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Advancements in Liquid Desiccant Technologies: A Comprehensive Review of Materials, Systems, and Applications

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Abstract: Desiccant agents (DAs) have drawn much interest from researchers and businesses because they offer a potential method for lowering environmental impact, increasing energy efficiency, and controlling humidity. As a result, they provide a greener option to conventional air conditioning systems. This review thoroughly analyzes current issues, obstacles, and future advancements in liquid desiccant agents (LDAs) for drying, air conditioning, and dehumidification applications. The importance of LDAs in lowering energy use and greenhouse gas emissions is highlighted, emphasizing their potential for environmentally friendly humidity control. The current review examines key parameters such as novel materials, enhancing desiccant qualities, integration with technologies, and long-term durability while examining recent developments in LDAs and investigating their applications in diverse industries. The main conclusions from the evaluated publications in this review are also highlighted, including developments in LDAs, new applications, and developing research fields. Overall, this review advances knowledge of LDAs and their potential to shift humidity control systems toward sustainability and energy efficiency.

Keywords: liquid desiccant; dehumidification; energy efficiency; hybrid systems; moisture removal

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1. Recent Developments in Desiccant Materials and Their Applications

Desiccant agents (DAs) are substances or compounds that strongly attract water molecules and remove moisture from the surroundings. DAs are used in different applications, such as controlling humidity levels, preventing moisture-related damage, and maintaining product quality. The working principle of desiccant materials (DMs) relies on the adsorption phenomenon. Adsorption is the adhesion ability of materials to other material surfaces. Due to their strong affinity for water molecules, liquid desiccant materials (LDMs) may efficiently absorb moisture from their surroundings (Figure 1), causing humidity to decrease dramatically.

Numerous research investigations have been carried out to improve the knowledge of and use of liquid desiccants. Despite significant contributions made by previous researchers, there are still unexplored research areas. There is a need for a comprehensive review of current issues, obstacles, and future advancements in the field of liquid desiccant agents (LDAs) for drying, air conditioning, and dehumidification applications. Therefore, it is essential to develop a comprehensive review to provide a better understanding of the state of the art in liquid desiccant research. Xiangjie Chen et al. [1] provided an overview of recent advances in liquid desiccant dehumidification and air conditioning systems. Their review discussed the different types of liquid desiccant materials and their dehumidification properties, in addition to new techniques that use mixed solvents to improve dehumidification. The use of various dehumidification techniques, the efficiency of their integration with liquid desiccant systems, and the application of liquid desiccant systems in various energy systems were also highlighted in the review. The review's authors concluded that further applicable study of mixed solvents and hybrid systems is required. Renyuan Li et al.'s [2] study examines numerous commercially available liquid desiccants, their composites, and various liquid desiccant dehumidifier setups. Additionally, their work provides performance metrics for evaluating system performance, advancing the study and development of liquid desiccant technology.

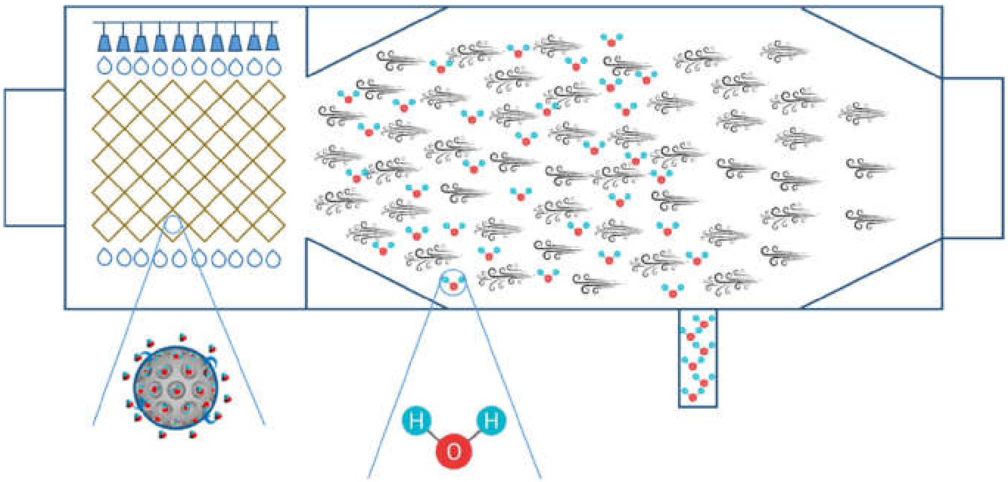

Figure 1. Mechanism of Liquid Desiccant Dehumidification.

