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Solar Adsorption Refrigeration: Materials, Cycles, and System Integration

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Abstract: Solar-driven adsorption refrigeration has emerged as a sustainable alternative to conventional vapor-compression cooling because it can utilize low-grade thermal energy and environmentally benign working fluids. Recent research has focused on improving adsorption materials, optimizing thermodynamic cycle configurations, and integrating systems into buildings and cold-chain applications to enhance overall coefficient of performance (COP), specific cooling power (SCP), and economic feasibility. Studies demonstrate that advanced adsorbents such as silica gel composites, activated carbon, zeolites, and metal–organic frameworks significantly improve adsorption capacity and heat–mass transfer characteristics, thereby enabling higher cooling efficiency under variable solar conditions.

In parallel, innovations in cycle design—including multi-bed configurations, heat and mass recovery strategies, and hybrid solar-assisted layouts—have contributed to improved operational stability and reduced energy consumption. System-level investigations further highlight the importance of climatic suitability, thermal storage integration, and techno-economic optimization for real-world deployment in residential buildings and agricultural cold storage. Despite measurable progress, challenges remain in material durability, intermittency of solar input, and large-scale cost competitiveness.

This review synthesizes recent advances in working-pair selection, cycle innovation, and integrated system design to provide a consolidated framework for future development of high-performance solar adsorption refrigeration technologies suitable for sustainable cooling and cold-chain preservation.

***Index Terms* - Solar adsorption refrigeration; Adsorbent–refrigerant working pair; Silica gel–water; Activated carbon–methanol; Metal–organic frameworks (MOFs); multi-bed adsorption chiller; Coefficient of performance (COP); Specific cooling power (SCP); Solar thermal integration; Cold-storage applications.**

I. Introduction

The increasing global demand for cooling has led to higher electricity consumption and environmental concerns associated with conventional vapor-compression refrigeration systems. To address these challenges, solar-driven adsorption refrigeration has gained attention as a sustainable alternative because it can utilize low-grade thermal energy and environmentally friendly working fluids instead of mechanical compression. Recent research in this field focuses on three key aspects: improvement of adsorbent–refrigerant working pairs to enhance cooling performance, development of advanced thermodynamic cycles and multi-bed configurations for higher efficiency under variable solar conditions, and system integration for applications such as residential buildings and agricultural cold storage. Despite significant progress, challenges related to solar intermittency, heat and mass transfer limitations, material durability, and economic feasibility remain. Therefore, a comprehensive review of materials, cycle innovations, and integrated system layouts is essential to support the development of efficient and scalable solar adsorption refrigeration technologies.

II. LITERATURE REVIEW

Mishra (2026) et al. – performed a life-cycle oriented assessment for solar-powered cold storage chains in rural India, directly connecting sorption-based refrigeration relevance to post-harvest loss reduction and sustainability metrics. These supports expanding the review's application scope beyond buildings into cold-chain and rural deployment, where low-electricity dependence is a primary advantage

Alsaman (2026) et al. – proposed a hybrid concept combining solar heating + geothermal cooling to avoid heavy water consumption and performance penalties associated with conventional cooling towers for adsorption systems. By using geothermal cooling to reject heat from the condenser and remove adsorption heat, they reported notable improvements in cooling capacity and COP, framing "integrated sinks/sources" (not only solar collectors) as a strong future direction for robust deployment.

Shao (2026) et al. – although focused on *MOF-based sorption composites for atmospheric water harvesting*, the paper is still relevant for adsorption cooling reviews because it shows how MOF composites can significantly enhance sorption-driven performance under real climates, strengthening the argument that next-generation porous materials (MOFs/composites) can translate into measurable system-level gains when stability and heat/mass transfer are addressed.

Ward (2025) et al. – performed a techno-economic assessment of a *solar-driven adsorption-based space-conditioning system* for low-energy multi-unit residential buildings in Canada, where adsorption is used to convert *excess solar heat* into cooling during summer while also supporting annual space heating/DHW via solar thermal. They emphasized that adsorption-based space conditioning can significantly reduce emissions in principle, but economic feasibility is strongly linked to grid carbon intensity, local climate, and capital cost, making policy and jurisdictional context critical.

