in general are known to have weaker mechanical strength compared to solid matrices, which means the repeated stress of freezing/thawing, ice-crystal formation (or attempted formation), volume changes, and polymer network shrinking/expansion can lead to cracking, delamination or structural fatigue. For Aloe vera hydrogels, much of the research to date has focused on biomedical or wound-healing applications (where mechanical loads are modest) rather than high-stress thermal cycling application.[8]

3. Scale-up, reproducibility and process control:

Translating laboratory-scale Aloe vera hydrogel systems into large-scale, industrially viable cooling media brings with it challenges of scale-up, reproducibility, and process control. The review of Aloe vera hydrogels for supercooling notes that "performance is affected by additives, composition, and concentration" and that "cost-effectiveness and scalability are among the challenges." [2]

4. Environmental sensitivity and constraints of cooling performance:

The cooling efficacy of hydrogels (including those based on Aloe vera) is strongly influenced by environmental parameters such as ambient temperature, humidity, wind/airflow, and heating load. In hydrogel-based cooling reviews (e.g., sweat - cooling or evaporative cooling), it is noted that their effect is limited under extreme conditions (very high ambient temperature, high humidity) and that the ambient conditions dictate how much cooling can be sustained.[20]

5. Thermal conductivity and heat transfer limitations:

Although hydrogels can retain a large amount of water and act as cooling reservoirs, their thermal conductivity and heat transfer characteristics may be limiting. Water-rich gels often have relatively low thermal conductivity compared to metallic or highly conductive phase change materials, which can limit how quickly heat can be drawn into or extracted from the hydrogel. Given that supercooling relies on efficient heat removal (or delayed heat influx) to maintain the low state, this constraint can slow response times or reduce the effective cooling power. While specific thermal conductivity values for Aloe vera hydrogels in supercooling application are still scarce, this is a recognized limitation in hydrogel cooling literature.[20]

6. Long-term stability, dehydration and degradation:

For practical deployment, the hydrogel must maintain its properties over extended timescales. However, hydrogels (especially plant-based ones) can suffer from dehydration, polymer degradation, microbial attack or structural changes over time, which can degrade performance. The review on Aloe vera hydrogels notes that exposure to air, processing conditions, or delayed handling may lead to loss of active polysaccharide fractions or altered gel properties.[20]

7. Cost, material sourcing and sustainability

Finally, while Aloe vera is a natural, renewable material and offers sustainability appeal, the costs of material preparation, purification (e.g., extraction of acemannan), gel formulation, and system integration must be considered. The review mentions cost-effectiveness as a challenge.[2]

Table 9.1: Challenges and Limitation

	Challenge /Limitation	Why it matters	Research gaps	Suggested mitigation
1.	Limited depth & stability of supercooling	Aloe-vera/acemannan hydrogels can retain very high water content but the achievable supercooling depth and the duration before spontaneous nucleation remain poorly quantified for many formulations.[2]	Quantitative data on maximum supercooling (°C below 0°C), time-to- nucleation under controlled perturbations, and the role od gel composition on nucleation kinetics are lacking.[2]	Systematic parametric studies (acemannan concentration, crosslink density, additive) and real-calorimetry/DSC + high-resolution nucleation imaging to map operating windows. Explore antifreeze protein mimics or nucleation inhibitors blended into gels.[2]
2.	Mechanical and cyclic durability	Repeated/cooling thawing (or attempted freeze events) causes mechanical stresses, microcracking, and network fatigue in hydrogels, threatening long- term reliability.[21]	Lack of long-term (>100 cycle) mechanical and functional retention studies for aloe-based hydrogels used as thermal reservoirs. Effects of ice-lens formation during partial crystallization are under-reported.[21]	Characterize mechanical fatigue over thermal cycles; test composite approaches (reinforcing fibers, porous frameworks, or polymer interpenetrating networks) to improve toughness. Report standard cycle tests (e.g., ISO-like protocols).[22]
3.	Thermal conductivity & heat-transfer bottleneck	Water -rich gels typically have low thermal conductivity vs. metallic/graphitic PCMs, limiting how rapidly they can absorb or release heat.[21]	Precise measurements of effective thermal conductivity in aloe gels (with/without filters) under operational temperature and during phase transitions; coupled heat-transfer modelling at device scale.[21]	Engineering solutions: add high-conductivity filler (graphene, metal foams, fins, or nanoparticles) or microencapsulation to increase surface area; design system-level heat exchangers (fins, channels) turned to gel properties. Validate for safety/compatibility with natural gel.[23]
4.	Dehydration, microbial degradation & long-term stability	Exposure to air, heat and time can cause water loss and biological degradation of plant polysaccharides, reducing latent capacity and	Shelf-life data under real environmental conditions (humidity, temperature cycling), and studies of bioburden or enzymatic degradation in	Encapsulation (barrier films/microcapsules), humectants/ antimicrobials compatible with acemannan, or composite CPCM (composite phase change material)