Nonporous tubular membranes and non-corrosive ionic liquid desiccants were utilized by Lingshi Wang et al. [3]. In their experimental work, the novel exchanger produced an average water vapor flux of 0.316 g/(h–m^2–Pa) and a specific vapor transportation rate of 778.6 g/(h–m^2) when utilized in the dehumidification loop. The performance is comparable to or better than conventional dehumidifiers that employ porous membranes and conventional liquid desiccants, which is a major advance over earlier designs using nonporous membranes. The experimental results and data offer new perspectives on sophisticated membrane-based ionic liquid desiccant systems.

The potential of atmospheric water as a plentiful alternative water source was investigated by Ho, K. et al. [4]. The water vapor harvesting, physical and chemical stability, and release capabilities of 14 common salt couples were assessed, with the most promising candidates being copper chloride, copper sulfate, and magnesium sulfate. As mentioned earlier, the salts were used to develop bilayer water collection devices with a photothermal top layer and a salt-loaded fibrous membrane bottom layer that can release water vapor even at low humidity levels (down to 15%). In an experimental study, Kavasoğulları, B. [5] measured the equilibrium water vapor adsorption of three types of zeolites: zeolite 3A, zeolite 13X, and delaminated Y zeolite (DAY). Different models and isotherms were used to assess the data after the experiments were carried out at varied pressures and temperatures. A.S.A. Mohamed et al. [6] developed an effective liquid dehumidification system under atmospheric conditions. Polycarbonate panels were employed in the absorber and desorber processes because they have a high surface tension that can enhance the wetting capability of liquid desiccants and promote mass transfer. Several characteristics were examined, including temperature, humidity, and concentration, to assess the system's performance.

The direction of air-to-solution flow influences the dehumidification efficacy and physical dimensions of liquid desiccant dehumidifiers. Li, G. et al. [7] compared counter-flow and cross-flow dehumidifiers in a controlled environment. Empirical models were developed to predict their performance under varying conditions of operation. Results indicated that increasing the inlet air humidity ratio enhanced the dehumidification performance of the counter-flow dehumidifier, while the cross-flow dehumidifier exhibited only modest improvement.

Alessandro Giampieri et al. [8] evaluated the performance of a cross-flow desiccant dehumidifier employing channel gauze structured packaging and a LiCl aqueous solution as the desiccant. The inlet parameters of the dehumidifier, including flow rates, temperature, concentration, and humidity ratio, were investigated to determine their influences on humidity reduction and dehumidification efficiency. Their results suggested that cross-flow dehumidifiers are more practicable than counter-flow dehumidifiers, consistent with other research findings.

Recent advancements in adsorbent materials for thermally driven atmospheric water harvesting (AWH) were investigated by Tanzeela Z. Wasti et al. [9]. Different adsorbent materials were investigated, including solid, liquid, and composite adsorbents. The most important characteristic of adsorbent material is its water production capacity at varying air temperatures and relative humidity (RH). MOF of the type MIL-101(Cr) and Zr-MOF-808 were discovered to have the highest water production capacity, at 3.10 $L/m^2/day$ and 8.60 $L/m^2/day$, respectively. In addition, silica gels and mesoporous silica gel had the highest water production capacity, at 1.30 $L/m^2/day$.

