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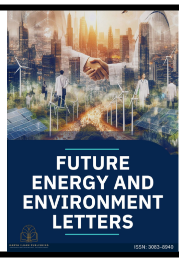

Solar-Powered Adsorption Refrigeration and Desalination Systems for Sustainable Energy and Water Solutions: A Systematic Review of Key Factors, Challenges, and Performance Enhancements

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ABSTRACT

The growing demand for cooling and freshwater is intensifying climate change and water scarcity, especially in remote and island regions. Solar-powered adsorption refrigeration and desalination systems offer low-carbon, environmentally friendly substitutes that assist in meeting SDG 11: Sustainable Cities and Communities. This study investigates key performance concerns in ARS and ADS systems and examines how these have been addressed in academic literature. This study investigates key performance concerns in ARS and ADS systems and highlights findings from existing scholarly research. A systematic review was conducted using the Web of Science and Scopus databases, following the PRISMA protocol, with 12 studies meeting the eligibility criteria. The results show that the choice of an appropriate adsorbent working pair is crucial since it has a direct impact on the two main measures of system efficiency, Specific Cooling Power (SCP) and Specific Daily Water Production (SDWP). The study also identifies current constraints that limit commercial scalability. Furthermore, optimization strategies across various system designs are discussed to improve integration and reliability. Overall, the review provides valuable insights to guide the deployment of adsorption refrigeration and desalination in island and off-grid communities, supporting climate adaptation and sustainable development efforts.

1. Introduction

The International Energy Agency (IEA) reports the global air conditioning units will triple from 2 billion to over 5.5 billion by 2050, significantly increasing greenhouse gases emissions (GHGs) and accelerating climate change [1]. This alarming trend aligns with COP29's [2] call to triple energy capacity and doubling energy efficiency by 2030 to mitigate these impacts. The U.S. EPA warns that rising global temperatures are causing widespread extreme weather, particularly tropical cyclones, which can have catastrophic consequences on both mainland and island residents [3]. Furthermore, GHG emissions have disrupted the hydrological cycle, warming and acidifying freshwater ecosystems leading to environmental degradation and water scarcity [4]. Water scarcity remains a critical issue,

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with the IPCC projecting that 60% of small island populations will face water shortages between 2043 and 2071 [5]. Sustainable water development is severely hampered by this, highlighting the pressing need for integrated solutions that can reduce emissions and deal with resource shortages [6] .

The usage of conventional refrigeration systems that run on fossil fuels worsens global warming by releasing waste heat and carbon dioxide into the atmosphere. Sustainable water development is directly threatened by climate change, which changes precipitation patterns and increases evaporation [7]. Integrated solutions that not only reduce emissions but also ease resource constraints, especially water scarcity, are desperately needed to address these interrelated issues. Alternative, environmentally friendly technologies, such as adsorption refrigeration system (ARS) and adsorption desalination systems (ADS), provide sustainable solutions that decrease greenhouse gas emissions while enhancing water availability. Traditional desalination methods, often powered by fossil fuel, contributes to significant carbon footprint, accounting for 69% CO_2 emissions during operations [8].On the other hand, ADS has superior performance in high removal capacity and little byproduct regeneration [9], while reducing GHG emissions by 94.97% compared to conventional desalination methods [10]. Both ARS and ADS operate with negligible carbon footprints, drastically cutting emissions while offering operational flexibility [11].

The integration of solar energy with adsorption systems has emerged as a viable approach to enhance sustainability and address challenges in areas with limited infrastructure, in line with SDG 11. Mariella *et al.*, [12] highlights that ARS is an effective technology for hot climates and remote locations that lack access to electricity grid. This approach is particularly beneficial for island communities where seawater and sunlight are abundant, but energy resources are limited and costly. In addition to improving energy efficiency, ARS systems offer flexibility by generating multiple products simultaneously, such as clean water, electric power and refrigeration [13]. Despite their benefits, information on key factors influencing ARS and ADS performance, including material selection, working pairs, geometrical configuration, system reliability, and integration with renewable energy, remains limited, pointing to significant knowledge gaps. Performance factors including COP, power generation, and freshwater production must be understood in order to optimize ARS and ADS designs. Additionally, working pair properties and selection, operating temperatures, and overall system setup are crucial factors that have significant effects on system efficiency [14,15]. Addressing these concerns is particularly important for island communities, where improved system efficiency can enhance water management and environmental sustainability.