			stored gels are	
		changing rheology.[23]	sparse. Quantity mass loss vs. performance loss.[23]	strategies to slow dehydration and biodegradation. Report accelerated aging studies.[23]
5.	Natural-source variability & reproducibility	Agrochemical, geographic, seasonal variation in aloe vera raw material causes batch-to-batch variability in polysaccharide content and gel properties.[24]	Standardized extraction protocols, characterization (molecular weight of acemannan, viscosity, ash content) and how those parameter map to cooling performance are missing.[24]	Propose standardized extraction & QC methods (e.g., Yield & acemannan assay), or move to semi- synthetic analogues/ blends that retain green credentials but reduce variability. Induce life-cycle & supply-chain assessment.[24]
6.	Scale-up, manufacturability & cost	Lab successes may not translate economically at scale because of purification, crosslinking reagents, drying/encapsulation costs and supply chain needs.[3]	Techno-economic analyses comparing aloe hydrogel system to conventional PCMs (cost per kWh of store cooling) and sensitivity to raw- material cost, processing energy and lifecycle impacts are lacking.[3]	Produce pilot-scale manufacturing studies, optimize low-energy extraction, reuse process streams, and co-locate with agricultural waste streams. Publish LCA/TEA (life-cycle & techno-economic analysis.[3]
7.	Environmental & operational constraints	Performance depends strongly on ambient conditions (humidity, airflow, heat load). Hydrogel strategies may underperform in high-humidity or extreme heat unless system is tailored.[25]	Field studies across climates (humid tropical, arid, temperate) comparing gel performance to established cooling solutions are missing. Models linking climate data to operational feasibility are underdeveloped.[25]	Run climate-specific prototypes (regional pilots), incorporate passive design (evaporative enhancement if appropriate), and specify operating envelopes in reporting (temperature, RH, load).[25]

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Future Prospect:

Figure 7: Future Prospects

The future of Aloe vera hydrogel-based cooling systems lies in advanced biomaterial engineering that can enhance supercooling stability, water retention, and thermal conductivity. Emerging nanofillers such as silver nanoparticles, graphene oxide, and cellulose nanofibers can be incorporated into Aloe vera matrices to improve heat transfer efficiency without using synthetic refrigerants.[26]

To transition Aloe vera hydrogel from laboratory research to commercial cooling technologies, scalable and cost-effective processing methods need to be established. Techniques such as 3D bioprinting, freeze-drying optimization, and crosslinking biotechnology can enable consistent material quality suitable for mass production.[27]

Integration of Aloe vera hydrogel into wearable cooling systems—including smart textiles and personal thermal comfort devices—is a rapidly growing opportunity. Combining hydrogel patches with flexible sensors and phase-change cooling can support physiological temperature control in athletes, industry workers, and patients with heat-sensitive illnesses.[28]

A promising futuristic direction is coupling Aloe vera hydrogel with renewable energy sources, such as solar-driven evaporative cooling or passive radiative cooling systems. These innovations can create zero-energy cooling solutions for buildings, food storage, and vaccine transport in remote areas.[29]

