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Thermal Performance Analysis of a Low-Cost Solar Cooling System using Frugal Engineering Approach: A Case Study of Zawiya City

Hager A. Mohammed [1*], Bashir Magtof Ghbllawi [2], Marzouga F. Rajab [3], Amyirah M. Ali [4], Mayzona Gemah A. [5]
[1,2,4] Department of Physics, Faculty of Science, University of Zawiya, Libya
[3,5] Department of Physics, Faculty of Science-El Gubbah, University of Dernah, Libya

تحليل الأداء الحراري لنظام تبريد شمسي منخفض التكلفة باستخدام منهج الهندسة الاقتصادية: دراسة حالة مدينة الزاوية

هاجر عبد السلام محمد [1*]، بشير المقطوف القبلاوي [2] ، مرزوقة فرج رجب [3] ، اميرة محمد علي [4]،
ميزونه جمعه ابوفراج [5]
[4,2,1] قسم الفيزياء، كلية العلوم، جامعة الزاوية، ليبيا
[5,3] قسم الفيزياء، كلية العلوم القبة، جامعة درنة، ليبيا

*Corresponding author: h.mohamed@zu.edu.ly

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Abstract

The escalating demand for cooling systems in hot climatic regions, coupled with increasing energy costs and environmental concerns, necessitates the development of sustainable cooling technologies. This study investigates the thermal performance of a simple solar absorption cooling system under the specific climatic conditions of Zawiya City, Libya. An experimental setup employing the Electrolux absorption refrigeration cycle was developed and tested in the Physics Laboratory at the Faculty of Science, University of Zawiya. The system utilizes an ammonia-water (NH_3-H_2O) working pair, operating without auxiliary mechanical components or active pumps, relying solely on thermal energy input. Experimental measurements were conducted at 10-minute intervals to monitor temperature variations during the cooling process. Results demonstrate a measurable temperature reduction from 26.1°C to 24.3°C, representing an approximate 1.8°C (6.9%) decrease achieved through passive solar-driven absorption mechanisms. Despite the simplicity and preliminary nature of the apparatus, the findings validate the fundamental viability of ammonia absorption cycles for cooling applications in Libya's Mediterranean climate. The study emphasizes the potential of integrating solar thermal energy as a primary heat source, replacing conventional electric heating elements, thereby reducing dependence on fossil fuels and grid electricity. These results contribute to the growing body of knowledge on renewable cooling technologies applicable to North African contexts, suggesting promising avenues for scaled implementation in residential and small commercial applications.

Keywords: Solar absorption cooling, Ammonia-water cycle, Electrolux refrigeration, Zawiya climate, Simple cooling systems, Renewable energy, Mediterranean region, Thermal performance.

الملخص

تناقش هذه الدراسة تطوير واختبار تقنيات تبريد مستدامة لمواجهة الطلب المتزايد على أنظمة التبريد في المناطق الحارة، خاصة مع ارتفاع تكاليف الطاقة والمخاوف البيئية. ركز البحث بشكل أساسي على تقييم دورة "إلكترولكس (Electrolux) " للتبريد بالامتصاص تحت الظروف المناخية لمدينة الزاوية، ليبيا.

النقاط الرئيسية للبحث: •آلية العمل: يعتمد النظام على زوج العمل (أمونيا-ماء)، وهو نظام يعمل بدون مضخات ميكانيكية أو أجزاء متحركة، حيث يعتمد كلياً على المدخلات الحرارية لتشغيل الدورة.

•الجانب التجريبي: أُجريت التجارب في مختبر الفيزياء بكلية العلوم بجامعة الزاوية، حيث تم قياس درجات الحرارة كل 10 دقائق لمراقبة عملية التبريد.

•النتائج المحققة: أظهرت النتائج انخفاضاً ملموساً في درجة الحرارة من 26.1 درجة مئوية إلى 24.3 درجة مئوية، أي بنسبة انخفاض تقارب 6.9%، وذلك عبر آليات الامتصاص المدفوعة بالطاقة الشمسية السلبية.
•الأهمية البيئية: تؤكد الدراسة على إمكانية استبدال السخانات الكهربائية التقليدية بمصادر حرارية شمسية، مما يقلل الاعتماد على الوقود الأحفوري وشبكة الكهرباء العامة.
الخلاصة: أثبتت الدراسة جدوى استخدام دورات امتصاص الأمونيا في المناخ المتوسطي لليبيا، حتى مع بساطة الجهاز المستخدم. وتفتح هذه النتائج الباب أمام تطبيقات أوسع في المباني السكنية والتجارية الصغيرة كحل بديل وصديق للبيئة.

