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Sorption Refrigeration Technologies: Literature Review

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Abstract

Sorption-based refrigeration systems, encompassing both absorption and adsorption cycles, have emerged as promising alternatives to conventional vapor-compression technologies for sustainable cooling applications. These systems offer significant advantages in terms of energy efficiency, environmental compatibility, and their potential integration with renewable energy sources such as solar thermal systems. This paper presents a comprehensive review of recent developments in sorption refrigeration technologies, focusing on working pairs, thermodynamic performance, system configurations, and heat management strategies. The analysis highlights the comparative performance of common working pairs such as NH_3-H_2O and LiBr-H_2O under various climatic and operational conditions. Special attention is given to dynamic modeling approaches, heat and mass transfer mechanisms, and innovations in adsorbent and absorbent materials, including metal-organic frameworks (MOFs) and composite sorbents. The review also discusses hybrid and solar-assisted configurations, as well as phase-change material (PCM) integration for improved system stability and efficiency. Overall, this work consolidates current knowledge, identifies existing challenges, and outlines future directions toward higher energy performance, reduced intermittency, and large-scale deployment in tropical climates.

Keywords

Absorption, Adsorption, Sorption Refrigeration, NH_3-H_2O, Solar Cooling, Dynamic Modeling, Renewable Energy

1. Introduction

Cooling and heating in buildings account for approximately 30% - 50% of global energy consumption, making improvements in their efficiency a crucial strategy to reduce total energy demand [1]. Traditional refrigeration systems employ chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs), which are harmful to the ozone layer and contribute significantly to global warming. The international community, through the Vienna Convention (1985) and the Montreal Protocol (1987), has established measures to phase out these substances. However, environmental deterioration persists, with significant ozone depletion still being observed [2]. The refrigeration sector represents about 17% of global electricity-related emissions [3]. Solar cooling for small- and medium-scale applications remains an emerging field with considerable potential for sustainable development [4]-[6]. Existing solar refrigeration systems based on sorption phenomena exploit either liquid-gas absorption processes or solid-gas adsorption processes. This paper presents a systematic and critical review of recent advances in solar-powered sorption refrigeration technologies, highlighting thermodynamic principles performance indicators, modeling techniques, and practical applications.

2. Methodology of the Literature Review

This literature review was carried out to provide a clear and up-to-date overview of the current state of research on sorption-based refrigeration technologies. To achieve this, relevant publications were collected from major scientific databases including ScienceDirect, Scopus, and Google Scholar S… The main keywords used in the search were: solar cooling, sorption refrigeration, adsorption and absorption systems, NH_3-H_2O, LiBr-H_2O, activated carbon-methanol, and solar thermal cooling. The focus was placed on studies published between 2010 and 2025, giving priority to recent works presenting experimental results, system modeling, or hybrid configurations using renewable energy sources. Articles were selected based on their contribution to the understanding of system performance, thermodynamic modeling, or material innovation. Publications that did not include quantitative performance data or that focused solely on system control without a thermal analysis were excluded.

3. Solar Sorption Refrigeration Technologies

3.1. Adsorption Systems

Adsorption is the process in which molecules from one phase (usually vapor) accumulate on the surface of a solid adsorbent. Conversely, absorption involves the transfer of a substance from one phase into the bulk of another. The key differences between these two mechanisms lie in the nature of the sorbent and the time required for the sorption cycle, which is generally longer for adsorption [7]. To evaluate the performance of a sorption machine, the solar COP ($\mathrm{COP}_{\mathrm{Solar}}$) and the thermal COP ($\mathrm{COP}_{\mathrm{Thermal}}$) must be evaluated. These two COPs are defined as follows:

$$\mathrm{COP}_{\mathrm{thermal}} = \frac{\dot{Q}_{\mathrm{cold}}}{\dot{Q}_{\mathrm{hot}}} \quad (1)$$

$$\mathrm{COP}_{\mathrm{solar}} = \frac{\dot{Q}_{\mathrm{cold}}}{\dot{Q}_{\mathrm{solar}}} \tag{2}$$

$$\mathrm{COP}_{\mathrm{solar}} = \mathrm{COP}_{\mathrm{thermal}} \times \eta_{\mathrm{solar\ collector}} \tag{3}$$

$\dot{Q}_{\mathrm{cold}}$: Cooling capacity (W); $\dot{Q}_{\mathrm{hot}}$: Heat supplied to the generator (W); $\dot{Q}_{\mathrm{solar}}$: Solar energy input (W); $\eta_{\mathrm{solar\ collector}}$: Efficiency of the solar collector.