Benramdane (2025) et al. – developed a modelling-and-optimization study under real weather conditions (Algeria) using a Dubinin–Astakhov (D–A) adsorption framework to quantify how operating parameters, collector location/site, and working-pair choice affect system performance. Their approach is important for review synthesis because it ties working-pair selection directly to solar variability and operating control rather than treating it as a purely materials-only decision.

Brice Clausel (2025) et al. – modelled a two-bed silica gel–water adsorption chiller and demonstrated that mass recovery, heat recovery, and combined heat+mass recovery can substantially improve performance (COP/SCP), making cycle "enhancement modes" a central pathway for competitiveness. The work also consolidates the idea that adsorption cooling performance is highly sensitive to condenser/evaporator temperature levels and that recovery strategies are among the most practical levers for uplift without changing the whole system architecture.

Hadi (2025) et al. – presented a broad review-style synthesis of adsorbent-material innovations, cycle design improvements, and integration challenges, explicitly highlighting that adoption is limited mainly by high upfront costs, climate dependence, maintenance/skills gaps, and market acceptance relative to conventional vapor-compression systems. Their discussion supports positioning your review around *working pairs + cycle innovations + integrated layouts* as the three pillars that jointly determine real-world feasibility.

Alhialy (2024) et al. – focused on dimensioning (sizing) of solar adsorption-powered cooling in hot regions, and their literature synthesis emphasized that low performance remains a key obstacle and that improvements are pursued through adsorbent-bed design, conductivity enhancement, multi-stage concepts, fins/additives, and geometry optimization (targeting COP/SCP gains). This positioning reinforces that "good cycle theory" is not enough; scalable adoption needs design rules and sizing methodology**.**

Mohammed (2024) et al. – studied a solar adsorption cooling system using activated carbon-based operation (activated carbon working concept) and contributes to the evidence base that carbonaceous adsorbents remain relevant for solar-driven adsorption due to regeneration feasibility and practical availability, especially when paired with suitable refrigerants and heat-exchanger designs.

Mostafa (2022) et al. – addressed the under-studied area of cold-store applications by building a transient simulation framework for a solar-assisted adsorption refrigeration system supplying a 60 m^3 cold store, and explicitly pointed out that much of the prior literature concentrates on air-conditioning while dynamic interaction between loads and storage temperatures in cold chains is less explored. They presented a full system schematic (solar field + adsorption chiller + cold store + fan coil unit) and evaluated performance using annual energy, COP, solar fraction, and levelized cost of cooling.

Missaoui (2022) et al. – investigated thermal/heat storage coupling for solar-assisted adsorption systems specifically in the context of preserving fruits, treating storage not as an optional add-on but as a requirement to stabilize cooling when solar input fluctuates. Their work supports the repeated conclusion across solar adsorption research that storage integration is essential for reliability in agri-cold-chain use cases (especially in off-sun hours).