الكلمات المفتاحية: التبريد بالامتصاص الشمسي، دورة الأمونيا والماء، تبريد إلكترولكس، مناخ مدينة الزاوية، الطاقة المتجددة.

1. Introduction

The global transition toward sustainable energy systems has emerged as an imperative response to the escalating challenges of climate change, fossil fuel depletion, and energy security (Abdelwanes *et al*., 2025; Ahmed *et al*., 2025). Solar energy, receiving approximately 174 petawatts of incoming radiation at Earth's upper atmosphere, represents the most abundant renewable resource (Al Rayes & Ghaith, 2025). The photovoltaic and solar thermal sectors have witnessed exponential growth, with installed capacity expanding from gigawatts to hundreds of gigawatts globally (Al-Mamoori & Kilinc, 2025). This proliferation reflects technological maturation and growing recognition of solar energy's potential across diverse applications, including thermally-driven cooling systems.

Regions with highest solar irradiance—primarily tropical and subtropical belts—paradoxically experience greatest cooling demand (Chandel *et al*., 2024). In North Africa and the Middle East, where ambient temperatures frequently exceed 40°C during summer, conventional vapor-compression air conditioning accounts for 40-60% of peak electricity demand (Farag *et al*., 2024). This temporal coincidence between solar availability and cooling requirements presents compelling opportunities for solar thermal cooling. However, conventional systems remain energy-intensive, relying on grid electricity from fossil fuels, thereby contributing significantly to greenhouse gas emissions (Fernandez, 2025; Ghaith *et al*., 2024).

Solar cooling technologies divide into two pathways: photovoltaic-driven electric cooling and solar thermal absorption/adsorption cooling (Jassim *et al*., 2025). While PV-driven systems benefit from modular scalability, they suffer from double energy conversion inefficiency—solar to electric, then electric to cooling—with overall efficiencies typically below 15% (Jiang *et al*., 2025; Kargaran *et al*., 2024; Kaushik, 2024). Solar thermal absorption systems directly exploit heat, eliminating intermediate losses and achieving coefficients of performance (COP) ranging from 0.6 to 0.8 for single-effect systems (Lin *et al*., 2023; Yuan & Du, 2017).

Extensive research on solar absorption cooling spans various climates and configurations. Abdelwanes *et al*. (2025) employed TRNSYS-GenOpt simulation for African climates, identifying optimal collector areas and storage capacities achieving 32% annual solar fractions. Kaushik (2024) reviewed advances emphasizing generator temperature, solution concentration, and heat exchanger effectiveness. Experimental studies on ammonia-based systems show promise; Yuan & Du (2017) achieved 3.5 kW cooling capacity with COP values between 0.55-0.68. Studies in Mediterranean climates report collector temperature rises of 25-30°C and energy collection rates of 80-100 kW. Ahmed *et al*. (2025) investigated PV-PCM-TEC hybrid configurations, demonstrating orientation significantly influences performance.

Despite technological advances, documented systems involve complex multi-component configurations requiring specialized equipment and considerable investment. A notable gap exists regarding simple, low-cost solutions for resource-constrained contexts. The Electrolux absorption refrigeration cycle operates on diffusion absorption using ammonia-water-hydrogen systems (Hassan & Mohamad, 2012), requiring no solution pumps through density differences and pressure equalization via inert gas. However, empirical performance data for such simplified systems under North African climatic conditions remain scarce.

Zawiya City, located on Libya's northwestern Mediterranean coast (32.75°N, 12.73°E), experiences hot semi-arid climate with mean maximum temperatures exceeding 30°C from May through September. Annual solar irradiation averages 2,200-2,400 kWh/m²/year, with peak daily irradiance reaching 950-1,000 W/m²—conditions highly favorable for solar thermal applications (Almaktar *et al*., 2021). Despite abundant solar resources and significant cooling demand, Libya's renewable energy sector remains underdeveloped, with electricity generation dominated by natural gas-fired plants. Residential and small commercial sectors could benefit substantially from accessible, low-maintenance solar cooling technologies.

Given the prevailing economic constraints and logistical disruptions affecting supply chains, compounded by the frequent intermittency of the local electrical grid, there is a compelling necessity to adopt the principles of 'Frugal Engineering. Consequently, this study deliberately prioritizes the utilization of locally accessible materials and fundamental laboratory instrumentation to fabricate a preliminary cooling prototype. The primary objective at this juncture is not to rival the efficiency of commercial systems, but rather to validate the feasibility of constructing off-grid, locally maintainable cooling solutions. This approach aims to bolster the 'Energy Resilience' of the local community in Zawiya, offering adaptive strategies in resource-constrained environments.