3.1.1. Operating Principle

The ideal adsorption refrigeration cycle consists of four thermodynamic processes, commonly represented on a Clapeyron diagram (**Figure 1**). During heating (A-B-D), the adsorbent releases the refrigerant vapor, which condenses at point C. Upon cooling (D-F-A), adsorption resumes as the refrigerant vapor is reabsorbed, producing the cooling effect in the evaporator [8].

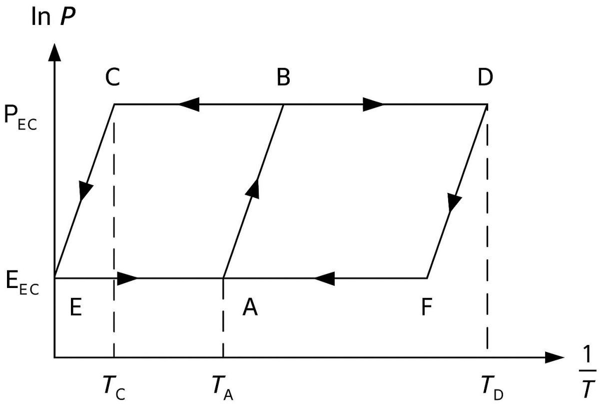

Figure 1. Clapeyron diagram of ideal adsorption cycle.

3.1.2. Critical Review and Comparative Analysis of Solar Adsorption Refrigeration

Adsorption cooling dates back to the 19th century, when Faraday first demonstrated vapor adsorption using solid sorbents. Early solid-vapor systems were technically simple but inefficient [9]. Recent developments have focused on improving performance through material optimization and system integration.

Early industrial development of adsorption refrigeration technology, notably introduced to the U.S. market by Nishiyodo Kuchouki Company Ltd. in 1986 [10], demonstrated the feasibility of adsorption systems for thermal refrigeration and related applications such as separation and purification processes [11]. However, subsequent research has highlighted that system performance remains highly sensitive to design choices and operating constraints.

From a working-pair perspective, activated carbon-methanol and silica gel-water dominate the literature, each offering distinct advantages and limitations. Mohand Berdjaa *et al.* [12], developed a solar-powered adsorption refrigeration system based on the activated carbon-methanol pair, explicitly targeting socio-economic constraints through low-cost components, minimal maintenance, and a valve-free configuration. Their semi-pilot prototype achieved a thermal COP of

0.49, which is relatively high for methanol-based systems operating with low-grade solar heat. This performance reflects a deliberate compromise: the system prioritizes technological simplicity and compatibility with low-temperature solar collectors over maximum thermodynamic efficiency. Nevertheless, the limited adsorption capacity and slower mass transfer kinetics of methanol on activated carbon inherently restrict further COP improvement.

In contrast, systems employing the silica gel-water pair generally report higher COP values due to superior adsorption affinity and faster kinetics. Ghilen Najeh *et al.* [13] achieved a COP of 0.62 and a cooling capacity of 5.64 kW using a two-bed silica gel-water system. The enhanced performance is not solely attributable to the working pair but also to the adoption of a multi-bed configuration and improved thermal management. Their validated numerical model further demonstrates that precise control of heat and mass transfer processes is essential to exploit the full potential of silica gel-water systems. However, these gains come at the expense of increased system complexity and a higher sensitivity to ambient temperature, particularly during heat rejection.

Experimental investigations by Himsar Ambarita and Hideki Kawai [14], further illustrate the influence of adsorbent composition on performance. By testing activated alumina, activated carbon, and mixed adsorbent beds under identical flat-plate solar collector conditions, they showed that pure activated carbon achieved the highest average COP (0.074), although absolute COP values remained low. These results emphasize that material selection alone is insufficient to achieve competitive performance without optimized heat transfer and cycle control.

