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Recent Advances and Challenges of Small-Capacity Air-Cooled Solar-Assisted Ammonia Absorption Chillers in Tropical Regions

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ABSTRAK

Permintaan sistem pendingin udara yang meningkat pesat telah meningkatkan konsumsi energi, dampak lingkungan, dan penggunaan air pada sistem pendingin konvensional berbasis kompresi uap. *Absorption chiller* dengan tenaga surya menawarkan alternatif rendah karbon dengan memanfaatkan energi termal terbarukan dan fluida kerja ramah lingkungan. Tulisan ini menyajikan tinjauan literatur mengenai perkembangan sistem *absorption chiller* bertenaga surya, dengan fokus pada *chiller* berkapasitas kecil, berpendingin udara menggunakan fluida kerja amonia. Tinjauan disusun secara kronologis, mencakup studi kelayakan awal hingga peningkatan kinerja, perancangan sistem yang lebih ringkas, serta adaptasi terhadap iklim panas dan tropis. Dibandingkan sistem berpendingin air, konfigurasi berpendingin udara menghilangkan penggunaan cooling tower, sehingga mengurangi konsumsi air, dan memungkinkan desain yang lebih sederhana, namun menghadapi tantangan dalam pelepasan panas pada suhu lingkungan tinggi. Sistem amonia–air menunjukkan potensi tinggi karena toleransi suhu tinggi, tanpa *Global Warming Potential*, dan kesesuaiannya untuk operasi berpendingin udara. Tinjauan ini mengidentifikasi kemajuan teknologi, keterbatasan utama, serta kesenjangan penelitian penting, khususnya untuk aplikasi di wilayah tropis seperti Indonesia.

Kata Kunci : Pendingin absorpsi, Air-amonia, Energi surya, Berpendingin udara, Iklim tropis

ABSTRACT

The rapidly increasing demand for air conditioning has intensified energy consumption, environmental impacts, and water use associated with conventional vapor compression cooling systems. Solar-powered absorption chillers offer a low-carbon alternative by utilizing renewable thermal energy and environmentally friendly working fluids. This paper presents a literature review on the development of solar-powered absorption chiller systems, with a focus on small-capacity, air-cooled chillers using ammonia as the working fluid. The review is structured chronologically, covering early feasibility studies through performance improvement, compact system design, and adaptation to hot and tropical climates. Compared to water-cooled systems, air-cooled configurations eliminate the use of cooling towers, thereby reducing water consumption and enabling simpler system designs, although they face challenges in heat rejection under high ambient temperatures. Ammonia–water systems show strong potential due to their high temperature tolerance, zero Global Warming Potential, and suitability for air-cooled operation. This review identifies key technological advances, major limitations, and important research gaps, particularly for applications in tropical regions such as Indonesia.

Keywords: *Absorption chiller, Ammonia-water, Solar energy, Air-cooled, Tropical climates*

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Introduction

The global demand for air conditioning has increased rapidly over the past decades due to population growth, urbanization, and rising living standards, particularly in developing and tropical countries. Conventional air conditioning systems, which are predominantly based on vapor compression technology, rely heavily on electricity generated from fossil fuels and often use synthetic refrigerants with

high global warming potential. As a result, the extensive use of these systems significantly contributes to greenhouse gas emissions, peak electricity demand, and environmental degradation [1,2]. This growing environmental burden has intensified the search for sustainable and energy-efficient alternatives for space cooling. In this context, solar-assisted absorption chillers have emerged as a promising solution, as they can utilize low-grade thermal energy from renewable sources while requiring minimal electrical input and employing environmentally friendly working fluids [3,4].

Indonesia represents a particularly suitable case for the implementation of solar-assisted cooling technologies. Located near the equator, the country benefits from abundant solar radiation and relatively stable sunlight availability throughout the year. Despite this vast solar energy potential, its utilization for cooling applications remains limited. Several studies have highlighted that Indonesia's climatic conditions and high cooling demand make solar thermal energy an attractive heat source for absorption chillers, offering significant potential to reduce electricity consumption and carbon emissions in the building sector [5,6]. Consequently, solar-driven absorption cooling systems are considered a viable and strategic solution for sustainable air conditioning in Indonesia and other tropical regions.