III. Basic Principle of Solar Adsorption Refrigeration System

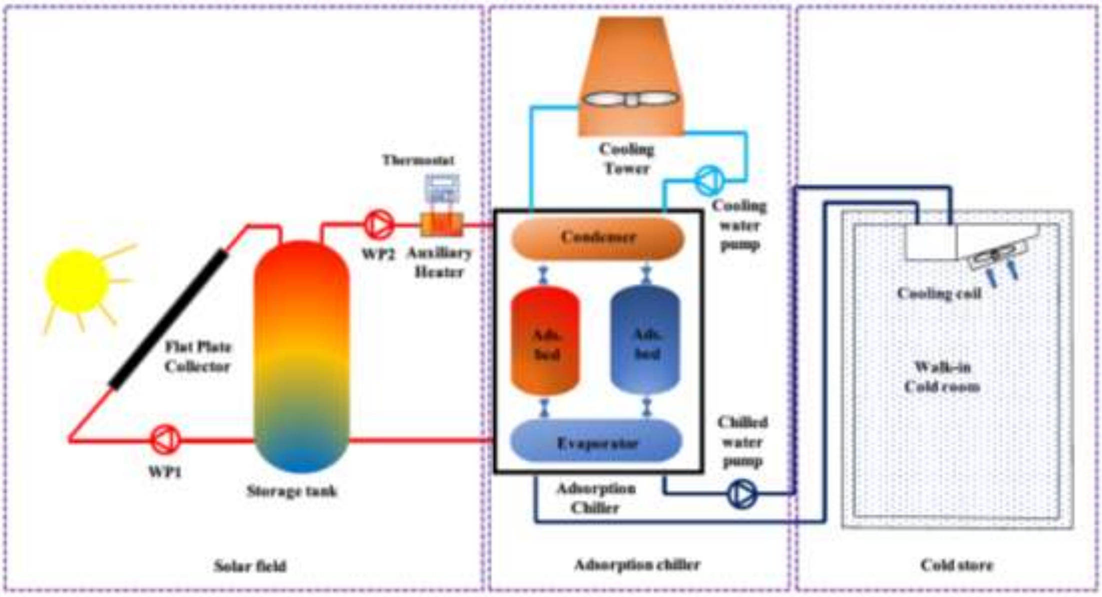

Fig.1 - Schematic diagram for a solar assisted adsorption chiller utilized for a cold store

III.I Fundamental Concept

Solar adsorption refrigeration is a thermally driven cooling technology that produces refrigeration using solar heat instead of electricity-driven mechanical compression. The system works on the physical phenomenon of adsorption, in which a refrigerant vapor is attracted and held on the surface of a porous solid material called an adsorbent. Typical components include:

- Solar thermal collector
- Adsorbent bed (silica gel, activated carbon, zeolite, MOF, etc.)
- Condenser
- Evaporator
- Expansion valve or throttling device
- Heat exchanger and cooling water loop

Because the process is driven by low-temperature solar heat, the system is environmentally friendly and suitable for regions with high solar radiation.

III.II Working Principle (Adsorption–Desorption Cycle)

The solar adsorption refrigeration cycle operates in four main thermodynamic steps**:**

(1) Adsorption Phase – Cooling Production

- The adsorbent bed is cooled by circulating cooling water.
- The refrigerant inside the evaporator evaporates at low pressure, absorbing heat from the refrigerated space and producing the cooling effect.
- The generated vapor moves to the adsorbent bed and is adsorbed onto the porous material.
- This maintains low evaporator pressure, allowing continuous evaporation and cooling.
- Result: Refrigeration is produced in the evaporator.

(2) Heating / Desorption Phase – Solar Regeneration

- Solar collectors heat the adsorbent bed.
- As temperature increases, the adsorbent releases (desorbs) the refrigerant vapor**.**
- The released vapor flows toward the condenser at higher pressure**.**
- Result: Solar heat regenerates the adsorbent for the next cycle.

(3) Condensation Phase

- The desorbed refrigerant vapor enters the condenser**.**
- Heat is rejected to ambient air or cooling water.

- Vapor condenses into liquid refrigerant**.**
- Result: Liquid refrigerant is stored for the next cooling step.

(4) Expansion & Evaporation Phase

- The condensed liquid passes through an expansion device, reducing its pressure.
- Low-pressure liquid enters the evaporator.
- It evaporates by absorbing heat from the cooling load (room, cold storage, etc.).
- Result: Cooling effect is generated again, and the cycle repeats.