Several studies underline the critical role of solar heat supply and thermal management. Rifat Ara Rouf *et al.* [15] demonstrated that integrating thermal energy storage with silica gel-water adsorption chillers improves operational stability and overall efficiency compared to direct solar coupling, albeit at the cost of additional collector area. Similarly, Sourav Mitra *et al.* [16] showed through simulation that cycle time optimization is essential to balance specific cooling capacity and COP, particularly under varying heat source temperatures. Their results indicate that COP is relatively insensitive to heat source temperature, whereas cooling capacity strongly depends on cycle timing and thermal input quality. Climatic operating conditions also significantly affect system performance. Under Dhaka climatic conditions, Rifat Ara Rouf *et al.* [17] reported a COP of approximately 0.35 and a cooling capacity of 10 kW, highlighting the detrimental impact of high ambient temperatures on heat rejection processes. These findings confirm that adsorption systems must be specifically adapted to local climatic constraints to maintain acceptable performance.

Material enhancement and compact system design represent two additional pathways explored in the literature. Shahab Edin Hamrahi *et al.* [18] demonstrated that incorporating nano-activated carbon into activated carbon-methanol beds can improve adsorption capacity and enhance performance by up to 33%, partially mitigating intrinsic material limitations. Shu Xu [19] and Zhaohong He *et al.* [20] independently emphasized the importance of heat and mass recovery, compactness, and advanced valve control. Their results show that simple single-bed systems suffer from low COP due to poor thermal utilization, whereas multi-bed configurations and compact designs significantly improve specific cooling power and volumetric performance.

Advanced cycle configurations further expand the operating envelope of adsorption systems. Z. H. He *et al.* [21] demonstrated that two-stage adsorption chillers can operate with driving source temperatures as low as 45˚C, albeit with moderate COP values. Complementarily, K. M. Ariful Kabir *et al.* [22] showed that incorporating mass recovery into two-bed solar adsorption systems can enhance cooling capacity by approximately 9%, confirming that system-level optimization strategies are as critical as material selection.

Overall, the reviewed studies highlight a fundamental trade-off in solar adsorption refrigeration technology. Systems emphasizing low cost, simplicity, and low-temperature operation achieve moderate COP values but offer high socio-economic relevance, particularly for decentralized applications. Conversely, higher-efficiency systems rely on advanced materials, multi-bed configurations, heat and mass recovery, and higher-quality solar heat, resulting in increased complexity and cost. Consequently, the selection and design of solar adsorption refrigeration systems must be guided by application-specific requirements, climatic conditions, and economic constraints rather than COP alone.

3.1.3. Critical Synthesis of Solar Adsorption Cooling Technologies

Beyond individual experimental and numerical studies, the performance of solar adsorption cooling systems strongly depends on the choice of the working pair, the driving heat source temperature, and the solar collector technology. Activated carbon-methanol systems typically operate at relatively low generation temperatures (80˚C - 120˚C), making them compatible with flat-plate or evacuated tube collectors. However, their COP generally remains limited (0.1 - 0.4), mainly due to low adsorption capacity and poor heat transfer within the adsorbent bed.

In contrast, silica gel-water systems require higher regeneration temperatures (above 80˚C) but exhibit superior mass transfer characteristics and higher achievable COP values, reaching up to 0.62 in optimized two-bed configurations. The performance gap between studies such as Berdjaa *et al.* (COP ≈ 0.49) and Najeh *et al.* (COP ≈ 0.62) can be primarily attributed to differences in adsorbent thermal conductivity, bed configuration, and cycle time optimization.

Several studies highlight that system-level enhancements, rather than material selection alone, are decisive for performance improvement. The integration of heat and mass recovery processes, thermal energy storage, and nano-enhanced adsorbents has been shown to increase COP by 10% - 33%. Furthermore, the choice between direct solar coupling and stored solar heat significantly affects system stability and daily cooling output, especially under fluctuating tropical solar conditions.