However, most commercially available absorption chillers are designed as water-cooled systems that require cooling towers for heat rejection. The use of cooling towers leads to higher capital investment, increased operational and maintenance costs, substantial water consumption, and additional space requirements, resulting in bulky and less compact system layouts [7,8]. These drawbacks significantly limit the applicability of water-cooled absorption chillers in dense urban areas and regions facing water scarcity. To address these limitations, air-cooled absorption chiller systems have been proposed as an alternative solution. By eliminating the cooling tower, air-cooled systems offer simpler installation, reduced water usage, lower maintenance requirements, and more compact designs, making them particularly attractive for small-capacity and decentralized cooling applications [4,6].

The selection of an appropriate working fluid is a critical factor in the performance and feasibility of air-cooled absorption chillers. Ammonia-based working fluids, such as ammonia–water (NH_3–H_2O) and ammonia–salt mixtures, have gained increasing attention due to their favorable thermophysical properties. Ammonia offers high latent heat, excellent heat transfer characteristics, and zero global warming potential, making it environmentally benign compared to synthetic refrigerants [9]. Moreover, ammonia-based systems can operate at higher heat rejection temperatures without the risk of crystallization, which is a major advantage over conventional LiBr–H_2O systems, especially for air-cooled applications under hot ambient conditions [4,10]. These characteristics make ammonia-based absorption chillers particularly suitable for solar-assisted and air-cooled configurations.

Despite the growing interest in air-cooled solar-assisted absorption chillers and ammonia-based working fluids, existing studies remain fragmented, focusing on specific system designs, performance

analyses, or climatic conditions. A comprehensive and structured synthesis of research developments in this field is still lacking, particularly for small-capacity air-cooled systems intended for hot and tropical regions. Therefore, the purpose of this work is to conduct a detailed literature review on air-cooled solar-assisted absorption cooling systems, with a particular emphasis on system configurations, working fluids, operating conditions, and performance characteristics reported in previous studies.

The remainder of this paper is organized as follows. Section 2 presents a chronological review of the development of combined solar-assisted and air-cooled absorption chiller systems, highlighting key research milestones and technological advancements. **Section 3 specifically discusses the research progress related to the use of working fluids in absorption chillers, with a particular emphasis on ammonia–water–based systems, including their thermophysical advantages, operational challenges, and suitability for air-cooled and solar-assisted applications.** Section 4 addresses research opportunities for cooling system development in Indonesia, focusing on the specific climatic conditions, energy challenges, and technological needs that motivate the adoption of air-cooled solar-assisted absorption cooling systems. Finally, section 5 concludes the paper with the main findings and recommendations for future research.

Research Development of Combined Solar-Assisted and Air-Cooled Absorption Chillers

The application of solar energy to drive absorption chillers has been investigated for several decades, with early developments primarily focusing on *water-cooled* systems due to their superior heat rejection capability and higher achievable coefficients of performance (COP). However, these systems require cooling towers and continuous water supply, which limit their applicability in water-scarce and hot regions. As a result, early conceptual and experimental studies began to explore *air-cooled absorption chillers* as an alternative, aiming to simplify system configuration and reduce water consumption. These early investigations were mainly laboratory-scale demonstrations intended to verify technical feasibility rather than performance optimization. It was observed that ammonia–water (NH_3–H_2O) working pairs were more suitable for air-cooled operation than lithium bromide–water (LiBr–H_2O), as they can tolerate higher condenser and absorber temperatures without crystallization issues [11,12].

Between 2010 and 2016, research on solar-assisted absorption cooling expanded significantly, supported by advances in solar thermal collectors and increasing interest in sustainable cooling technologies. During this period, air-cooled absorption chillers began to be systematically investigated as part of integrated solar cooling systems. Aliane et al. (2016) provided an illustrated review of experimental solar absorption cooling studies and reported that several experimental setups employed air-cooled condensers and absorbers to eliminate cooling towers. These studies highlighted that the main performance limitation of air-cooled systems lies in insufficient heat rejection under high ambient temperatures, leading to reduced COP and cooling capacity. Consequently, research efforts focused on

enhancing heat transfer through finned heat exchangers, forced air convection, and improved absorber designs [12].