This work reviews recent studies on the benefits and drawbacks of ARS and ADS methodologies. By providing insights into optimizing ARS and ADS system performance, this review aims to assist engineers in improving water management and promoting environmental sustainability in island communities. Focusing on addressing water scarcity, the study examines factors that influence energy efficiency and overall system performance.

2. Methodology

This paper presents a systematic review using research from various databases accessed through the Heriot-Watt University (HWU) Library, including journals, conference proceedings, and technical papers. The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, selected to ensure a transparent, structured, and enable accurate searches based on research terminology, and improve the validity of the review [16-18]. Catrin *et al.,* [19] emphasize that the PRISMA method promotes comprehensive and transparency for documenting all papers included in systematic review. The PRISMA checklist ensures the quality of the systematic review and methodological quality of study. Similarly, Intan *et al.*, [20] highlights that PRISMA enhances systematic review quality. With these strengths, PRISMA is widely used in review study across various sector [21,22].

2.1 Search Strategy

To conduct a comprehensive review, the literature study was guided by two main research questions:

RQ 1: How can ARS and ADS be optimized for improved energy efficiency and system performance.

RQ 2: What are the key factors influencing the performance and resilience of ARS and ADS applications.

RQ 3: What strategies and emerging technologies to enhance the integration of ARS and ADS with renewable energy sources for sustainable energy and water production.

This study explores how these technologies can be optimized for water scarcity and sustainability in island applications, focusing on improving their performance and adaptability. In order to assess their impact on the efficiency and resilience of ARS and ADS, this study takes into consideration a number of variables, including system configuration, working pair selection, and system operational mode.

To ensure that the search remained aligned with the study's scope, the following inclusion criteria were applied:

- Journal papers published between 2020 and 2025.
- Technical papers related to optimizing ARS and ADS.
- Peer-reviewed journal papers and written in English.

The exclusion criteria are as follows:

- Remove duplicates paper
- Papers that are not related to primary research inclusion criteria.

These criteria ensured that the selected studies were both current and directly relevant to the optimization of ARS and ADS systems, addressing both the benefits and limitations that engineers need to consider for improving system performance in island communities.

2.2 Review Protocol

Figure 1 illustrates the overall process involved in PRISMA methodology in search strategy [23]. The review followed the PRISMA flowchart methodology for systematic literature selection and inclusion, involving four key steps: identification, screening, eligibility and inclusion. Using targeted keywords and an advanced search, 1352 articles were located in four databases during the resource identification phase, reducing irrelevant documents. Following abstract screening, duplicates were eliminated, and 1179 publications were disqualified. Technical papers from 2020 to 2025 were selected via a full-text review of articles that satisfied the website's requirements. While 173 technical papers were chosen, the remaining 90 articles were eliminated because they were beyond the research range, had irrelevant results, or were not detailed enough. Bibliographic details were kept up to date using EndNote.