III.III Continuous Cooling Using Multi-Bed Systems

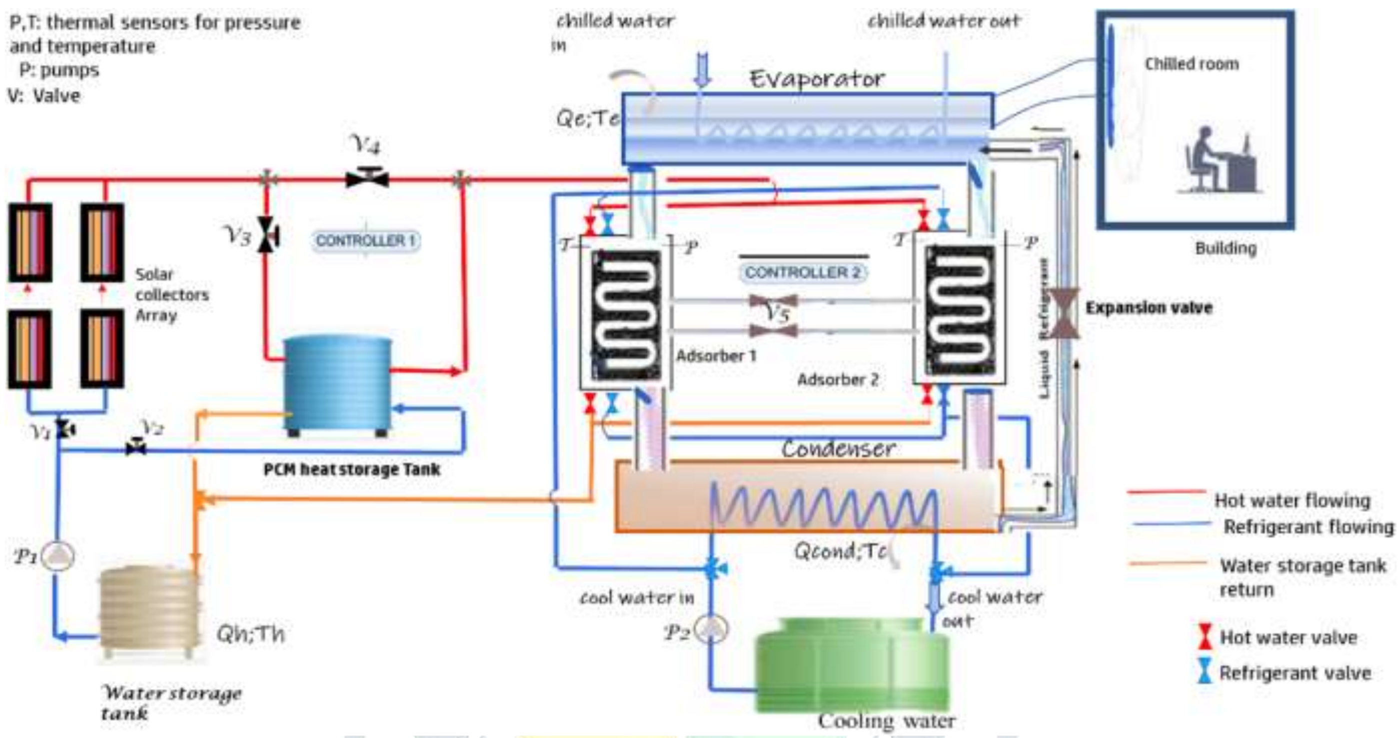

Fig.2 – Adsorption System Design

A single adsorption bed produces intermittent cooling because adsorption and desorption cannot occur simultaneously. Therefore, practical solar adsorption chillers use:

- Two-bed systems
- Multi-bed configurations
- Heat and mass recovery between beds

These arrangements allow quasi-continuous cooling and improve:

- Coefficient of Performance (COP)
- Specific Cooling Power (SCP)
- System stability under fluctuating solar radiation

III.IV Energy Flow in Solar Adsorption Refrigeration

The complete energy transformation can be summarized as:

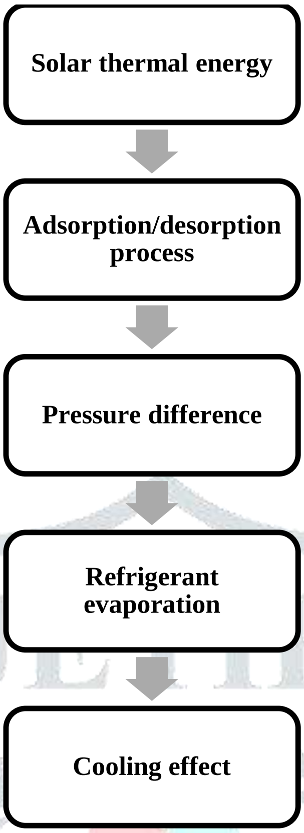

Fig. 3 – Energy Flow in Solar Adsorption Refrigeration

Thus, the system converts renewable heat energy into useful refrigeration without mechanical compression.