Finally, international collaborations between biotechnology researchers, textile manufacturers, and refrigeration industries are essential to establish regulatory frameworks, safety standards, and commercialization pathways for bio-cooling products.[30]

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Aloe vera hydrogel properties relevant to supercooling:

Figure 8: Aloe vera hydrogel properties relevant to

1. High water content / high porosity and swelling capability:
The gel in Aloe vera leaves is extremely high in water (typically ~98–99 % water in the inner gel of the leaf) [8]. Hydrogels derived from Aloe vera (or containing Aloe vera extract) likewise exhibit high water uptake, swelling and porous microstructure (for example, one study found a swelling of ~12,693 % relative to the xerogel weight, because the fresh hydrogel was ~98–99 % water) .A hydrogel with very high water content and open network/porous structure provides a large thermal mass and capacity for latent heat absorption (freezing or super-cooling of water). The porous network also allows for controlled freezing or delayed crystallization (thus enabling super-cooling).[31]
2. Biopolymeric structure with acemannan and polysaccharides:
Aloe vera's gel is rich in the polysaccharide acemannan (a glucomannan type) and other polysaccharides (mannose, glucose, rhamnose, uronic acids, etc.) [8]. The acemannan-based hydrogel is noted to be biocompatible, biodegradable and customizable (e.g., network modifications) in the review on super-cooling applications. [2]
3. Ability to absorb/retain large amounts of water (up to ~99 % of weight):
The recent review states that acemannan hydrogels "can absorb and retain up to 99 % of their weight" (i.e., ~99 % water by weight) which is beneficial for long-period super-cooling.[2]
4. Thermal / morphological tunability and cross-linking behaviour:
Studies on hydrogels with Aloe vera (for example an alginate/PVA hydrogel with 20 % Aloe vera) show that the Aloe vera additive promotes cross-linking and affects thermal transitions (via DSC analysis) and morphology.[5]
5. Biocompatibility, biodegradability and sustainable "green" material:
Aloe vera hydrogels have been widely researched for wound-healing/biomedical applications because of their biocompatibility and biodegradability.[8]
6. Potential for delayed freezing / super-cooling stability:
The review specifically on Aloe vera hydrogel for super-cooling applications highlights that very limited studies exist but the material shows promise for longer super-cooling hold times (i.e., the hydrogel's capacity for super-cooling is discussed).[2]

7. Thermal mass and latent heat capacity implications:
Although direct latent heat data for Aloe vera hydrogel may be scarce, the fact that it holds large amounts of water and has a polymeric network implies high thermal mass and latent heat potential when freezing occurs. The review indicates the importance of understanding the hydrogel's thermal behaviour (composition, network, freezing/crystallization behaviour) for super-cooling device development.[2]
8. Mechanical integrity during freeze/thaw cycles:
While the primary literature emphasises biomedical/thermal properties rather than mechanical cycling, hydrogels generally may suffer structural damage during freezing/thawing due to ice crystal growth. The network of Aloe vera hydrogel (acemannan polymer) may mitigate some ice‑crystal damage by restricting crystal growth. The review mentions challenges and potential pathways for enhancing functionality/performance for super-cooling.[2]

Applications of Aloe vera hydrogel as a cooling medium:

Figure 9: Applications of Aloe vera hydrogel as a cooling medium
1. Aloe vera hydrogel: properties and potential:
The gel of Aloe vera contains a high water content and the polysaccharide acemannan, giving it high biocompatibility, biodegradability and tunable physical‑chemistry. A recent review notes that acemannan hydrogels can absorb and retain up to ~99 % of their weight in water, making them excellent candidates for super-cooling applications. In super-cooling contexts, the hydrogel network can impede ice‑nucleation and help maintain a metastable liquid state at sub‑freezing temperatures, delivering a prolonged cooling effect. However, the current literature on Aloe hydrogel in super-cooling is still limited (especially compared with cellulose/chitosan/alginate hydrogels). [2]