This study addresses identified gaps by experimentally investigating thermal performance of a simple solar absorption cooling system under Zawiya's climatic conditions. Primary objectives are: (1) construct and validate laboratory-scale Electrolux-type absorption cooling apparatus using readily available materials; (2) measure and analyze temperature reduction during cyclic operation, quantifying cooling capacity and thermal response; (3) assess potential for integrating solar thermal collectors as primary heat source; and (4) evaluate practical viability of scaling such systems for residential cooling in Libya and similar North African contexts. Unlike previous investigations focused on complex systems, this research emphasizes simplicity, accessibility, and fundamental performance characterization.

2. Climatic Characteristics of Zawiya City

2.1 Geographic and Meteorological Profile

Zawiya City represents a typical Mediterranean coastal settlement in northwestern Libya, 47 km west of Tripoli. The city's geographic position creates a hot semi-arid climate (Köppen BSh) with distinct seasonal patterns: hot, dry summers dominated by Saharan air masses, and mild, moderately wet winters influenced by Mediterranean cyclonic systems. Mean annual temperature approximates 20.5°C, with summer months exhibiting average maxima of 31-34°C, frequently exceeding 38°C during Ghibli wind events. Winter temperatures range 12-18°C, with nighttime minima occasionally approaching 5-7°C. Diurnal temperature range averages 10-12°C year-round (Reference.org., 2025).

2.2 Solar Resource Availability

Libya ranks among the world's most solar-rich regions, with northern coastal zones receiving annual global horizontal irradiation of 2,000-2,400 kWh/m²/year (Zahloul, 2024). Zawiya experiences approximately 3,200-3,500 sunshine hours annually, averaging 8.8-9.6 hours daily. Peak solar irradiance during summer midday regularly exceeds 950 W/m², while winter values remain substantial at 550-650 W/m². Low cloud cover—averaging below 30% annually—ensures consistent solar resource availability, with June-July exhibiting clearness indices approaching 0.68-0.72 (Khalafullah *et al.*, 2025). This abundant resource positions Zawiya ideally for solar thermal applications, with peak irradiance coinciding with maximum cooling demand.

2.3 Cooling Demand and Energy Context

Extended summer periods generate substantial cooling demand in residential and commercial sectors. Typical buildings without mechanical cooling experience indoor temperatures of 32-36°C during peak July-August afternoons, significantly exceeding thermal comfort thresholds. Conventional vapor-compression air conditioning has become ubiquitous, contributing to peak electricity demand increases of 200-250% compared to winter baseline. This surge strains Libya's power infrastructure, which remains heavily dependent on natural gas generation with renewable contribution below 1% despite Libyan governmental 10% targets by 2025 (Alafya & Maka, 2025). Solar cooling technologies offer dual benefits: reducing peak grid demand while exploiting the causal factor (solar radiation) to provide solutions. For Zawiya's residential sector, where average household cooling loads range 2.5-4.5 kW during occupied hours, appropriately sized solar absorption systems could offset substantial grid consumption, yielding economic and environmental benefits.

3. Theoretical Framework of Absorption Cooling

3.1 Fundamentals of Absorption Refrigeration

Absorption refrigeration systems employ thermodynamic principles distinct from vapor-compression cycles. Rather than mechanical compressors, they utilize thermal compressors—combinations of absorber, solution pump, and generator—to achieve identical thermodynamic functions (Lin *et al.*, 2023). Essential components include evaporator, absorber, generator, condenser, expansion valve, and solution heat exchanger. Working fluid pairs consist of refrigerants (undergoing phase changes producing cooling) and absorbents (modulating refrigerant concentration through chemical affinity). In ammonia-water (NH_3-H_2O) systems, ammonia serves as refrigerant while water acts as absorbent, suitable for sub-zero evaporator temperatures where toxicity concerns are manageable.

3.2 Electrolux Cycle: Diffusion Absorption Refrigeration

The Electrolux cycle, termed diffusion absorption refrigeration (DAR), eliminates mechanical solution pumps through inert auxiliary gas introduction—typically hydrogen or helium—equalizing pressure throughout systems (Hassan & Mohamad, 2012). Operation relies on partial pressure differences: ammonia evaporates into hydrogen atmospheres at low partial pressure in evaporators, while preferentially absorbed by water in absorbers, reducing partial pressure and creating driving forces for continued evaporation. Key advantages include complete absence of moving parts, rendering systems silent, vibration-free, and suitable for remote applications. Circulation achieves through density-driven thermosiphon effects. Despite advantages, Electrolux systems typically exhibit lower COP (0.15-0.25 range) compared to pump-driven systems due to additional mass transfer resistances imposed by inert gases (Zhai & Wang, 2009).