1.1. Innovative Liquid Desiccants

The evaluation of alternative solutions employable as working fluid was conducted to overcome the common drawbacks of common desiccants, such as corrosion, crystallization, and high cost-effectiveness. Mohsen Shakouri et al. [10] investigated the use of starch particles (SPs) coated with Cetyl Pyridinium Bromide (CPB) as a potential desiccant material for air-to-air energy exchangers. Their experimental work used a small-scale exchanger coated with SP-CPB 0.5 to conduct single-step and cyclic water vapor sorption tests. SP-CPB 0.5, which has the optimal surface area and pore structure properties, was discovered to have a higher water vapor absorption capacity than unmodified starch and other desiccants tested. Their results demonstrate that it performed significantly better than other coated exchangers, with enhanced latent efficacy and increased durability due to the CPB surface coating. In addition, as a sustainable desiccant coating, the SP-CPB 0.5 can be used in air-to-air energy exchangers for ventilation systems, according to the study's findings.

In another investigation, water was extracted from the air using silica gel. The experimental results revealed that up to 159 g of water per kilogram of silica gel can be extracted from the air in a 12 h cycle. With a 25 mm silica layer thickness, the device produced 800 mL of water per day at an overall efficacy of 50%. Increasing relative humidity can increase water collection and capture rates. The device can be improved by adding multiple sorbent layers with improved adsorption and desorption properties [11]. Hasila Jarimi et al. [12] reviewed sustainable methods for harvesting water from atmospheric fog and dew. Their review focused on fog collector performance, feasibility studies, and efficiency enhancements. Fog harvesting is known to be limited by the frequency of global fog, while condensation water harvesting requires a chilled condensing surface but is available everywhere. There are three techniques for collecting dew water: radioactive chilling surface, solar-regenerated desiccant system, and active condensation technology. Hesamoddin Salarian et al. [13] examined desiccant systems as an alternative to vapor compression air conditioning that is more energy efficient. Liquid desiccant systems have advantages over solid desiccant systems, mainly when solar energy is used for regeneration. Their experimental work included examining the effects of design parameters such as air and liquid flow rates, air humidity, desiccant temperature, and concentration on the height of a packed tower and the humidity performance of the column. Their study concluded that additional practical research is required on blended solvents and hybrid systems. X.N. Wu et al. [14] explored the effect of using substrate in rotary desiccant wheel air conditioning systems. Both porous ceramic and glass fiber paper are used as the substrate for the rotary desiccant wheel, focusing on selecting substrates that offer high porosity and thermal conductivity to improve dehumidification capacity. Their study suggested that porous fiber paper is typically the best substrate for non-rotary solid desiccant dehumidification systems. However, the short lifespan and poor adsorption performance of current desiccant wheels indicate the need for additional studies to better understand the interaction between substrates and desiccant materials.

1.2. Solar-Powered Desiccant Cooling System

Renewable and wasted energies, such as solar power, can be exploited for desiccants and rationalize energy consumption. Moreover, these resources can also be used to reduce emissions, create a more sustainable future, and improve air quality. There have been many studies conducted on the use of renewable energy sources, especially solar energy [14,15] that tend to increase energy savings while increasing the complexity and cost of the unit. As most of the other components have evolved to a great extent, the performance of the desiccant systems and, therefore, the savings, are mainly dependent on the performance of the dehumidifier. Consequently, the selection of a high-quality dehumidifier is essential for achieving the highest levels of energy efficiency. Ghoulem M. et.al. [16] studied the use of liquid desiccant cooling systems in greenhouses in hot climates that were powered by solar energy. Figure 2 illustrates the three process fluids in the system: liquid desiccant, cooling water, and air. A porous desiccator dehumidifies the outdoor air before it is cooled by the evaporative cooling pad. The liquid desiccant absorbs the moisture from the air, the cooling water absorbs the heat from the air, and the evaporative cooling pad cools the air by evaporating the cooling water. The cooled and dehumidified air is then circulated in the greenhouse to lower the temperature. Using a solar regenerator, the system removes the water from the liquid desiccant and restores its dehumidifying abilities. Furthermore, cooling tubes are included in the desiccator to remove the latent heat that is created by condensation. An exhaust fan drives air through the greenhouse. According to the study, the results of this study were compared with those of previous studies using other liquid desiccants. The findings showed that the solar regenerator was more efficient in cooling air and reducing humidity. The system also showed higher energy savings when compared with other desiccant systems.