In parallel, Nkwetta and Sandercock (2016) reviewed solar air-conditioning technologies and identified a growing body of work addressing *air-cooled single- and double-effect absorption chillers*, particularly for building cooling applications. Their review emphasized that air-cooled adiabatic absorbers and finned-tube condensers using ambient air were among the most promising solutions to mitigate performance degradation in hot climates, especially in regions where water availability is limited [13].

From 2017 onward, research trends shifted toward improving system performance and adapting air-cooled absorption chillers to extreme environmental conditions. Studies increasingly targeted compact and small-capacity systems suitable for residential and small commercial applications. Reviews by Sheikhani et al. (2018) and Banu and Sudharsan (2018) discussed thermodynamic analyses and system configurations aimed at improving COP, emphasizing that air-cooled systems require careful optimization of operating parameters due to their sensitivity to ambient air temperature [14,15].

Ayou and Coronas (2020) provided a comprehensive review of new developments in absorption chillers for solar cooling applications and highlighted notable progress in small-capacity air-cooled absorption chillers. Their work reported prototypes and commercial units designed to operate at ambient temperatures as high as 41 °C, including ammonia-based systems such as $NH_3/LiNO_3$, which demonstrated stable operation without crystallization risk. Additionally, hybrid and compressor-assisted absorption chiller configurations were introduced during this period to enhance cooling performance under harsh climatic conditions [4].

In the same year, Lima et al. (2021) reviewed ammonia-based absorption refrigeration systems using different absorbents and confirmed the strong potential of air-cooled NH_3-based systems for solar cooling in hot and dry climates. Their review included experimental and numerical studies reporting competitive COP values for air-cooled systems, despite the inherent limitations of air-based heat rejection [9].

More recent studies from 2021 onward have concentrated on performance enhancement, system reliability, and long-term sustainability of air-cooled solar-assisted absorption chillers. Mustafa et al. (2021) reviewed solar absorption cooling systems operating under diverse climatic conditions and highlighted that air-cooled absorption chillers are particularly attractive for extremely hot regions when appropriately designed. Their analysis emphasized the importance of condenser and absorber thermal design, airflow management, and solar collector selection in maintaining stable operation and acceptable performance levels [16].

Further performance improvement strategies were summarized by Verma et al. (2023), who reviewed various methods for enhancing the COP of absorption refrigeration systems. Their overview

included studies on air-cooled LiBr–H_2O and ammonia-based systems, focusing on cycle modifications, advanced heat exchanger designs, and alternative working pairs to overcome the limitations imposed by air cooling [17].

The most recent reviews, such as those by Kaushik et al. (2024) and Abdelwanes et al. (2025), indicate that small-capacity air-cooled absorption chillers are emerging as a promising solution for sustainable solar cooling, particularly when combined with thermal energy storage and advanced control strategies. These studies suggest that future research should focus on improving heat rejection efficiency, system compactness, and year-round operational stability to enhance the commercial viability of air-cooled solar-assisted absorption chiller systems [18,19].

Table 1. Summary of Previous Studies on Air-Cooled Solar-Assisted Absorption Chillers

Year	Authors	Working Pair	System Configuration	Cooling Capacity / Operating Conditions	Key Findings
<2010	Early studies (various)	NH_3–H_2O, LiBr–H_2O	Single-effect, air-cooled (prototype)	Laboratory and pilot scale	Demonstrated technical feasibility of air-cooled absorption systems; performance strongly affected by ambient temperature (Ghafoor & Munir, 2015).
2015	Bowie & Cruickshank	LiBr–H_2O	Single-effect, solar-driven	Residential-scale applications	Single-effect chillers identified as most suitable for solar operation; air-cooled systems recognized as emerging but promising for small capacities.
2016	Aliane et al.	LiBr–H_2O, NH_3–H_2O	Solar-assisted, air-cooled	Experimental systems in hot climates	Identified growing use of finned air-cooled condensers and absorbers; air-cooled systems suitable for arid regions despite lower COP (Aliane et al., 2016).
2016	Nkwetta & Sandercock	LiBr–H_2O	Single- and double-effect, air-cooled	Building cooling applications	Use of adiabatic air-cooled absorbers and forced convection condensers improved heat rejection under high ambient temperatures.
2018	Sheikhani et al.	LiBr–H_2O	Solar-assisted, air-cooled with auxiliaries	Various climatic conditions	Integration with auxiliary devices and optimized control strategies shown to mitigate performance