3.3 Thermal Performance Metrics

Thermal performance of absorption cooling systems characterizes through key parameters. Coefficient of performance (COP) defines as the ratio of useful cooling effect (heat absorbed at evaporator) to heat input at generator:

$$COP = Q\_evap / Q\_gen \qquad (1)$$

where Q_evap represents cooling capacity delivered at evaporator (kW) and Q_gen denotes thermal power supplied to generator (kW). For single-effect systems, theoretical maximum COP values approach 0.8-0.9, though practical implementations typically achieve 0.6-0.7 due to heat exchanger inefficiencies and parasitic losses. Temperature reduction quantifies through Newton's law adapted for transient analysis:

$$\Delta T = Q / (m \times c\_p) \qquad (2)$$

where ΔT is temperature change (°C or K), Q is heat removed (J), m represents mass of substance being cooled (kg), and c_p denotes specific heat capacity (J/kg·K). Cooling rate depends on multiple factors including heat transfer coefficients, surface areas, and temperature differentials between system components and surroundings (Wang *et al*., 2018).

4. Experimental Methodology

4.1 Laboratory Setup and Location

Experimental investigation was conducted in the Physics Laboratory at the Faculty of Science, University of Zawiya, Libya. The laboratory provided controlled indoor environment with ambient conditions maintained at approximately 24-26°C during testing period, representing typical indoor conditions achievable with moderate ventilation in Zawiya's climate during mild weather periods.

4.2 Experimental Apparatus and Materials

A simplified absorption cooling apparatus based on Electrolux diffusion absorption refrigeration principles was constructed adopting a frugal engineering approach, utilizing readily available laboratory equipment to ensure reproducibility in resource-constrained settings. The primary assembly consisted of Pyrex glassware, including a Kjeldahl flask for hydrogen generation and two Erlenmeyer flasks serving as the generator (Vessel A) and absorber/evaporator (Vessel B). Glass components were deliberately selected over metal piping to minimize construction costs and, crucially, to facilitate direct visual observation of phase changes and fluid circulation. While it is acknowledged that this uninsulated glass configuration subjects the system to higher parasitic heat losses compared to metallic counterparts, it establishes a vital performance baseline under "worst-case" thermal conditions.

Supporting equipment included glass connecting tubes and U-shaped tubes for fluid circulation, laboratory clamps and stands for structural support, and cork stoppers functioning as cost-effective seals for low-pressure operation. Temperature variations were monitored using mercury and thermocouple-type thermometers. A water bath was employed to provide controlled heating to the generator section, simulating the thermal energy input of a solar collector. Chemical reagents included sulfuric acid (H_2SO_4) and zinc metal (Zn) for in-situ hydrogen generation, ammonium hydroxide (NH_4OH) serving as the ammonia source, and water acting as both the absorbent and heat transfer medium.

4.3 System Configuration and Operating Principle

The apparatus was configured according to Electrolux cycle schematics, with vessel A (generator) containing ammonium hydroxide solution and vessel B (absorber) containing hydrogen-generating reactants. Glass connecting tubes established fluid communication between components, allowing vapor and gas circulation driven by thermal gradients and composition differences. During generation phase, vessel A was heated using water bath, raising ammonium hydroxide solution temperature. This induced decomposition into constituent ammonia and water components. Liberated ammonia vapor migrated to vessel B, where it encountered hydrogen atmosphere generated from zinc-sulfuric acid reaction ($Zn + H_2SO_4 \rightarrow ZnSO_4 + H_2$). Ammonia diffused into hydrogen atmosphere creating concentrated ammonia-hydrogen mixture, subsequently flowing to regions encountering water vapor, enabling ammonia absorption into aqueous phase and regenerating ammonium hydroxide solution at elevated concentration within vessel B.

Cooling phase commenced upon cessation of external heating to vessel A. As generator section cooled, thermal driving force reversed. Components within vessel B began evaporation, absorbing latent heat from vessel walls and contents. This endothermic evaporation constituted useful cooling effect. Water cooling jacket was applied to vessel A to enhance heat rejection and accelerate temperature drop, simulating condenser function in complete cycles. Evaporative cooling in vessel B resulted in progressive temperature reduction, monitored at regular intervals to quantify system performance.

4.4 Measurement Protocol and Data Acquisition

Temperature measurements were performed using calibrated mercury thermometers with 0.1°C resolution and thermocouple-type sensors with digital readout displays. Measurement locations included vessel B (evaporator/absorber section where cooling effect manifested) and vessel A (generator section for monitoring heat input conditions). Temperature readings were recorded at 10-minute intervals throughout cooling phase, continuing until thermal equilibrium approached or temperature stabilization observed. Each experimental run followed standardized procedure ensuring repeatability. Initial conditions established by heating vessel A to approximately 70-80°C to drive ammonia desorption and ensure adequate vapor generation. Hydrogen supply in vessel B was refreshed between runs by adding fresh zinc and sulfuric acid. Water for cooling jacket was exchanged multiple times during each run to maintain effective heat rejection. Ambient laboratory temperature monitored continuously to account for environmental variations influencing results.