IV. Selection of Working Pair

IV.I Meaning of "Working Pair"

In solar adsorption refrigeration, a working pair means:

- Adsorbent (solid porous material): silica gel, activated carbon, zeolite, MOF, composites
- Adsorbate / refrigerant (working fluid): water, methanol, ethanol, ammonia, etc.

The pair is selected so that adsorption and desorption can occur effectively at solar-heating temperatures and required cooling temperatures.

IV.II Why Working-Pair Selection is Critical

The working pair directly controls:

- COP (Coefficient of Performance) and SCP (Specific Cooling Power)
- Required regeneration/desorption temperature (important for solar collector selection)
- Safety (toxicity, flammability, corrosiveness)
- Operating pressure level (vacuum constraints, sealing requirements)
- Long-term cycle stability and maintenance cost

A key conclusion from modelling studies is that system performance varies strongly with the pair choice and local solar/operating conditions.

IV.III Core Selection Criteria REPORTED:

The most explicit "selection framework" is given for building-integrated adsorption cooling (facade-integrated ACFS). That work defines requirements such as:

1. Non-toxic and environmentally friendly
2. Low cost
3. Long service life and good cycle stability
4. Low regeneration temperature
5. High adsorption capacity
6. Low enthalpy of adsorption (to limit heat generation during adsorption)

It also stresses application suitability: in residential/building integration, safety and non-toxicity become dominant constraints, so water is preferred as adsorbate under the non-hazard principle.

IV.IV Application-Based Working-Pair Selection

(A) Building Cooling (especially residential / facade-integrated)

- Preferred adsorbate: Water (safe and non-toxic).
- Typical adsorbents: silica gels, some molecular sieves/zeolites, selected carbons (if compatible with design constraints). The facade-screening study narrowed hundreds of candidates by screening (cost, stability, driving temperature, adsorption capacity) and then evaluating system metrics such as adsorber temperature and cooling power.
- Design implication: building-integrated systems often prioritize low regeneration temperature to improve collector efficiency and reduce peak adsorber temperature.

(B) Cold Storage / Agricultural Refrigeration

- Cold-store work frequently selects silica gel–water because it is widely used for cooling with low-temperature heat sources (< 100 °C), which matches typical solar thermal delivery.
- Design implication: for cold rooms, you need stable performance under daily solar fluctuations; therefore, pair selection is linked to the ability to run with realistic collector outlet temperatures and available thermal storage.

IV. V Common Working Pairs and What the Papers Indicate

1) Silica gel – Water

- Widely used for low-temperature, solar-driven adsorption cooling, including two-bed systems and cold-store modelling.
- Favoured because water is safe and silica gel is practical and commercially established, especially for building applications.
- Limitation: vacuum operation and heat/mass transfer limitations can restrict SCP unless the bed design/cycle is optimized.

2) Zeolite – Water

- Can achieve strong COP in some comparative analyses (especially when heat and mass recovery is used). A comparison cited in the two-bed modelling paper reports zeolite/water with recovery reaching the highest COP among several pairs considered.
- Often requires higher regeneration temperature than silica gel depending on zeolite type, so it must be matched carefully to collector technology.

3) Activated Carbon – Methanol / Ethanol / Ammonia

- The activated-carbon review paper summarizes carbon-based options and notes that activated carbon can be paired with methanol, ethanol, or ammonia, and carbon-fiber variants are also studied.
- For ice-making / low-temperature refrigeration, literature comparisons indicate activated carbon–methanol performed better than activated carbon–ethanol in some solar ice-maker contexts.
- Ethanol is described as non-toxic, chemically stable, eco-friendly, and attractive for low-freezing-point operation, although its adsorption heat is typically lower than methanol.

❖ **Trade-off:**

- Methanol often offers stronger performance but has toxicity concerns.
- Ethanol improves safety but may reduce performance in some designs.