2. Comparison with other biopolymer hydrogels (cellulose‑, chitosan‑, alginate‑based):
Hydrogels derived from cellulose, chitosan, alginate and starch have been widely studied as hydrogel matrices due to their natural origin, tunable porosity and good mechanical properties. For example, an alginate/poly(vinyl alcohol) hydrogel incorporating 20 % Aloe vera solution showed that the Aloe additive promoted crosslinking, altered morphology, and impacted thermal properties.[5]

3. Comparison with bio‑based phase-change materials (PCMs):
Beyond hydrogels, there is a growing interest in biopolymer‑based phase‑change materials (PCMs) for thermal energy storage and passive cooling. A systematic review of biopolymer PCMs notes that natural polymers (lipids, lignin, polysaccharides, proteins) and their composites are being developed for latent heat storage, with a view to sustainable cooling/thermal management [32]. These PCM systems typically rely on solid–liquid phase transitions (e.g., fatty acids, paraffins) embedded in biopolymeric scaffolds, achieving latent enthalpies of ~150 J/g in some cases.[33]

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Relative to these, Aloe hydrogel acts more like a high‑water‑content cooling medium (evaporative or supercooling) rather than a pure latent heat PCM. The advantage of Aloe hydrogel lies in being natural, biodegradable and possibly cost-effective, with the ability to absorb heat via water phase change (freezing/thawing) or super-cooling. On the other hand, conventional PCMs can store higher latent heat per unit mass and are designed for repeated phase‑change cycles, but often rely on synthetic or hybrid polymers, encapsulation, and may suffer leakage or low thermal conductivity issues.[34]

4. Application evaluation: strengths of Aloe hydrogel in bio-cooling:

Sustainability & biocompatibility: Aloe gel is from a renewable plant source, biodegradable and non-toxic—important for "bio‑cooling revolution" narratives.[8]

High water‑content reservoir: The ability of Aloe hydrogel to retain large amounts of water (up to ~99 %) means large thermal mass and potential for prolonged cooling via freezing/thawing or supercooling.[2]

Flexibility and form factor: Hydrogels can be shaped, coated, layered into devices (e.g., thermal pads, cooling vests) and may allow innovative cooling form-factors.[2]

Super-cooling potential: The review highlights the potential of Aloe hydrogels to maintain super-cooled states, enabling cooling without ice formation (thus avoiding frost damage) and delivering latent heat when triggered.[2]

5. Application evaluation: limitations and challenges:

Thermal performance quantification limited: The literature on Aloe hydrogel specifically in cooling applications (e.g., cooling capacity per kg, cycle life, thermal conductivity) is quite limited.[2]

Thermal conductivity and heat transfer: Hydrogels (including Aloe) typically have low thermal conductivity compared to metals or filled composite PCMs, which may limit rapid cooling or heat flux capability. Without conductive fillers, the hydrogel's heat transfer may be a bottleneck.[32]

Freezing/ice‑crystal damage and mechanical integrity: If used in freezing modes (ice formation or supercooled freezing trigger), the expansion of ice crystals could damage the hydrogel matrix or cause micro-fractures, reducing cycle life.[32]

Leakage and dehydration: Over many cycles, hydrogels can lose water via evaporation or dehydration, altering cooling performance. For super-cooling, nucleation control is critical; if nucleation happens prematurely, the cooling window is lost.[32]

Scalability and cost: While Aloe is abundant, processing into high‑performance hydrogels with controlled microstructure, durability and tailored freezing behaviour may incur cost and complexity. Comparatively, bio‑PCMs have more mature encapsulation and commercial development.[32]

Sustainability and environmental impact:

Figure 10: Sustainability and environmental impact

1. Aloe vera–based hydrogels are intrinsically bio-based, biocompatible and largely biodegradable, making them attractive alternatives to petroleum-derived polymers in cooling applications.[35]
2. Because aloe gel is a natural polysaccharide (rich in acemannan and other mucilaginous sugars), aloe-hydrogels typically display high water retention and enzymatic degradability that support end-of-life biodegradation or composting under appropriate conditions.[2]
3. Replacing or supplementing energy-intensive vapor-compression refrigeration (and high- GWP refrigerants) with bio-cooling media such as aloe hydrogels could reduce lifecycle greenhouse gas (GHG) emissions from the cooling sector — which already accounts for a large and growing share of global GHGs.[36]
4. That said, net climate benefits depend on the full material lifecycle: cultivation, extraction, chemical treatments (if any), crosslinkers or grafted monomers, processing energy, transport and disposal must be quantified with a Life-Cycle Assessment (LCA) to avoid burden- shifting.[37]
5. Many published aloe hydrogel formulations for biomedical and packaging uses report low toxicity and favorable ecological profiles, but formulations that include synthetic monomers (e.g., acrylics) or heavy-metal crosslinkers can compromise biodegradability and create toxic residues if not managed.[38]
6. Water and land use for aloe cultivation are generally lower than for many agricultural feedstocks used to make biopolymers, and agro-residues (Aloe rind) can potentially be valorized to reduce waste, but regional agronomic practices determine the true environmental footprint.[39]
7. Manufacturing hotspots for hydrogels are often energy for drying/processing and chemical inputs; studies of other bio-hydrogels and polymeric aerogels show that production energy and solvent use can dominate impacts unless green processing is used.[40]
8. From an end-of-life perspective, truly bio-based and unmodified aloe hydrogels can be composted or biodegraded, lowering plastic pollution risks compared with synthetic gels — however, crosslinked or hybrid materials require dedicated waste streams or controlled degradation studies before large-scale deployment.[9]
9. Socioeconomic and circular-economy benefits include the potential for smallholder aloe farming, low-tech processing, and integration with local value chains (e.g., wound-care, packaging, bioplastics), but these gains require supply-chain development and quality control to avoid unintended environmental trade-offs.[41]
10. Policy context matters: broader gains depend on parallel shifts away from high-GWP refrigerants and on incentives for LCAs, green procurement and standards that recognize low- impact bio-cooling solutions.[42]
11. Research & reporting recommendation for your review: include (a) a comparative LCA scenario that contrasts aloe-hydrogel cooling systems with conventional refrigerant+compressor systems, (b) sensitivity analysis on processing energy and chemical additives, and (c) explicit treatment of land/water use and end-of-life options — these elements are essential to support robust sustainability claims.[47]

Enhancement strategies for aloe vera hydrogel:

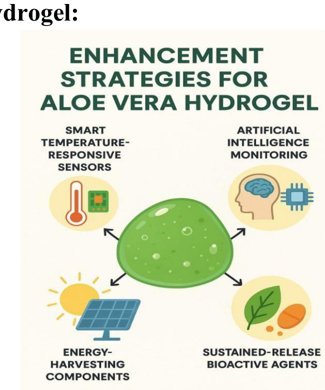

Figure 11: Enhancement strategies for aloe vera hydrogel

1. Incorporation of high-thermal-conductivity fillers:
By embedding thermally conductive particles (e.g., graphene, boron nitride, metal/metal-oxide nanofillers) into the Aloe vera hydrogel matrix, the thermal conductivity of the hydrogel can be significantly improved, thereby enhancing the ability to remove or transfer heat. For hydrogels in general, incorporation of nanocomposites is reported as an effective route to improve thermal conductivity.[43]
When applied to Aloe vera hydrogels, this could translate into faster cooling response and more efficient super-cooling retention. A supporting point: hydrogels based on Aloe vera (acemannan hydrogels) offer a large water retention capacity (up to ~99 wt %) which provides a good medium into which fillers can be dispersed.[2]
2. Optimization of cross-linking density and network architecture:
The polymer network architecture (cross-link density, pore size, connectivity) influences heat transfer, swelling behavior, mechanical stability and thaw/freeze behaviour. In hydrogels, increased crosslinking can both increase heat conduction pathways and increase phonon scattering.[44]
For Aloe vera hydrogels, tuning the network (for example by controlling acemannan gelation, or by blending with supporting polymers) can lead to enhanced mechanical durability under temperature cycling (important for super-cooling) and improved thermal response. For example, in Aloe-gel composites for biomedical uses, higher Aloe vera content and optimized network showed improved properties.[6]
3. Phase-change material (PCM) integration:
Integrating a phase-change material (PCM) into the Aloe vera hydrogel matrix can exploit latent heat absorption/release during cooling/heating, thus enhancing the super-cooling capacity (i.e., better thermal storage and release). Literature on hydrogels for thermal management emphasises embedding PCMs to boost thermal responsiveness.[22]
4. Cooling via evaporative/desorptive mechanisms:
Given the high water content of Aloe vera gels (and their high swelling/resorption potential), one route to enhance cooling is to exploit evaporative cooling: as water evaporates from the hydrogel, latent heat is removed, thereby reducing temperature.While direct literature on Aloe vera hydrogel evaporative cooling is sparse, general hydrogels in thermal applications use evaporation/latent heat removal. The Aloe vera gel’ s high water retention (≈99 %) gives good potential for this mechanism[2]
5. Hybrid cooling with additives for freeze-point/thermal-stability optimization:
For super-cooling applications (i.e., maintaining liquid at below its normal solidification point), one needs to suppress freezing and optimize thermal stability of the hydrogel matrix. In general hydrogel literature, strategies such as introducing soluble ions, organic solvents, or modifying polymer chains are used to reduce freezing point and improve thermal stability.[43]
6. Surface functionalization and architecture design for enhanced heat-transfer:
Another strategy is to design the Aloe vera hydrogel’s macro/micro-architecture to support enhanced heat transfer: for example, creating aligned channels, anisotropic filler alignment, or thin layered structures that increase conduction path and reduce thermal resistance. Literature in hydrogels for thermal management shows that directionally aligned fillers or network architectures can improve thermal conductivity.[22]
7. Durability and cycling stability for practical applications:
For a super-cooling medium in a “bio-cooling revolution”, the material must sustain multiple cooling/heating cycles without degradation (mechanical, thermal, structural). For Aloe vera hydrogels, enhancing durability involves preventing dehydration (maintaining water content), avoiding microbial growth or gel breakdown, ensuring fillers remain dispersed, and maintaining network integrity. Literature on Aloe vera hydrogels primarily in wound-healing shows that high-content Aloe vera hydrogels can be designed with stability in mind.[6]
8. Integration with system-level cooling design:
Finally, to realize the potential of Aloe vera hydrogels as a natural super-cooling medium, they should be integrated into system - level design: e.g., embedding hydrogel layers in heat - exchange modules, constructing hydrogel cooling jackets, coupling with radiative cooling surfaces, or using them in passive thermal storage panels. While this is more on

the application side than material enhancement, designing the hydrogel with system compatibility in mind (mechanical form factor, thermal contact, ease of implementation) is an important enhancement strategy.Given that the reviewed article on Aloe vera hydrogels for super-cooling specifically emphasises the potential of acemannan hydrogels for super-cooling devices.[2]

II. CONCLUSION

The emergence of aloe vera hydrogel as a natural super-cooling medium represents a significant advancement in the field of bio-cooling and sustainable thermal management. Its unique physicochemical characteristics — such as high-water content, biocompatibility, thermal buffering capacity, and slow evaporation rate — enable efficient cooling while minimizing the risk of tissue damage or environmental hazards commonly associated with synthetic refrigerants. Advancements in polymer reinforcement, nanotechnology integration, and cross- linking strategies have further enhanced its mechanical stability and cooling performance, making it a competitive alternative to conventional cooling materials.

Moreover, aloe vera-based hydrogels address global demands for eco-friendly and energy- efficient cooling systems, particularly in biomedical applications including cryopreservation, first-aid burn management, drug delivery, and wearable temperature-control devices. Despite its promising potential, challenges such as microbial degradation, dehydration, limited long- term durability, and standardization issues still require research focus.

Overall, the bio-cooling revolution driven by aloe vera hydrogel underscores a future where natural materials can successfully replace hazardous, energy-intensive cooling technologies. Continued innovations in formulation and large-scale production will be essential to fully unlock its clinical, industrial, and environmental benefits — positioning aloe vera hydrogel as a key contributor to the next generation of sustainable cooling solutions.

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