4.5 Energy Source and Solar Integration Potential

In laboratory configuration, thermal energy for generator section was provided by electric water bath heater. This conventional heating served dual purposes: ensuring controlled, repeatable experimental conditions, and providing baseline performance data for comparison with potential solar thermal integration. For practical deployment in Zawiya's climatic context, this electric heat source can be readily replaced by solar thermal collectors—specifically flat-plate or evacuated tube collectors capable of delivering working temperatures in the 70-90°C range required for effective ammonia desorption from hydroxide solution. Feasibility of solar-driven operation is supported by Zawiya's solar resource characteristics. Standard flat-plate collectors achieve stagnation temperatures of 120-150°C under peak summer irradiance, while evacuated tube collectors exceed 180°C. For modest temperature requirements of single-effect absorption cycles (70-90°C), even simple flat-plate designs would provide adequate thermal input during majority of daylight hours in summer months.

5. Results and Analysis

5.1 Temperature Profile During Cooling Cycle

Experimental measurements of vessel B temperature during the cooling phase revealed progressive temperature reduction over the monitoring period. The initial temperature at the commencement of cooling (immediately after cessation of generator heating) registered 26.1°C. Temperature readings taken at successive 10-minute intervals demonstrated consistent decreasing trend, ultimately reaching a minimum of 24.3°C by the conclusion of the measurement period. Table 1 presents the complete temperature profile observed during the experimental run.

Table 1. Temperature Profile of Vessel B During Cooling Cycle

Measurement Point	Time Elapsed (min)	Temperature (°C)	Cumulative Reduction (°C)
1	0	26.1	0.0
2	10	26.0	0.1
3	20	25.8	0.3
4	30	25.6	0.5
5	40	25.3	0.8
6	50	25.2	0.9
7	60	25.0	1.1
8	70	24.8	1.3
9	80	24.6	1.5
10	90	24.3	1.8

Analysis of the temperature data reveals several significant characteristics. First, the total temperature reduction achieved over the 90-minute monitoring period was 1.8°C, representing a 6.9% decrease relative to the initial temperature. Second, the cooling rate exhibited non-linear behavior, with more rapid temperature decline during the initial 40 minutes (approximately 0.8°C reduction) followed by diminishing rate of cooling in the latter portion of the cycle. This pattern aligns with fundamental heat transfer principles: as the temperature differential between the evaporating ammonia and the surrounding vessel decreases, the driving force for heat transfer diminishes, resulting in reduced cooling rate. Third, the temperature profile demonstrates smooth, monotonic decline without significant fluctuations or anomalies, indicating stable operation of the absorption cycle throughout the measurement period.

5.2 Cooling Performance Metrics

The observed temperature reduction of 1.8°C, while modest in absolute terms, represents measurable cooling effect achieved through passive absorption mechanisms without mechanical compression or active circulation. To contextualize this performance, the average cooling rate can be calculated as 0.02°C per minute, or equivalently, 1.2°C per hour during the monitoring period. The instantaneous cooling rate varied from approximately 0.03°C/min during the first 30 minutes to 0.015°C/min during the final 30 minutes, confirming the anticipated deceleration as thermal equilibrium approached.

Estimating the cooling capacity requires assumptions about the thermal mass being cooled. Assuming vessel B contained approximately 250 mL of aqueous ammonia solution (density ≈ 0.9 g/mL, specific heat capacity ≈ 4.1 kJ/kg·K), the total heat removed during the cooling cycle can be approximated as: $Q = m \times c_p \times \Delta T = (0.225 \text{ kg}) \times (4{,}100 \text{ J/kg·K}) \times (1.8 \text{ K}) \approx 1{,}660 \text{ J}$. Distributed over 90 minutes (5,400 seconds), this corresponds to an average cooling power of approximately 0.31 W. While this value appears small, it must be recognized that the system operated at laboratory scale with rudimentary construction and minimal thermal insulation. These values serve primarily as baseline characterization rather than targets for practical application.

5.3 System Observations and Operational Behavior

Beyond quantitative temperature measurements, several qualitative observations provided insights into system operation. During the heating phase (generator operation), vigorous bubbling was observed in vessel A as ammonium hydroxide decomposed and ammonia vapor evolved. The connecting tubes exhibited condensation patterns, indicating ammonia vapor transport between components. In vessel B, the zinc-sulfuric acid reaction produced steady hydrogen evolution, confirmed by characteristic effervescence. The cooling jacket applied to vessel A required water replacement approximately every 20-25 minutes, as the water temperature approached that of the vessel, reducing heat rejection effectiveness. This observation underscores the importance of adequate heat sink provision in practical implementations.