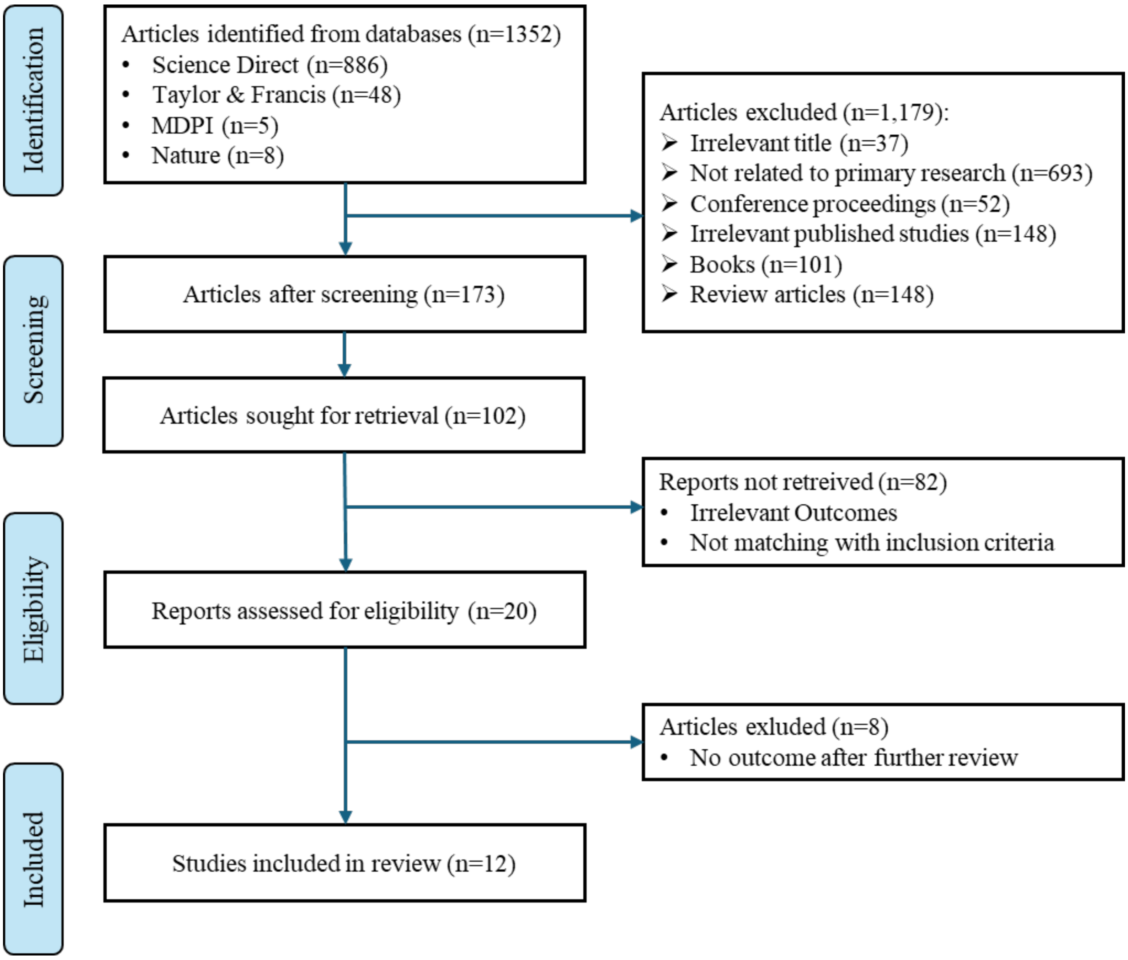

Fig. 1. PRISMA flowchart outlining the systematic review process for article selection and inclusion

2.3 Review of ARS and ADS

In this section, the twelve key papers selected from the previous section are reviewed, with the search strategy mentioned above. Table 1 summarizes recent studies on ARS-ADS, outlining the methodologies and key findings while emphasizing trends such as hybrid integrations, advanced adsorbent materials and data-driven optimization reflecting clear shift toward enhancing performance, sustainability, and adaptability under diverse operating condition.