V. Process of Solar Adsorption Refrigeration System

V.I Overview of the Process

The solar adsorption refrigeration process converts solar thermal energy into cooling through a cyclic sequence of adsorption and desorption. Unlike vapor-compression systems, this process does not use a mechanical compressor**.** Instead, pressure variation is created by heating and cooling the adsorbent bed**.** The complete operation occurs in a repeating thermodynamic cycle that produces refrigeration continuously when two or more adsorption beds are used.

V.II Main Stages of the Adsorption Refrigeration Cycle

The working process consists of four fundamental stages.

Stage-1: Adsorption and Cooling Production

- The adsorbent bed is cooled using cooling water or ambient air.
- Refrigerant inside the evaporator evaporates at low pressure.
- During evaporation, the refrigerant absorbs heat from the cooling space, producing the refrigeration effect.
- The generated vapor moves toward the adsorbent bed and becomes adsorbed on the porous surface.
- Outcome: Continuous adsorption maintains low pressure in the evaporator, allowing steady cooling.

Stage-2: Heating and Desorption (Solar Regeneration)

- Solar collectors supply hot water or thermal energy to the adsorbent bed.
- Rising temperature causes the adsorbent to release the previously adsorbed refrigerant vapor.
- The released vapor pressure increases and flows toward the condenser.
- Outcome: Solar heat regenerates the adsorbent, preparing it for the next cooling cycle.

Stage-3: Condensation of Refrigerant

- High-pressure refrigerant vapor enters the condenser**.**
- Heat is rejected to cooling water or surrounding air.
- Vapor changes into liquid refrigerant and is stored temporarily.
- Outcome: Liquid refrigerant becomes available for the next evaporation step.

Stage-4: Expansion and Evaporation

- Liquid refrigerant passes through an expansion valve or capillary tube.
- Pressure suddenly drops to evaporator level.
- Low-pressure liquid enters the evaporator and evaporates by absorbing heat from the refrigerated space.
- Outcome: Cooling effect is produced again, and the cycle repeats continuously**.**

V.III Intermittent vs Continuous Operation

Single-Bed System

- Adsorption and desorption occur one after another, not simultaneously.
- Cooling is therefore intermittent.
- Suitable mainly for small or experimental systems.

Multi-Bed System (Two-Bed or More)

- One bed performs adsorption while the other performs desorption.
- Beds switch periodically using valves and heat transfer control.
- Provides quasi-continuous cooling, higher COP, and improved system stability.
- This configuration is widely used in practical solar adsorption chillers.

V.IV Heat and Mass Recovery in Advanced Cycles

Modern adsorption systems include performance-enhancement processes, such as:

- Heat recovery between hot and cold beds
- Mass recovery of refrigerant vapor between beds
- Combined heat-and-mass recovery cycles.

These techniques:

- Reduce energy loss
- Increase cooling capacity
- Improve overall coefficient of performance (COP)
- Thus, cycle design optimization is as important as material selection for high efficiency.

V.V Energy Transformation in the Process

The overall energy pathway in solar adsorption refrigeration is:

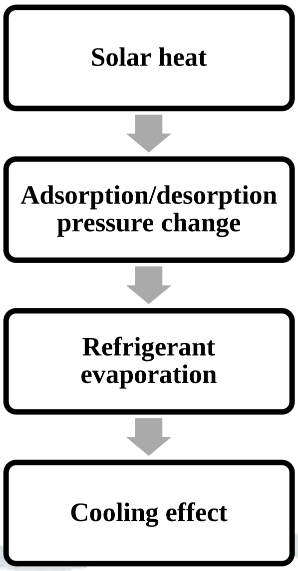

Fig. 4 - Overall Energy Pathway in Solar Adsorption Refrigeration

Therefore, the system produces refrigeration using:
- Renewable thermal energy
- Environment-friendly working fluids
- Minimal electricity consumption (only for pumps and valves)

V.VI Key Practical Observations

- Performance strongly depends on solar temperature, cycle timing, and working pair.
- Thermal storage can stabilize operation during low-sunshine periods.
- Hybrid heat-rejection methods (e.g., geothermal or improved cooling water systems) can further enhance efficiency.
- These process-level improvements are essential for real-world deployment in buildings and cold-storage applications.