Overall, adsorption cooling systems remain attractive for off-grid and low-temperature applications; however, their deployment in tropical climates requires careful matching between collector type, driving temperature, and cycle control strategy to overcome inherent limitations in specific cooling capacity.

3.2. Absorption System

3.2.1. Operating Principle

In absorption systems (**Figure 2**), the refrigerant vapor is absorbed into a liquid solution and then regenerated using heat. Depending on the regeneration process, systems can be classified as single-effect, half-effect, or double-effect [23]. Heat supplied to the generator separates the refrigerant (water or ammonia) from the absorbent. The vapor then condenses and evaporates in subsequent components, producing the cooling effect. This cycle uses a heat source (11) to produce cooling, unlike compression systems which require mechanical work. The provided heat in the generator separates the refrigerant vapor (1) from the solution. This vapor is then cooled and condensed into a liquid (2) in the condenser. After its pressure is reduced, the refrigerant enters the evaporator, where it absorbs heat from the environment (17) and evaporates, creating the cooling effect. The resulting low-pressure refrigerant vapor (4) is then reabsorbed by the weak solution (6) in the absorber, forming a new, rich solution (5). This solution is finally pumped (P) back to the generator to restart the cycle. This process is particularly efficient in applications where a low-cost or waste heat source is readily available.

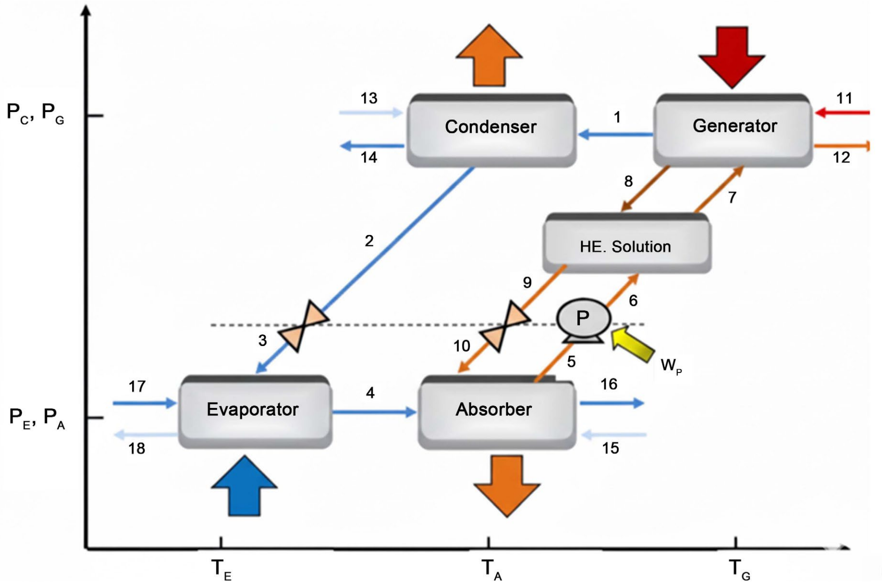

Figure 2. Schematic diagram of the absorption system.

3.2.2. Critical Synthesis of Solar Adsorption Cooling Technology

Absorption chillers using solar thermal energy are excellent alternatives to mechanical refrigeration. Absorption cooling systems are mature technologies that have proven their ability to provide clean cooling using low-grade solar and waste heat [24]. Early thermodynamic and numerical investigations focused primarily on conventional working pairs and steady-state cycle behavior. Omar Ketfi *et al.* [24] performed a detailed thermodynamic analysis of a commercial 70 kW Yazaki single-effect LiBr-H_2O absorption machine, demonstrating that the COP increases with generator and evaporator temperatures while decreasing with condenser and absorber temperatures. Their reported maximum COP of 0.77 at a generator temperature of 92˚C closely matches manufacturer data, validating the reliability of classical LiBr-H_2O absorption models. Similar numerical conclusions were obtained by Sérgio Hanriot *et al.* [25] for NH_3-H_2O systems; however, their work clearly demonstrated that operating an absorption machine outside its design envelope-such as using highly fluctuating automotive exhaust heat-can lead to extremely poor performance, with COP values as low as 0.05.