Table 1
Recent research contributions on ARS and ADS

Year/ Source	Title	Methodology	Findings
2025/[14]	Performance Enhancement of Adsorption Cooling and Desalination Systems by Fluidized Bed Integration: Experimental and Big Data Optimization	Integrated a fluidized bed into adsorption cooling and desalination systems, tested experimentally, and optimized using big data and AI modelling.	• SCP and SDWP was found to enhance by 30% and 25% respectively compared to fixed bed systems. • The AI model demonstrated a maximum relative error of 9.3% between predicted and experimental results, underscoring its reliability.
2025/[24]	Energy, Environmental, and Economic Feasibility Assessment of Solar Adsorption Cooling System Under Different Climate Conditions in China	Investigated a solar adsorption cooling system using aluminophosphate adsorbent. Comparing Life Cycle Cost compare with conventional systems Assessed environmental impact by estimating CO_2 emissions reduction.	• Use of aluminophosphate adsorbent enhances adsorption efficiency with COP of 0.75. • CO_2 emissions reduced by 200–300 tons per year per system. • LCC ranges $0.05–$0.08/kWh, competitive with conventional cooling.
2025/ [25]	Performance assessment of a solar hybrid potable atmospheric water generator using vapour adsorption-thermo electric cooling system	The hybrid system combines a vapour adsorption unit and a thermoelectric cooler (TEC) to optimize water production. Evaluated water production rates and system efficiency under varying environmental conditions.	• Integrating the two technologies significantly boosts water production (121 mL/h from adsorption + 71 mL/h from TEC), enhancing overall efficiency. • Offers sustainable and flexible solution for potable water generation in off-grid regions.
2024/ [26]	Towards enhanced heat and mass exchange in adsorption systems: The role of AutoML and fluidized bed innovations	Authors utilized Automated Machine learning (AutoML) to optimize adsorption cooling and desalination systems. They also proposed new concept of fluidized bed-type application in adsorption chillers.	• Selecting the best operating and design parameters is crucial, and utilizing big data optimization procedures proves highly effective.
2024/[27]	Effect of adsorption isotherm and kinetics on the performance of silica gel-based adsorption desalination system with heat and mass recovery	Authors investigates adsorption isotherms and kinetics influence the efficiency of silica gel-based adsorption desalination systems, using silica gels GEL200 and NS10. Heat and mass recovery techniques are incorporated to enhance performance.	• SDWP was found to be predominantly influenced by adsorption isotherms rather than adsorption kinetics. • Maximum improvements in SDWP and PR with heat and mass recovery were 14% and 23% for GEL200, and 9% and 38% for NS10, respectively.
2023 /[28]	Review of Fluidized Bed Technology Application for Adsorption Cooling and Desalination Systems	Authors review current fluidized bed technology and its applications in ARS and ADS systems, focusing on fluidized bed designs to enhance heat, and comparing performance with traditional packed bed systems.	• Significantly improve heat and mass transfer mechanisms. • Lower COP (0.5-0.6) • Cost effective and environmentally friendly • Highlighted adsorbent's mechanical properties are important.