VI. System Layout
VI.I Overview of System Layout

The system layout of a solar adsorption refrigeration system represents the physical arrangement and interconnection of all major components required to convert solar thermal energy into useful cooling. A typical layout integrates:
- Solar heat collection
- Thermal energy storage
- Adsorption refrigeration unit
- Heat rejection system
- Cooling distribution to the load (room or cold storage)

The effectiveness of the overall system strongly depends on proper component arrangement, heat-transfer paths, and control of fluid circulation.

VI.II Main Components in the Layout

1. Solar Thermal Collector
- Captures solar radiation and converts it into hot water or thermal energy.
- Supplies the required desorption temperature to the adsorbent bed.
- Common types:
  - Flat-plate collectors
  - Evacuated tube collectors
- Collector performance directly influences system COP and cooling capacity.

2. Hot Water Storage Tank (Thermal Storage)
- Stores excess solar heat during peak sunshine hours.
- Supplies heat to the adsorption bed during low or fluctuating solar radiation.
- Ensures stable and longer operating hours of the cooling system.
- Thermal storage is especially important for cold-storage and building applications.

3. Adsorption Chiller Unit

This is the core component of the system and includes:

- Adsorbent beds (single, double, or multi-bed)
- Condenser
- Evaporator
- Valves and heat exchangers

The adsorption chiller performs the adsorption–desorption refrigeration cycle and produces the cooling effect. Multi-bed arrangements are commonly used to achieve continuous cooling and higher efficiency**.**

4. Heat Rejection System

- Removes heat from the condenser and adsorbent bed during adsorption.
- Usually consists of:
  - Cooling tower
  - Cooling water loop
  - Dry air cooler
  - Geothermal heat sink (in hybrid systems)
- Efficient heat rejection is essential to maintain low condenser temperature and higher COP.

5. Cooling Distribution System

- Transfers produced cooling to the application space, such as:
  - Residential room air conditioning
  - Cold storage chamber
  - Agricultural preservation unit

Typically includes:

- Chilled water loop
- Fan coil unit or air handling unit
- Insulated piping network

VI.III Flow Arrangement in the Complete Layout

- The overall flow sequence in a solar adsorption refrigeration layout is:

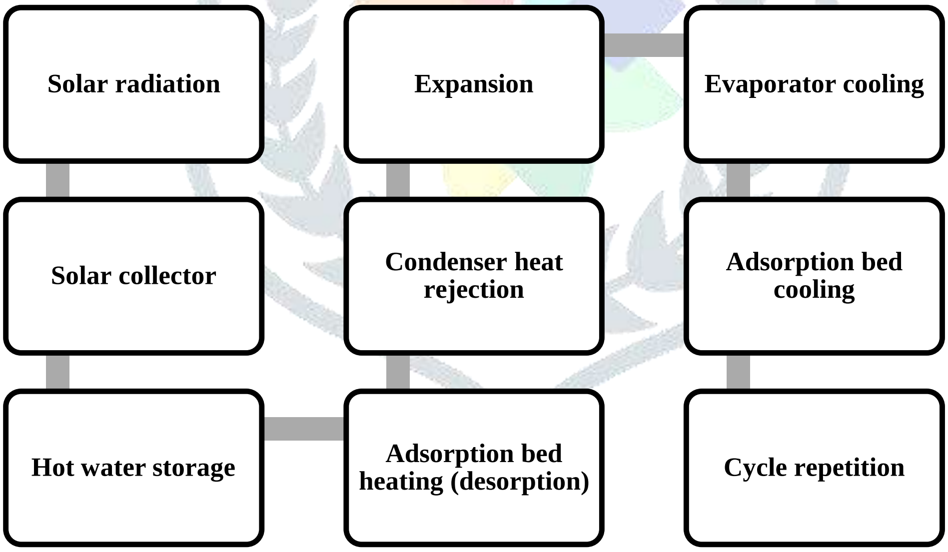

Fig.5 - Overall Flow Sequence in a Solar Adsorption Refrigeration Layout

- This closed-loop arrangement enables continuous conversion of solar heat into refrigeration**.**

VI.IV Variations in Practical Layouts

Different applications use modified layouts:

A. Building Cooling Systems

- Integrated with space conditioning and domestic hot water.
- May include facade-mounted collectors or roof solar arrays.
- Focus on energy savings and emission reduction.