Year	Authors	Working Pair	System Configuration	Cooling Capacity / Operating Conditions	Key Findings
					degradation of air-cooled systems.
2018	Banu & Sudharsan	LiBr–H_2O	Air-cooled absorption systems	Thermodynamic analysis	Highlighted crystallization and heat rejection challenges in air-cooled water-based systems; emphasized parameter optimization.
2019	Altamirano & Le Pierrès	LiBr–H_2O	Single-stage absorption chiller	Small-scale applications	Single-stage systems identified as the most practical and commercially viable for small-capacity air-cooled applications.
2020	Ayou & Coronas	NH_3/$LiNO_3$, LiBr–H_2O	Small-capacity, air-cooled	Ambient temperature up to 41 °C	Demonstrated stable operation of ammonia-based air-cooled systems under extreme temperatures without crystallization (Ayou & Coronas, 2020).
2021	Lima et al.	NH_3–H_2O, NH_3-based mixtures	Air-cooled absorption systems	Experimental and numerical studies	Reported competitive COP values for air-cooled ammonia-based systems; high suitability for hot and dry climates.
2021	Mustafa et al.	LiBr–H_2O	Solar-assisted, air-cooled	Middle East & North Africa climates	Emphasized importance of condenser–absorber thermal design for stable air-cooled operation under extreme weather conditions.
2023	Verma et al.	LiBr–H_2O, NH_3-based	Single- and double-effect, air-cooled	Various operating conditions	Reviewed COP enhancement techniques including cycle modification and advanced heat exchanger design for air-cooled systems.
2024	Kaushik et al.	LiBr–H_2O, NH_3–H_2O	Solar-assisted, air-cooled	Review of recent systems	Identified trend toward compact, water-free air-cooled absorption chillers integrated with solar thermal systems.

Year	Authors	Working Pair	System Configuration	Cooling Capacity / Operating Conditions	Key Findings
2025	Abdelwanes et al.	LiBr–H_2O, NH_3-based	Air-cooled with thermal storage	Experimental & simulation studies	Highlighted integration of air-cooled absorption chillers with PCM storage to improve reliability and sustainability.

Ammonia-Based Working Fluids for Air-Cooled Solar Absorption Chillers

Ammonia-based working fluids have attracted sustained research interest for solar-driven absorption cooling systems due to their favorable thermophysical properties, environmental benignity, and capability to operate at sub-zero evaporation temperatures. Compared to conventional LiBr–H_2O systems, ammonia-based cycles offer higher operational flexibility, making them particularly suitable for air-cooled configurations where heat rejection efficiency is limited by ambient conditions.

Early Developments and System-Level Feasibility (2021)

Initial studies focused on demonstrating the feasibility of ammonia-based absorption chillers driven by solar and waste heat sources. Bellos et al. (2021) performed a comprehensive annual energetic, exergetic, and economic evaluation of a parabolic trough solar-driven NH_3–H_2O absorption refrigeration system, confirming its technical viability under real climatic conditions [20]. Similarly, Ali & Ratismith in 2021 investigated a semi-circular trough solar collector coupled with a single-effect NH_3–H_2O absorption chiller, achieving an average COP of 0.42 and demonstrating the feasibility of non-tracking collectors for solar air-conditioning [21].