2023/[29]	Comprehensive Investigation of Cooling, Heating, and Power Generation Performance in Adsorption Systems Using Compound Adsorbents: Experimental and Computational Analysis	The study involved adsorption system with vermiculite compound adsorbents with $\mathrm{CaCl_2}$ and LiCl solution. Experiment was conducted and further tested with computational analysis to predict the system's performance on key metrices under various conditions.	• With vermiculite- LiCl working pair, system can generate 5.76 kW of cooling effect at 25 °C of adsorbent bed temperature. • The integrated system, with diverse refrigeration and desalination output, can generate electricity and desalinate seawater, especially in winter or extreme weather countries.
2022/[30]	Experimental investigation of hybrid photovoltaic solar thermal collector (PV/T)-adsorption desalination system in hot weather conditions	Combination of PVT collectors with adsorption desalination units, utilizing the electrical output for system controls and thermal output for driving the adsorption process. Evaluation of SDWP, COP and system efficiency under various climate conditions.	• SDWP enhances by 46% compared to conventional setups. • PVT integration led to a 24.1% increase in electricity production due to improved panel cooling.
2022/[31]	Computational fluid dynamic study on the adsorption-based desalination and cooling system	Authors analyse a transient CFD model to simulate pressure and distribution inside the finned tube bed. By varying bed porosity, the system's performance is evaluated under different conditions like cycle time and heat source temperature.	• Forward porosity distributions enhance SCP and SDWP with 12.6% compared to uniform distributions • Silica gel- water working pair has the highest SCP (0.219kW/kg) and SDWP (7.5 m^3/ton-day)
2021/[32]	Pore-size engineered nanoporous silica for efficient adsorption cooling and desalination cycle	Authors enhance conventional silica gel by coating it with aluminium foam ligaments, integrating it into the adsorbent bed for cooling and desalination. A mathematical model validates experimental comparisons with conventional silica gel.	• New silica gel has 0.53kg/kg of water uptake, which is 50% compared to conventional silica gel. • New silica gel SDWP (28.7 m^3 /ton) is 62% higher than conventional silica gel (17.7 m^3 /ton)
2021/[33]	Optimisation of Operation of Adsorption Chiller with Desalination Function	This study involves a three-bed adsorption chiller with desalination, investigating the effect of varying adsorption and desorption cycle times on key performance indicators.	• Increase duration of cycle time will increase system's COP 0.64 and SCP of 154W/Kg • System was driven by low grade heat source indicates that the system as a way that able to improve energy efficiency and sustainability.
2020/[34]	A novel cycle for adsorption desalination system with two stages-ejector for higher water production and efficiency	Authors propose an integrated adsorption desalination system with two ejectors using a silica gel working pair.	• SDWP (79.4 m^3 /ton), increases 300% compared to traditional ADS • COP (1.64) improved with 192% compared to traditional ADS

3. Discussion on ARS and ADS Setup and Operational Aspects

This section provides an overview of the setup and operational aspects of ADS and ARS. The main elements of each system, their working mechanisms, and the numerous variables affecting their effectiveness and performance in diverse contexts are the main topics of the review.

3.1 ARS Powered by Solar Energy with Integrated Desalination and Power Generation

Studies have demonstrated that integrating solar energy with adsorption systems provides an effective solution for refrigeration and desalination. According to Abdullah *et al.,* [35], solar-powered adsorption systems can achieve a 74% reduction in energy costs and a 75% reduction in CO_2 emissions compared to conventional vapor compression systems. The integrated ADS powered by solar energy offers a sustainable approach to addressing water scarcity by coupling desalination with power generation.