Subsequent studies explored alternative working pairs and system configurations to reduce generator temperature requirements while maintaining acceptable performance. Ridha Ben Iffa *et al.* [26] investigated multiple absorption cycles using NH_3-H_2O, NH_3-NaSCN, NH_3-$LiNO_3$, and LiBr-H_2O. Their results showed that NH_3-$LiNO_3$ systems combined with a compressor-assisted configuration can achieve COP values up to 0.71 at generator temperatures as low as 60˚C, highlighting the potential of hybrid solutions. Comparable COP values were reported by Raluca Porumba *et al.* [27] for LiBr-H_2O systems through numerical simulation, reinforcing the maturity and efficiency of lithium bromide-water cycles under moderate thermal conditions.

The integration of solar energy as the primary heat source introduced new constraints related to heat source stability and temperature level. P. Soto *et al.* [28] demonstrated that a solar-driven NH_3-$LiNO_3$ absorption system could achieve evaporator temperatures as low as 7˚C with COP values ranging from 0.28 to 0.48, depending on solar availability. Optimization methodologies were further introduced by Virang H. Oza and Nilesh M. Bhatt [29], who applied Taguchi design and regression analysis to NH_3-H_2O systems, identifying an optimal COP of 0.65 and highlighting the strong sensitivity of system performance to generator temperature and flow ratios. Application-specific studies continued to expand the operational envelope of absorption systems. Manu Thimmaiah and T.K. Chandrashekar [30] showed that LiBr-H_2O absorption heat pumps used for electronic chip cooling can achieve COP values exceeding 0.84 under favorable thermal conditions. At the same time, hybrid configurations were explored by D. Lounissi *et al.* [31] who demonstrated that compression-absorption systems using novel working fluids can reach COP values comparable to conventional NH_3-H_2O systems while enhancing operational flexibility. Efforts to improve system robustness and reduce operating temperatures intensified in later studies. Osman Wageiallah Mohammed and Guo Yanling [32] showed that integrating internal heat exchangers into NH_3-H_2O absorption systems significantly lowers cut-in temperatures and improves both COP and exegetic efficiency. Diffusion absorption systems were also investigated during this period; F. Schmid *et al.* [33] and Osman Wageiallah Mohammed and Guo Yanling [34] reported COP values typically below 0.3, reflecting the intrinsic limitations of diffusion-based cycles despite their mechanical simplicity and suitability for small-scale solar applications. Comparative and parametric studies further clarified the trade-offs between different ammonia-based working pairs. Jasim M. Abdulateef *et al.* [35] demonstrated that NH_3-NaSCN systems outperform NH_3-H_2O cycles at generator temperatures above 80˚C, although crystallization risks limit their low-temperature operation. Practical demonstrations by Darwesh *et al.* [36] confirmed that solar absorption systems can be locally manufactured for agricultural applications, albeit with modest COP values under variable operating conditions.

System-level modifications and solar collector integration were addressed by M. Benramdane *et al.* [37] and Jasim Abdulateef *et al.* [38], who showed that multi-generator and evacuated-tube-based NH_3-H_2O systems can operate efficiently at generator temperatures around 70˚C, achieving COP values close to 0.6. Experimental investigations of diffusion absorption systems by R. Mbarek and W. Mbarek [39] Abir Hmida *et al.* [40], Mohamed Izzedine Serge Adjibade *et al.* [41] and Asmaa A. Harraz *et al.* [42] consistently reported COP values between 0.24 and 0.8, depending on system scale, working fluids, and heat input quality. Climatic effects and seasonal performance became a major focus in more recent studies. Y. Agrouaz *et al.* [43] demonstrated significant COP variations across different Moroccan climates, while Dione F. *et al.* [44] showed that high-temperature solar collectors such as linear Fresnel reflectors can reliably supply NH_3-H_2O absorption machines during peak solar hours. Abu Shaban *et al.* [45] confirmed that both NH_3-H_2O and LiBr-H_2O systems exhibit comparable COP values within the generator temperature range of 90˚C - 120˚C, reinforcing the thermodynamic consistency of absorption models. Seasonal analyses by Elbir [46] further highlighted the influence of local climate on COP stability.