At the same time, alternative ammonia-based working pairs were explored to enhance absorption performance. Zhou et al. (2021) experimentally evaluated an exhaust-heat-driven absorption refrigeration cycle using NH_3–NaSCN as the working pair, reporting COP values up to 0.653 and highlighting the suitability of ammonia–salt mixtures for low-grade heat utilization [22]. Complementary numerical studies by Zapata et al. (2021) employed CFD modeling to analyze ammonia vapor absorption in tubular bubble absorbers using NH_3/$LiNO_3$, emphasizing the influence of hydrodynamics and cooling conditions on mass transfer rates [23].

Thermo-economic comparisons further showed that ammonia-based absorption systems remain competitive with LiBr–H_2O cycles when integrated with solar thermal energy, particularly in applications requiring air cooling and low-temperature refrigeration [24].

Component-Level Modeling and Performance Enhancement (2022)

Subsequent research shifted toward detailed component-level analysis and system optimization. A parametric study of compact ammonia–water absorption chillers, demonstrating that system performance is highly sensitive to heat exchanger effectiveness and cycle configuration [25]. Braccio et

al. (2022) developed a numerical simulation framework based on exchanger effectiveness, NTU, and Jakob number formulations, enabling accurate prediction of ammonia–water absorption cycle performance across a wide range of operating conditions [26].

In parallel, Mathilde Wirtz in 2022 developed and experimentally validated a falling-film desorber that integrates ammonia vapor generation and purification within a single component, resulting in improved compactness and enhanced thermal performance [27]. Experimental adsorption studies by Boltaev et al. (2022) investigated the thermotechnical characteristics of $SrCl_2$ as an ammonia adsorbent, expanding the understanding of ammonia absorption limits relevant to solar-driven cycles [28].

The application of data-driven methods also emerged during this period. May Tzuc et al. (2022) employed artificial neural networks to optimize ammonia mass transfer in plate heat exchanger-type absorbers using NH_3–H_2O, demonstrating the potential of AI-based approaches for performance enhancement [29]. System-level studies by Amaris et al. (2022) further assessed solar/gas-assisted $NH_3/LiNO_3$ absorption cooling systems for commercial buildings, achieving COP values up to 0.64 under tropical conditions [30].

Transition Toward Air-Cooled and Compact Systems (2024)

More recent studies have increasingly emphasized air-cooled absorption chillers to address water scarcity and simplify system deployment. Desy Agung in 2024 developed and experimentally tested a 5 kW ammonia–water absorption chiller equipped with air-cooled absorber and condenser units, demonstrating stable operation, reduced system footprint, and lower maintenance requirements compared to water-cooled designs [6].

Operational challenges associated with air cooling under high ambient temperatures were addressed by Palacios-Lorenzo & Marcos (2024), who proposed a downsizing strategy for air-cooled, indirectly fired ammonia–water absorption chillers operating under part-load conditions [31]. Their results highlighted the importance of pressure level control in mitigating performance degradation and component oversizing.

Advanced cycle configurations were also explored to improve low-temperature solar heat utilization. A hybrid ammonia–water refrigeration cycle combining absorption and mechanical compression, showing enhanced operational flexibility and improved performance under fluctuating solar heat inputs [32].

Advanced Working Fluids and Heat Transfer Studies (2025)

Recent literature has focused on refining ammonia-based working fluids and improving heat and mass transfer mechanisms. El Amine Chikh et al. (2025) systematically analyzed the effect of ammonia concentration on the performance of solar absorption refrigeration systems, identifying optimal NH_3 mass fractions around 25% for maximizing COP [33]. Márquez-Nolasco et al. (2025) further evaluated

the energy performance of ammonia–water absorption chillers under varying pressures, temperatures, and heat exchanger characteristics, confirming their suitability for low-temperature solar applications [34].

Experimental investigations demonstrated the feasibility of commercial air-cooled absorption chillers using natural refrigerant R717 powered by Fresnel solar collectors, achieving COP values around 0.65 [35]. At the component level, comprehensive experimental data on flow boiling heat transfer characteristics of $NH_3/LiNO_3+H_2O$ mixtures, offering critical insights for absorber and generator design [36].