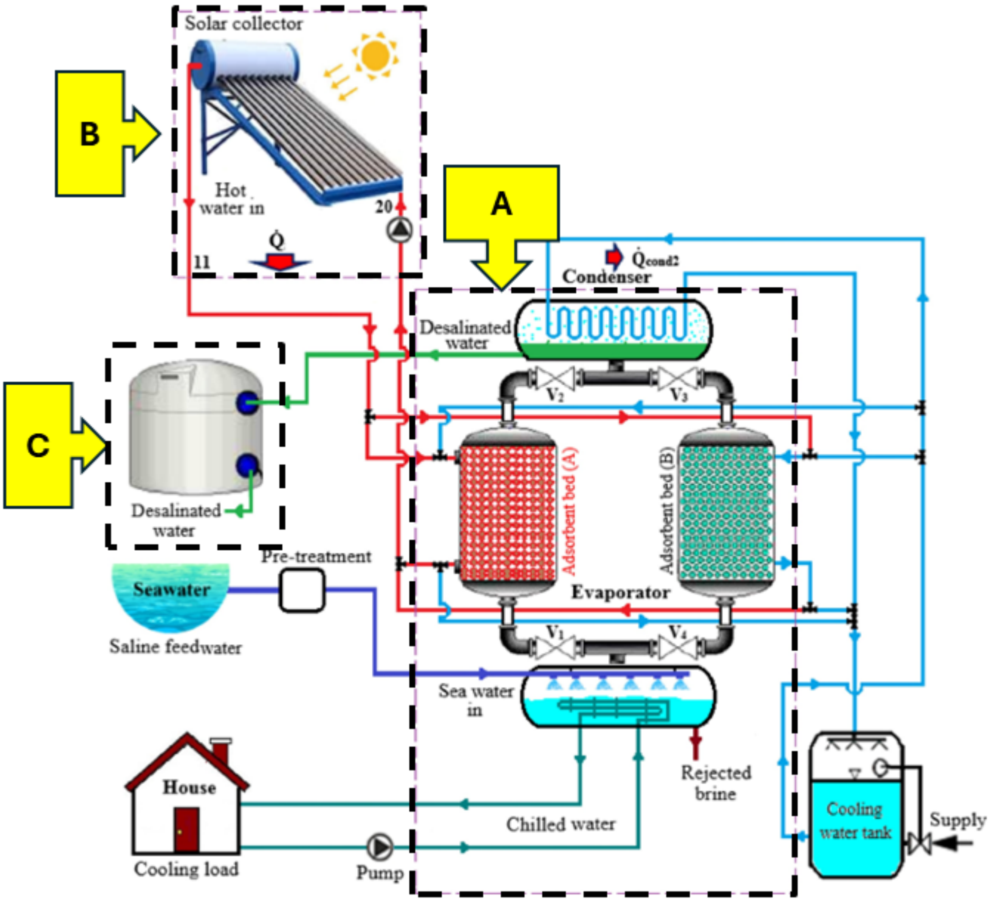

Fig. 2. Conventional solar powered adsorption system with desalination and power generation [36]

Figure 2 depicts the integration of an ADS powered by solar energy, which includes desalination and power generation. The system is divided into three main components: Component A (refrigeration system), Component B (solar energy system), and Component C (desalination process). The ADS operates as a two-bed adsorption system, where saline water is evaporated and adsorbed onto silica gel in Bed B. The heat generated during adsorption is removed via circulating cold water. Once the silica gel in Bed B is saturated, it is regenerated with hot water, and the adsorbed water is transferred to the condenser for freshwater production. Solar energy (Component B) supplies the necessary hot water for regeneration, while desalinated water from Component C is directed to the condenser, and the excess heat is transferred to a cooling water tank to optimize system efficiency.

Table 2
Comparison of single-bed and multi-bed adsorption systems

Cycle type	Advantages	Disadvantages	Ref.
Single bed, Double stage	• Simplest design • Lowest initial cost	• Low COP (0.2-0.4) • Low SCP (50-80 W/Kg)	[37]
Multi-bed, Multistage	• Highest efficiency (COP 0.96) • High SCP (191 W/Kg) • Greater flexibility	• High initial cost • Complex control system	[38] [39]

Configuration has a significant effect on ARS performance, with multi-bed, multi-stage systems providing important benefits, especially when combined with desalination procedures. Multi-bed, multi-stage designs are recommended because of their higher COP (0.96), which is almost 100% greater than that of single-bed, double-stage systems (see Table 2). A major performance improve is also demonstrated by the fact that the Specific Cooling Power (SCP), a crucial indicator of system efficiency [40], is substantially greater in multi-bed, multi-stage systems, ranging from 191 W/Kg, as opposed to 50 to 80 W/Kg for single-bed, double-stage systems.

In addition to increasing the number of beds, selecting the optimal working pair is crucial for enhancing the COP and SCP of adsorption systems. As highlighted by Sumit, K. S. *et al.*, [41], the choice of working pair has a significant impact on overall system performance, particularly regarding energy efficiency and environmental sustainability.