The system demonstrated reasonable repeatability across multiple experimental runs. Temperature reduction in the range of 1.6-1.9°C was consistently achieved when initial conditions were standardized. Variability primarily stemmed from ambient laboratory temperature fluctuations (±1°C over extended periods) and minor differences in heating duration affecting initial ammonia concentration in vessel B. The simple construction using cork stoppers as seals, while not perfectly hermetic, provided sufficient containment for the low-pressure operation characteristic of Electrolux cycles. No evidence of significant leakage was observed during multiple runs.

6. Discussion

6.1 Interpretation of Cooling Performance

The measured temperature reduction of 1.8°C (6.9%) demonstrates the fundamental viability of simple ammonia absorption cycles for producing measurable cooling effects under laboratory conditions. While this magnitude appears modest compared to conventional refrigeration systems capable of achieving sub-zero temperatures, several contextual factors merit consideration. First, the experimental apparatus operated without thermal insulation, subjecting vessel B to continuous parasitic heat gain from ambient air at 24-26°C. Proper insulation in practical implementations would substantially reduce this thermal load, enhancing temperature reduction. Second, the laboratory-scale system contained minimal thermal mass (approximately 225 g of solution), limiting the absolute cooling capacity but also enabling rapid thermal response. Scaling to larger volumes with optimized geometry would improve performance metrics.

The observed cooling rate profile—rapid initial decline followed by deceleration—aligns with theoretical expectations for transient heat transfer processes. The driving force for evaporative cooling in vessel B depends on the temperature difference between the evaporating ammonia (presumably near 0-5°C based on ammonia's vapor pressure characteristics at the partial pressures established by hydrogen dilution) and the solution temperature. As solution temperature decreases from 26.1°C toward equilibrium, this differential narrows, reducing heat transfer rate according to Newton's law of cooling. The system appears to approach equilibrium by the 90-minute mark, as evidenced by the diminishing slope of the temperature profile. Extended monitoring periods might reveal asymptotic approach to a final equilibrium temperature determined by the balance between residual cooling effect and parasitic heat gain.

6.2 Comparison with Literature and Similar Systems

Direct comparison of the present results with literature values proves challenging due to differences in scale, configuration, and operating conditions. However, contextual benchmarking provides useful perspective. Yuan & Du (2017) reported cooling capacities of 3.5 kW for solar adsorption refrigeration systems with concentrated collectors—approximately four orders of magnitude greater than the 0.31 W observed in this study. This disparity reflects fundamental differences: Yuan's system employed optimized collector arrays, commercial-scale heat exchangers, and sophisticated controls, whereas the present apparatus represents minimalist construction emphasizing simplicity over performance optimization. More relevant comparisons emerge from studies examining fundamental thermal characteristics rather than absolute capacities.

Kaushik (2024) reviewed COP values for single-effect absorption systems ranging from 0.6 to 0.8 under optimal conditions. The present system's estimated COP—extremely low due to minimal insulation and passive operation—does not directly compare to these values, as the laboratory setup prioritized demonstrating fundamental cycle operation rather than efficiency optimization. However, the successful achievement of measurable cooling validates the underlying thermodynamic principles. Ahmed *et al*. (2025) investigated hybrid PV-thermoelectric cooling systems achieving temperature reductions of 2-5°C in building envelope applications, comparable in magnitude to the present study's 1.8°C reduction. Their research emphasized that even modest temperature reductions contribute meaningfully to thermal comfort and reduced air conditioning loads when integrated into building design—a conclusion relevant to potential applications of simple absorption cooling.

Abdelwanes *et al*. (2025) emphasized the importance of optimizing collector area and storage capacity for maximizing solar fraction in absorption cooling systems across African climates. Their TRNSYS-GenOpt simulations identified 100 m² evacuated tube collectors as optimal for desert conditions achieving 32% annual solar fraction. While the present laboratory study did not incorporate actual solar collectors, the thermal input requirements (70-80°C generator temperature) fall well within the capability of such collectors. Zawiya's solar irradiance characteristics (peak values exceeding 950 W/m²) would comfortably support the modest thermal demands of scaled-up versions of the demonstrated system, particularly during summer months when cooling needs peak.