Finally, a comprehensive review by Pham et al. (2025) synthesized recent advances in NH_3–H_2O absorption heat pumps and chillers, emphasizing the growing importance of air-cooled configurations and ammonia-based working fluids for sustainable cooling technologies [37].

Summary and Research Gap

Overall, the literature demonstrates that ammonia-based working fluids—ranging from conventional NH_3–H_2O pairs to advanced ammonia–salt mixtures—offer significant potential for air-cooled solar absorption chillers. While substantial progress has been made in component modeling, working fluid optimization, and experimental validation, most studies still address isolated aspects of system performance. Integrated assessments that simultaneously consider working fluid selection, air-cooled heat rejection constraints, and solar integration under real operating conditions remain limited, indicating a clear research gap for further investigation.

Research Opportunities for Cooling System Development in Indonesia

Indonesia's tropical climate, rapid urbanization, and growing energy demand have positioned cooling systems as a critical sector for both climate adaptation and energy transition. Cooling demand in buildings, transportation, food supply chains, and emerging technologies such as electric vehicles and renewable energy systems is increasing rapidly, creating a multidimensional research landscape that spans technological, socio-economic, and policy dimensions.

Urban Heat, Thermal Comfort, and Climate Adaptation

Recent studies highlight the growing challenge of urban heat stress and thermal discomfort in Indonesian cities. Maninggar et al. (2024) examined thermal justice in Surabaya's kampungs, emphasizing that low-income urban communities are disproportionately affected by extreme heat and lack access to adequate cooling infrastructure [38]. Their work identified a strong need for low-cost, decentralized cooling solutions tailored to dense urban settlements.

At the building scale, persistent indoor temperatures exceeding 30 °C in low-cost housing used for home-based enterprises in Surakarta, underscoring the limitations of current passive coping strategies [39]. Similarly, the reliance on air conditioning significantly increases household energy consumption, whereas natural ventilation and fan-based cooling can maintain acceptable thermal comfort with

substantially lower energy use [40]. These findings collectively point to research opportunities in hybrid cooling strategies that integrate passive design, behavioral adaptation, and efficient mechanical systems.

At the urban planning level, Pradana et al. (2025) assessed green and blue infrastructure strategies for Indonesia's new capital city, Nusantara, using urban climate modeling [41]. Their results showed that increasing blue–green space coverage to 65% could reduce surface temperatures by approximately 2 °C, indicating the importance of coupling urban cooling strategies with building-scale cooling technologies.

Energy-Efficient Cooling in the Building Sector

The building sector represents one of the largest opportunities for cooling system innovation in Indonesia. A series of cost-benefit analyses by Kim et al. (2023) and Muehleisen et al. (2024) [42][43] systematically evaluated twelve passive and low-energy cooling strategies for Indonesian buildings. These studies identified ceiling fans with temperature setback, roof insulation, wall insulation, and cool roofs as the most cost-effective energy conservation measures, offering substantial reductions in electricity consumption, CO_2 emissions, and peak load demand.

Szum & Levinson in 2024 further quantified the life-cycle economic benefits of these strategies, highlighting their relevance for national-scale energy planning and policy design [44]. However, in high-rise commercial buildings, active cooling system upgrades—such as cooling tower replacement, chilled water pump optimization, and building automation systems—remain critical for achieving significant emissions reductions [45]. These findings reveal a research gap in integrating low-energy cooling measures with advanced HVAC control strategies under tropical operating conditions.

Hybrid, Advanced, and Sector-Specific Cooling Technologies

Beyond conventional buildings, emerging research points to opportunities in sector-specific cooling applications. Hybrid cooling systems combining passive architectural features with mechanical cooling could reduce annual cooling loads by up to 29.86% in mid-rise office buildings in Jakarta [46]. This indicates strong potential for further research into adaptive hybrid cooling configurations optimized for Indonesia's climate.

In the transportation sector, significant challenges in maintaining thermal comfort and humidity control in long-distance train HVAC systems, suggesting the need for improved control strategies and system designs [47]. Dipocaksono et al. (2025) expanded this perspective to electric vehicles, proposing locally sourced cooling system components for EV batteries, drivetrains, and cabins [48]. Their work highlights opportunities for domestic manufacturing and system integration research tailored to Indonesia's industrial capabilities.