Table 3
Comparison of working pair involved in adsorption systems

Working pair	Advantages	Drawbacks	Ref.
Silica gel/ Water	• Low regeneration temperature (50-75 ℃) • Non-toxic and environmentally friendly • High thermal and chemical stability, scalability	• Low COP (0.2-0.42) and SCP • Low thermal conductivity • Weak heat and mass transfer performance	[42] [43] [44] [45]
MOF/ Water	• High adsorption capacity and versatility • High COP (0.65) and SCP (80-105W/Kg) • Enhanced thermal stability	• Limited commercial viability due to complex synthesis • Complex regeneration process and synthesis requirements • High initial cost	[46] [47] [48]
Ammonia/ Water	• Suitable for a wide range of heating temperatures (100-300 ℃) • Economic viability • High efficiency	• Potential material degradation due to ammonia's corrosive properties • The toxic and corrosive nature of ammonia is hazardous to health. • High operational pressure (20-150 bar)	[49] [50]

The performance of adsorption systems is significantly affected by the selection of working pair, as Table 3 illustrates. Although silica gel/water has a low COP and SCP, it has environmental advantages and a low regeneration temperature. MOF/water offers greater COP and SCP, but its regeneration is costly and complicated. Due to ammonia's toxicity and high operating pressure requirements, ammonia/water can only function at high temperatures. To maximize system feasibility, scalability, and efficiency, these criteria need to be balanced. Water is frequently selected as the refrigerant because of its high energy efficiency and environmental friendliness, according to the findings Ahmed *et al.*, [51]. Because of their high latent heat of vaporization and excellent compatibility with a variety of adsorbents, water is especially well-suited for refrigeration and desalination system [52].

3.2 Adsorption Desalination System (ADS)

For island applications where freshwater shortage is a major concern, adsorption refrigeration systems employing water-based working pairs can effectively use surplus heat for seawater desalination, providing a viable alternative [53]. With COP values of 0.7 and freshwater production rates 15-20 m^3/ton per day, researchers are developing desalination technology to create high-quality drinkable water with low energy usage, which is getting close to commercialization [54]. Such advancements are particularly relevant for island applications, where efficient water production is crucial for sustainability. Furthermore, a solar-powered silica gel-based adsorption desalination system was assessed by Kim *et al.,* [55], who showed that it could lower seawater total dissolved solids (TDS) to 10 ppm, meeting WHO drinking water criteria and making it appropriate for emergency use and in remote areas [56] .

Table 4
Review of advantages and disadvantages of commercialized and emerging desalination technologies

Technology	Advantages	Drawbacks	Energy Consumption (kWh/m^3)
Seawater Reverse Osmosis (SWRO) [54, 57]	• Low initial capital cost • High production capacity • High quality water	• High operational costs for chemical and membrane replacement • High risk of mechanical failures and biofouling • Require regular maintenance	Moderate (2.5-5)
Membrane Distillation (MD) [54, 58, 59]	• Operates at low pressures and temperatures, • Low energy requirements • High separation efficiency	• High risk of fouling • Larger space required • Thermal polarization, reducing efficiency	Highest (43)
Adsorption Desalination System (ADS) [60, 61]	• Produces high-quality freshwater with cooling • Zero carbon emissions, environmentally friendly • Energy-efficient, low maintenance	• Low COP (0.45) • Longer cycle time	Lowest (1.38)

Membrane distillation (MD), Adsorption Desalination System (ADS), and seawater reverse osmosis (SWRO) are the three primary types of desalination processes. SWRO effectively removes salts from saltwater by forcing it through semi-permeable membranes with high-pressure pumps, however this process requires a large amount of energy. Membrane distillation uses vapor pressure differences and hydrophobic membranes to separate freshwater; it uses less energy but has limited scalability. ADS, on the other hand, offers an energy-efficient, low-maintenance solution by utilizing the adsorption and desorption of adsorbent/refrigerant; however, it typically produces lower freshwater volumes than SWRO and MD. Table 3 summarizes the advantages and limitations of these technologies.