Finally, high-performance systems operating under optimized thermal and climatic conditions were reported by Chikh *et al.* [47] and Al-Harbi *et al.* [48] who demonstrated that advanced NH_3-H_2O absorption systems coupled with hybrid solar technologies can achieve COP values exceeding 1.0. These results confirm that absorption refrigeration performance can be significantly enhanced when system design, heat source quality, and operating conditions are coherently optimized.

Overall, the chronological evolution of the literature clearly indicates that absorption refrigeration technology has progressed from basic thermodynamic validation toward climate-adapted, high-performance solar systems. While LiBr-H_2O cycles remain the most efficient option for air-conditioning, NH_3-H_2O and alternative ammonia-based systems offer greater flexibility for refrigeration applications in tropical and arid regions. Consequently, future developments should prioritize integrated system design and solar heat management rather than isolated improvements in individual components.

3.2.3. Comparative and Critical Analysis of Solar Absorption Systems

The reviewed absorption refrigeration studies clearly demonstrate that system performance is predominantly governed by the thermodynamic properties of the working pair and the achievable generator temperature provided by the solar heat source. LiBr-H_2O systems consistently exhibit higher COP values (0.7 - 0.8) under moderate generator temperatures (70˚C - 95˚C), which makes them well suited for flat-plate and evacuated tube collectors. However, their operation is restricted to evaporation temperatures above 0˚C - 2˚C, limiting their application to air conditioning and chilled water production.

Ammonia-water absorption systems, while offering lower average COP values (0.4 - 0.6), present a wider operational range, including sub-zero evaporation temperatures. This makes them more suitable for refrigeration and cold storage in tropical and arid regions. The variability in reported COP values among NH_3-H_2O systems is primarily linked to generator temperature level, heat exchanger effectiveness, and solution heat recovery.

Studies employing advanced solar collectors, such as evacuated tubes or concentrating collectors like Linear Fresnel Reflector, report significantly improved system performance by enabling higher and more stable generator temperatures. In tropical climates, where high solar irradiance coincides with high ambient temperatures, absorption system efficiency becomes particularly sensitive to condenser and absorber heat rejection, emphasizing the importance of system integration and thermal management.

Consequently, absorption refrigeration systems powered by solar energy represent a mature and scalable solution, provided that the working pair, collector technology, and climatic constraints are jointly considered during system design.

4. Comparative Study of Sorption-Based Solar Cooling Technologies

The following Table 1 illustrates the comparisons of sorption-based solar cooling technologies in terms of heat source temperature, evaporation temperature and COP.

The comparative performance of sorption refrigeration technologies cannot be assessed solely based on COP values, as each technology addresses different cooling demands and operating constraints. In tropical climates, absorption systems using NH_3-H_2O demonstrate better adaptability due to their ability to operate at higher ambient temperatures and produce sub-zero cooling when required.

Adsorption systems, although characterized by lower COP values, benefit from simpler mechanical design and reduced corrosion issues. However, their dependence on higher regeneration temperatures and longer cycle times limits their applicability unless advanced adsorbents or heat recovery techniques are employed.

Table 1. Comparisons of solar sorption cooling technologies [41].

Technologies for producing cold by sorption	Heat source temperature	Evaporation temperature (˚C)	COP
Single-effect LiBr-H_2O absorption	70˚C - 90˚C	>2˚C	~0.7
Single-effect H_2O-NH_3 absorption	80˚C - 200˚C	From positive to negative	~0.5
Water-silicone gel adsorption	170˚C - 220˚C	>2˚C	0.3 - 0.7
Methanol activated Carbon adsorption	80˚C - 120˚C	<0˚C	0.1 - 0.4
Absorption diffusion	160˚C - 230˚C	From positive to negative	0.2 - 0.3

The superior performance of certain working pairs in tropical regions is fundamentally linked to their thermodynamic affinity, vapor pressure characteristics, and tolerance to high heat rejection temperatures. Therefore, the selection of a sorption technology must be driven by the targeted cooling temperature, solar resource availability, and system integration strategy rather than COP alone.