B. Agricultural Cold Storage Systems

- Include large insulated cold rooms and thermal storage tanks.

- Designed for stable temperature maintenance during night hours.
- Useful in rural or off-grid regions.

C. Hybrid Solar Systems

- Combine solar heating with geothermal or auxiliary heat rejection.
- Improve continuous operation and efficiency when solar input fluctuates.

VII. Conclusion

Solar adsorption refrigeration is a clean and sustainable cooling technology that operates using solar thermal energy and environmentally safe working fluids instead of mechanical compression.

Recent studies show clear progress in:

- Improved working pairs (silica gel, activated carbon, zeolites, MOFs)
- Advanced cycle designs (multi-bed systems, heat and mass recovery)
- Real applications in buildings, cold storage, and hybrid renewable systems

However, practical deployment is still limited by:

- Solar intermittency
- Low heat–mass transfer inside adsorbent beds
- Material durability issues
- High initial system cost

Thus, the technology is promising but not yet fully commercialized.

VIII. Future Scope

Future development should focus on:

- Next-generation adsorbent materials with higher capacity and stability
- Optimized multi-bed thermodynamic cycles for continuous cooling
- Enhanced heat-transfer and thermal-storage integration
- Hybrid renewable integration (geothermal, waste heat, smart solar control)
- Cost reduction and life-cycle sustainability improvement

With these advancements, solar adsorption refrigeration can become a practical low-carbon solution for buildings, agriculture, and off-grid cooling in the near future.

REFERENCES

[1] Mishra, N. 2026. Life-Cycle Analysis of Solar-Powered Cold Storage Chains for Reducing Post-Harvest Losses in Rural India Journal of Environmental Sustainability, Climate Resilience, and Agro-Ecosystems, 3(1): 17-23.

[2] Alsaman, A. 2026. A new combination of a solar-powered adsorption cooling system with a geothermal cooling source, Adsorption (2026) 32:7, 1-20.

[3] Shao, Z. 2026. Synergistic MOF-based composite enabling significant solar-to-water generation enhancement in climate-resilient AWH, Nature Communications.

[4] Ward, C. 2025. Technoeconomic assessment of a solar-driven adsorption-based space conditioning system for low-energy multi-unit residential buildings in Canada, Applied Thermal Energy, 1-15.

[5] Benramdane, M. 2025. Modeling and Optimization of a Solar Adsorption Cooling System under Weather Conditions in Algeria, Journal of Renewable Energy and Sustainable Development (RESD), 11(1): 106-116.

[6] Clausel, B. 2025. Performance modelling of a two-bed silica gel-water pair adsorption chiller, Results in Engineering.

[7] Hadi, F. 2025. Solar Adsorption Cooling: Innovations in Adsorbent Materials and Cycle Design, Al-Rafidain Journal of Engineering Sciences.3(1): 167-190.

[8] Alhialy, N. 2024. Dimensioning of a Solar Adsorption-Powered Cooling Bed for Generating Relief Cooling, International Journal of Heat and Technology. 42(3): 830-850.

[9] Mohammed, M. 2024. Solar adsorption cooling system operating by activated–carbon–ethanol bed, International Journal of Renewable Energy Development. 13(3): 430-447.

[10] Mostafa, A. 2022. Transient simulation and design parameters optimization of a cold store utilizes solar assisted adsorption refrigeration system, Case Studies in Thermal Engineering.

[11] Missaoui, K. 2022. Heat storage in solar adsorption refrigeration systems: A case study for indigenous fruits preservation, Case Studies in Thermal Engineering.