Recent studies have concentrated on improving ADS's performance [26,27,62], despite its comparatively low freshwater production and COP because as Table 3 illustrates, it provides a safer operating environment with fewer safety threats than SWRO and MD. Silica gel/water-based ADS systems, for example, achieve a COP of 0.3 to 0.6 and produce 7.1 m^3/ton per day of freshwater. Increasing the Specific Daily Water Production (SDWP) is a key approach to improve ADS performance. Zohir *et al.,* [63] stated SDWP refers to the volume of freshwater produced per unit mass of adsorbent per day, and increasing this value indicates more efficient use of the adsorbent material, thus improving system output. Incorporating additives such as calcium chloride has been shown to improve the COP to 0.6 and increase the SDWP to 19.65 m^3/ton per day [64]. Furthermore, advanced designs, such as the silica gel-based two-bed adsorption refrigeration system with an expander, have demonstrated promising results. Fadhel *et al.,* [65] found that this system can generate up to 681 W/kg of power while simultaneously providing cooling, showing significant potential for future energy-efficient desalination applications.

4. Key Factors Influencing the Performance of ARS and ADS

Figure 3's circular flow highlights the dependence of SCP, COP, Power Output, and SDWP as performance metrics and highlights their significance for desalination applications. For instance, increasing cooling power improves SCP and COP, which raises energy efficiency and freshwater output. Since energy use and water production are closely related, enhancing one of the indicators can enhance the entire performance of the system.

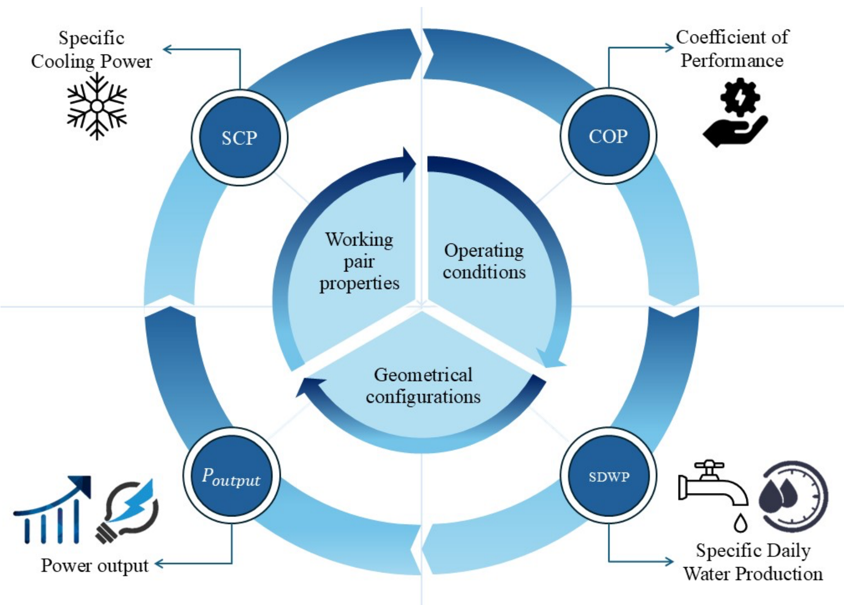

Fig. 3. Framework of key factors influencing ARS-ADS performance

The importance of these links in the advancement of ARS and ADS technologies for effective and durable desalination solutions is highlighted in Figure 3. By enhancing any of these factors, engineers can develop ARS and ADS technology, increasing its effectiveness and adaptability, especially in island-based setup.

5. Conclusion

This review concludes by highlighting the crucial elements that affect the functionality of adsorption-based systems, specifically ARS and ADS. A systematic PRISMA-guided selection of twelve key papers ensures that the insights are comprehensive and evidence-based. The considerable potential of these systems for water desalination in remote or island areas experiencing severe water shortage is shown by a thorough study of performance indicators including SCP, power production, COP, and SDWP. These indicators' interdependence emphasizes how crucial optimization is to achieving total performance gains. Although ADS provides a green and energy-efficient substitute, its comparatively low COP and SDWP continue to be issues that need more study and improvement. By resolving these issues, ADS and ARS technologies can become more viable for environmentally friendly water production and cooling, offering a strong substitute for traditional desalination and refrigeration techniques in areas with limited resources.

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