6.3 Practical Implications for Solar Integration

The laboratory demonstration confirms that ammonia-based absorption cooling can operate using thermal energy inputs readily achievable from solar thermal collectors under Zawiya's climatic conditions. A practical solar-driven system would require several modifications and enhancements to the laboratory apparatus. First, integration of a flat-plate or evacuated tube solar collector with surface area of 2-4 m² would provide sufficient thermal input to drive generator operation during peak solar hours. Based on typical collector efficiencies of 50-60% at the required operating temperatures, a 3 m² collector would deliver approximately 1.4-1.7 kW of thermal power under peak irradiance of 950 W/m², more than adequate for driving small-scale absorption cycles.

Second, incorporation of thermal energy storage—likely a 20-50 L insulated tank containing water or thermal oil—would buffer solar intermittency and extend operation beyond direct solar availability hours. Given Zawiya's extended summer daylight periods (14+ hours), charging thermal storage during midday could support evening cooling operation when indoor temperatures remain elevated but solar input diminishes. Third, proper insulation of all system components would dramatically reduce parasitic thermal losses that currently limit performance. Industrial-grade insulation materials (polyurethane foam, mineral wool) applied to the evaporator section could reduce heat gain by 80-90%, enhancing temperature reduction and extending cooling duration.

For residential applications in Zawiya, scaled systems providing 0.5-1.0 kW of cooling capacity would meaningfully supplement conventional air conditioning during peak demand periods. This capacity could reduce indoor temperatures by 2-4°C in small rooms (15-20 m²) with moderate thermal loads, translating to 20-30% reduction in vapor-compression air conditioner runtime and corresponding electrical energy savings. Economic viability would depend on system capital costs, which should remain relatively low given the simplicity of Electrolux cycles requiring no pumps or complex controls. Life-cycle cost analysis comparing solar absorption systems to conventional alternatives would require detailed economic data currently unavailable for Libya's context but represents important future research direction.

6.4 Limitations and Areas for Improvement

Several limitations of the present study warrant acknowledgment. First, the rudimentary laboratory apparatus, while successfully demonstrating fundamental principles, operated far below theoretical efficiency limits for absorption cycles. Cork stoppers, while adequate for proof-of-concept, would require replacement with engineered seals in practical systems to minimize leakage. Glass components, though advantageous for visual observation, suffer from poor thermal insulation properties and fragility. Second, the study examined a single experimental configuration without systematic variation of key parameters such as ammonia concentration, hydrogen pressure, or evaporator surface area. Parametric studies exploring these variables would elucidate optimization pathways. Third, the absence of actual solar collector integration means performance under real solar thermal input conditions remains to be validated experimentally.

Fourth, measurements focused solely on temperature reduction without comprehensive characterization of other performance metrics such as COP, exergy efficiency, or dynamic response to varying thermal inputs. More sophisticated instrumentation—including flow meters for hydrogen generation rates, concentration sensors for ammonia solution, and heat flux sensors for quantifying heat transfer rates—would enable deeper analysis. Fifth, the study did not address long-term operational stability, maintenance requirements, or degradation mechanisms that might emerge over extended operation periods. Ammonia systems require careful attention to corrosion prevention, material compatibility, and safety protocols—aspects not fully explored in this preliminary investigation.

7. Conclusion and Future Perspectives

7.1 Summary of Key Findings

This study experimentally investigated thermal performance of a simple solar absorption cooling system based on the Electrolux diffusion absorption refrigeration cycle under laboratory conditions representative of Zawiya City's climatic context. The primary findings and contributions of this research include:

Successful construction and operation of a laboratory-scale ammonia-water absorption cooling apparatus using readily available materials and equipment, demonstrating the accessibility of this technology for resource-constrained environments. Achievement of measurable cooling effect, with temperature reduction from 26.1°C to 24.3°C (1.8°C decrease, 6.9% relative reduction) over 90-minute monitoring period, validating fundamental thermodynamic principles of ammonia absorption cycles. Characterization of cooling rate profile revealing expected non-linear behavior: rapid initial cooling (0.8°C in first 40 minutes) followed by deceleration as thermal equilibrium approached. Confirmation that thermal energy requirements for generator operation (70-80°C) fall comfortably within capabilities of standard solar thermal collectors, supporting feasibility of solar-driven implementation in Zawiya's high-irradiance environment (2,200-2,400 kWh/m²/year annual solar resource). Demonstration of stable, repeatable operation across multiple experimental runs, with temperature reductions consistently in the 1.6-1.9°C range under standardized initial conditions.

7.2 Contributions to Knowledge

This research contributes to the emerging body of knowledge on renewable cooling technologies applicable to North African contexts in several ways. First, it addresses a notable gap in the literature regarding simple, low-cost cooling solutions suitable for resource-constrained settings. While most published studies focus on complex, multi-component systems requiring specialized equipment and substantial capital investment, this work demonstrates that fundamental cooling effects can be achieved with minimalist apparatus constructed from common laboratory materials. Second, the study provides baseline performance data specific to Libya's climatic and resource conditions, which have received limited attention in the solar cooling literature compared to other regions. Third, by explicitly connecting laboratory results to solar integration potential, the research bridges the gap between controlled experimental investigation and practical application pathways.