While the COP is a key metric for evaluating sorption refrigeration systems, it is crucial to note that the values reported in the literature can vary considerably based on specific operating conditions and prototype designs. The COP is defined as the ratio of the cooling capacity ($\dot{Q}_{cold}$) to the heat supplied to the generator ($\dot{Q}_{hot}$). For adsorption systems using the silica gel/water pair, some studies have reported a COP of 0.62 with a cooling capacity of 5.64 kW. This result is notably higher than the general range of 0.3 to 0.7 mentioned in comparative tables. This difference can be explained by the optimization of operating parameters, such as the heat source temperature and cycle time, which can improve COP. The addition of nano-activated carbon can even increase the cooler's performance by up to approximately 33%. Similarly, for absorption systems using the NH_3-H_2O pair, a COP of 0.6 was achieved in some studies, which is higher than the average value of 0.5 often cited. These higher performances are the result of using more efficient solar collectors, such as evacuated tube solar collectors, and optimizing the operating cycles for local climatic conditions. The COP of the system increases as the generator and evaporator temperatures increase, while it decreases with increasing condenser and absorber temperatures (**Table 2**).

Table 2. COP variation with generator temperature for major sorption systems.

Technology	Working Pair	Heat (˚C)	COP	Main advantages	Main Limitations
Absorption (LiBr-H_2O)	LiBr-H_2O	70 - 95	0.6 - 0.8	High efficiency, well-developed technology	Crystallization risk, requires cooling water
Absorption (NH_3-H_2O)	NH_3-H_2O	80 - 200	0.4 - 0.6	Works at sub-zero temperatures	Toxicity, high pressure
Adsorption (Silica gel-H_2O)	Silica gel-H_2O	170 - 220	0.3 - 0.7	Eco-friendly, simple design	Large size, slow mass transfer
Adsorption (Activated Carbon-Methanol)	C-CH_3OH	80 - 120	0.1 - 0.4	Operates at low temperature	Low COP, intermittent operation
Diffusion absorption	NH_3-H_2-H_2O	160 - 230	0.2 - 0.3	Compact system, no moving parts	Low efficiency, limited scalability

The comparative behavior of different sorption systems Table 2 shows that the coefficient of performance (COP) of absorption systems such as LiBr-H_2O and NH_3-H_2O increases progressively with generator temperature, reaching a maximum around 100˚C - 120˚C.

In contrast, adsorption systems-particularly silica gel-water and activated carbon-methanol-maintain moderate COP values but remain functional over a wider range of heat source temperatures, often exceeding 150˚C. This analysis suggests that hybrid solar systems, combining adsorption cycles with thermal energy storage or optical concentrators like Linear Fresnel Reflectors, could overcome the intermittency of solar input and provide more stable cooling performance throughout the day.

5. Conclusion

Solar sorption cooling systems, such as adsorption and absorption, offer a sustainable alternative to traditional technologies that use ozone-depleting fluids. These technologies are distinguished by their Coefficient of Performance (COP). For example, LiBr-H_2O absorption machines achieve a high COP of around 0.77, but they are limited to evaporation temperatures above 2˚C. Adsorption systems, although generally having a lower COP (from 0.1 to 0.4), can operate at temperatures below 0˚C, which is ideal for feelings. The efficiency of these systems can be improved. Studies have shown that cycle optimization and the use of new materials, such as the addition of nano-activated carbon, can increase the COP by around 33%. In addition, the mass recovery process can improve cooling capacity by nearly 9%. These technologies are a viable solution for reducing energy consumption and protecting the environment by adapting the choice of system and working fluids to the specific needs of the application. This critical synthesis demonstrates that while much progress has been made, localized adaptation and system integration remain key for deployment in developing regions. By coupling absorption machines with PCM and LFR, it is possible to design robust, efficient, and sustainable solar-powered cold storage solutions. Dione *et al.* [44] reported a maximum outlet temperature of 169.24˚C using a Linear Fresnel Reflector. These findings are consistent with our own preliminary observations on similar systems, reinforcing the feasibility of hybridization with cold thermal storage.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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