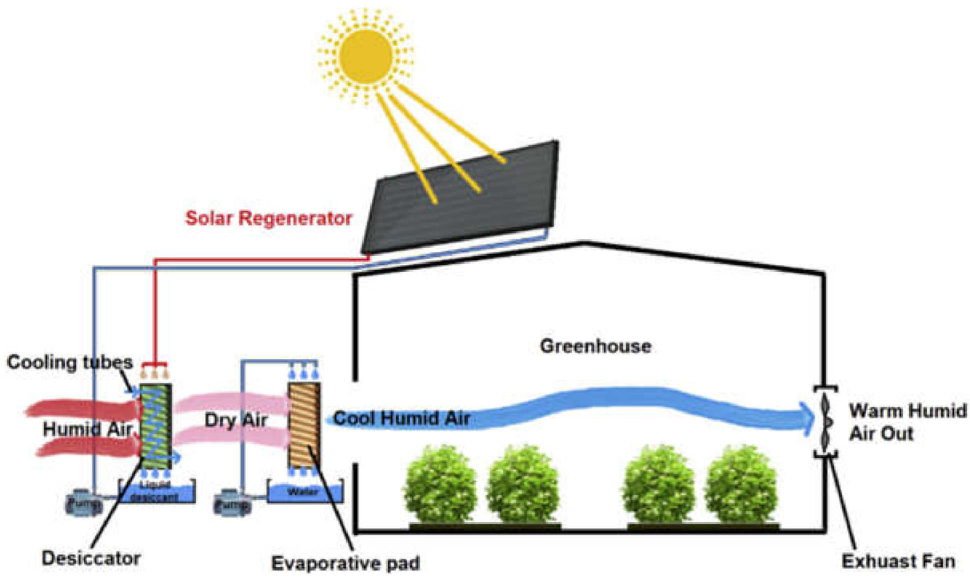

Figure 2. Illustration of a solar-powered liquid desiccant cooling system for greenhouses in hot climates [16].

Water is essential for many aspects of society, but factors including population growth, industrialization, urbanization, and poor water management have led to water scarcity and environmental concerns on a global scale. Even though there is sufficient water, it is unevenly distributed, resulting in shortages and the need for portable fresh water [15]. Over two billion people live in water-stressed regions; therefore, Yinyin Wang et al. [17] examined research on extracting water from atmospheric air, including theoretical and practical methods, as depicted in Figure 3. They compared results and discussed the efficacy of water extraction systems and restrictions that affect efficacy. Most air conditioning systems use refrigerants that contribute to global warming and the depletion of the ozone layer. As environmentally friendly as evaporative cooling systems are, their performance is negatively impacted by high inlet air humidity. Utilizing desiccant material is a remedy for this issue.