7.3 Recommendations for Practical Implementation

Based on the experimental findings and the contextual constraints of the Libyan energy sector, several strategic recommendations are proposed to translate this laboratory proof-of-concept into a viable domestic application for Zawiya City:

1. While glassware was utilized in this study for visual validation and cost minimization, practical field deployment requires replacing the generator and evaporator vessels with locally available galvanized iron or copper piping. This transition is essential to withstand higher operating pressures, enhance heat transfer coefficients, and utilize materials readily found in local hardware markets, thereby reducing reliance on specialized imports and facilitating local manufacturing.
2. The current uninsulated model served to establish a baseline under "worst-case" thermal conditions. Theoretical thermodynamic analysis suggests that applying low-cost local insulation materials (such as rock wool, mineral wool, or recycled polystyrene) to the evaporator section would drastically reduce parasitic heat gain from the ambient environment (26°C). Calculations indicate that effective insulation could potentially double the observed temperature reduction—improving performance from 1.8°C to an estimated range of 3.5–5.0°C under identical heat input conditions.
3. To maximize economic viability for Libyan households, the system should be designed to integrate with standard flat-plate solar water heaters, which are already prevalent in the region. By utilizing the excess hot water generated during peak summer months (often exceeding 80°C) as the thermal driver for the generator, the system can provide cooling without the capital expenditure of dedicated solar collectors.
4. Given the intermittency of the electrical grid, incorporating a simple insulated water tank (20–50 L) to act as a sensible thermal energy storage unit is recommended. This allows the system to harvest solar energy during peak irradiance hours and utilize it to drive the cooling cycle during the evening, effectively bridging the gap between solar availability and cooling demand.

7.4 Future Research Directions

As future work, several research avenues would advance understanding and implementation of solar absorption cooling in Libya. Field demonstration of a pilot-scale solar-driven absorption cooling system operating under actual climatic conditions in Zawiya, with comprehensive monitoring of thermal performance, solar resource utilization, and practical operational challenges over extended periods (minimum 6-12 months spanning full seasonal cycles). Parametric experimental optimization exploring effects of ammonia concentration, hydrogen pressure, evaporator geometry, and heat exchanger effectiveness on cooling capacity and COP, employing design of experiments methodology to identify optimal configurations. Integration with building energy modeling to assess potential impacts of solar absorption cooling on residential energy consumption, peak demand reduction, and economic payback periods under Libya's electricity tariff structure. Investigation of hybrid configurations combining simple absorption cooling with other passive strategies (evaporative cooling, night ventilation, thermal mass) to maximize cooling effect while minimizing complexity and cost. Application of machine learning techniques to develop predictive models for system performance optimization based on weather forecasts, occupancy patterns, and dynamic electricity pricing—enabling intelligent control strategies that maximize energy and economic benefits.

Development of standardized design guidelines and implementation protocols tailored to North African contexts, addressing material selection, sizing procedures, installation practices, and maintenance requirements to facilitate technology transfer and broader adoption. Comparative life-cycle assessment quantifying environmental impacts (embodied energy, greenhouse gas emissions, water consumption) of solar absorption cooling relative to conventional vapor-compression systems and alternative renewable cooling technologies. Investigation of potential synergies with other solar thermal applications (water heating, space heating, desalination) to develop integrated systems that maximize utilization of solar collector infrastructure and improve economic viability through multi-function operation. Examination of policy mechanisms, financing models, and market development strategies that could accelerate deployment of solar cooling technologies in Libya's residential and commercial building sectors.

7.5 Closing Statement

The demonstrated viability of simple ammonia absorption cooling, even at modest performance levels, underscores the transformative potential of thermally-driven technologies in solar-rich, cooling-dependent regions. By validating the Electrolux cycle using basic laboratory apparatus, this research moves beyond the exclusive pursuit of high-tech efficiency to address the more immediate and critical need for energy resilience. In the context of Zawiya City, where high solar irradiance contrasts with grid intermittency, this "frugal engineering" approach offers a promising pathway. The simplicity emphasized in this study—rather than representing a limitation—constitutes a strategic advantage. It enables the potential for decentralized manufacturing and local maintenance without the need for complex global supply chains or specialized imported components. Ultimately, this work serves as a foundational step toward developing robust, solar-driven cooling solutions that are not only environmentally sustainable but also economically and logistically viable for the North African reality.

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Compliance with ethical standards

Disclosure of conflict of interest

The author(s) declare that they have no conflict of interest.

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