Cooling for Renewable Energy and Water Systems

Cooling challenges are not limited to comfort applications. High ambient temperatures significantly reduce photovoltaic (PV) efficiency across Indonesia, emphasizing the need for PV cooling

systems adapted to regional climatic variations [49]. Similarly, incorporating active cooling elements into solar distillation systems can substantially improve freshwater production efficiency in coastal regions [50].

These studies suggest a promising research direction in multifunctional cooling systems that simultaneously support energy generation, water security, and climate resilience.

Cold Chain and Food System Cooling

Cold chain infrastructure represents another critical area for cooling system development. Significant inefficiencies and losses in Indonesia's agricultural and fisheries cold chains, driven by inadequate infrastructure and unreliable temperature control [51] and [52]. Basbeth et al. further emphasized the importance of cold chain logistics for small-scale fishermen cooperatives, highlighting opportunities for renewable-powered and decentralized cooling solutions [53].

These findings underscore the need for integrated research on energy-efficient refrigeration, logistics optimization, and digital monitoring technologies for Indonesia's food systems.

Emerging Research Directions and Policy Alignment

A bibliometric analysis by Purwanto et al. (2024) revealed that Indonesia is among the most active contributors to global research on energy efficiency and cooling, indicating strong academic momentum [54]. However, legacy refrigerants such as R22 remain widely used in Indonesian industry due to economic constraints, highlighting the need for transitional solutions that balance efficiency gains with investment feasibility [55].

Finally, Setiawan et al. (2025) explored the potential of nuclear cogeneration for district cooling in Jakarta, opening discussions on large-scale, low-carbon cooling infrastructure [56]. While still conceptual, such studies expand the horizon of cooling system research beyond conventional paradigms.

Synthesis and Research Opportunities

Overall, the literature reveals substantial research opportunities for cooling system development in Indonesia across multiple scales and sectors. While significant progress has been made in passive cooling, cost-effective building measures, and sector-specific applications, gaps remain in system integration, adaptive control under tropical climates, and the alignment of technological innovation with socio-economic realities. Future research should focus on integrated cooling frameworks that combine passive design, efficient mechanical systems, renewable energy integration, and policy-driven deployment strategies tailored to Indonesia's diverse climatic and socio-economic contexts.

Conclusion

This review has examined the development of **solar-assisted absorption cooling systems**, with a particular focus on **small-capacity air-cooled configurations and ammonia–water working fluids**, using a chronological perspective. The analysis shows a clear research shift from early feasibility studies toward performance improvement, system compactness, and suitability for hot and tropical climates.

Although water-cooled absorption chillers have long dominated solar cooling applications, their dependence on cooling towers leads to high water consumption, system complexity, and large installation footprints. These limitations have driven increasing interest in **air-cooled absorption chillers**, which offer water-free operation and greater suitability for decentralized and small-scale applications, despite ongoing challenges related to reduced heat rejection efficiency under high ambient temperatures.

Among the working fluids reviewed, **ammonia–water systems emerge as particularly well suited for air-cooled and solar-assisted operation**, owing to their high tolerance to elevated operating temperatures, absence of crystallization risk, and zero global warming potential. Recent studies report notable progress in component design, cycle configuration, and experimental validation of compact ammonia-based air-cooled absorption systems.

Nevertheless, existing research remains fragmented, with limited integrated assessments that simultaneously address air-cooled heat rejection, working fluid selection, solar energy utilization, and real climatic conditions. This gap is especially pronounced for small-capacity systems designed for tropical regions.

In this context, **Indonesia represents a highly relevant and underexplored case**, where abundant solar resources, high cooling demand, water constraints, and urban density strongly support the development of compact, air-cooled solar absorption cooling technologies. Overall, this review confirms that **small-capacity air-cooled solar-assisted ammonia absorption chillers offer a promising pathway toward sustainable cooling**, while also providing a clear foundation for future research focused on system integration, performance optimization, and practical deployment in hot and tropical environments.

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