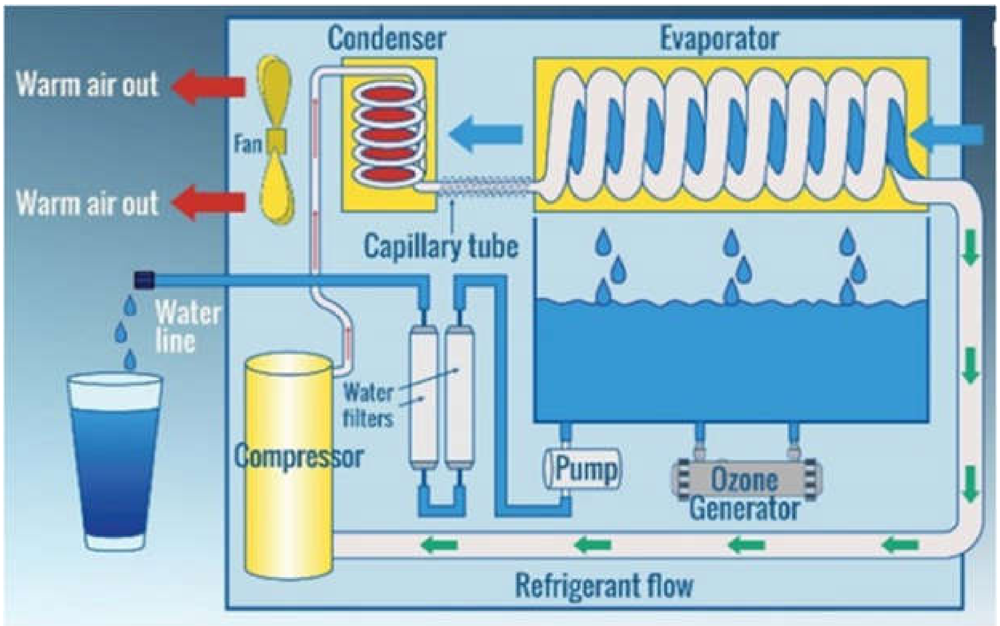

Figure 3. Extracting water from atmospheric air [17].

Taresh, H.M. et al. [18] designed a heat exchanger coated with silica gel for use as a dehumidifier. The effects of various parameters on the performance of the system were studied. The outcomes of their study indicate that the system could function effectively in hot and humid climates, such as Iraq. Eslami, M. et al. [19] analyzed a system that employs thermoelectric coolers to extract water from moist air. This system comprises ten coolers, heat sinks, fans, and solar panels. The effect of electric current on water production was studied, and the optimal flow rate and temperature were identified. At 318 degrees Celsius and 75% relative humidity, 29.9 mL/h of water is produced.

The global water scarcity crisis is today's most challenging problem, particularly in hot and dry regions. Alternative water sources must be discovered to satisfy the rising demand for water caused by population growth. Atmospheric water, also called atmospheric humidity, is a readily available resource that can be harvested sustainably [20]. Lin Liu et al. [21] investigated the influence of adsorption and desorption characteristics of single-channel silica-gel-coated adsorber in solid desiccant cooling systems. A modified LDF model was developed through numerical modeling to evaluate the kinetics and estimate the total mass transfer rate. The results indicate that the enhanced model accurately represents the kinetics of isothermal dehumidification. Additionally, they found that the moisture transfer strongly depends on kinetic constants, isotherm geometries, and thermal boundaries, as revealed by parametric studies. Further, it was discovered that the maximal value of the transient mass transfer rate of the adsorption process under an ideal isothermal boundary was nearly double that of the third type thermal and adiabatic boundary, respectively. Leila, D. et al. [22] investigated using energy wheels to reduce the energy required for ventilated air conditioning. Recent advancements in energy wheel design utilizing biopolymer desiccant materials, particularly high amylose starch (HAS) coatings, were the focus of this research. They investigated a HAS-coated exchanger on a modest scale. It was found that higher regeneration flow rates and temperatures enhanced the regeneration capacity. However, it reduced the efficacy of moisture recovery at higher air flow rates. The findings suggest that biopolymer desiccants can play a significant role in developing biopolymer-coated energy exchangers.

A new solid desiccant component called the solid desiccant-coated heat exchanger (DCHE) has been developed in which solid desiccant material was used to coat a conventional sensible heat exchanger (SHE) surface. The performance of a DCHE and a SHE functioning in series was investigated through experimentation. The results showed that the cooling power and COP increased by about 75% and 13%, respectively, using an auxiliary the SHE. The system's performance was improved by lowering the cooling water temperature, increasing the inlet air temperature and relative humidity ratio, and utilizing different air velocities for different purposes [23]. In the 1990s, the HVAC industry faced energy resource and demand challenges, necessitating the development of more energy-efficient technologies. Desiccant dehumidification and refrigeration technologies can provide energy-efficient solutions for industrial applications and exceptional circumstances requiring controlled humidity levels. It is anticipated that desiccant technology will develop due to its potential applications and benefits [24].

1.3. Energy Use of Liquid Desiccant Systems

Natural gas is an important primary energy source saturated with water vapor under normal production conditions. The presence of water vapor increases the corrosivity of natural gases, particularly caustic gases. This motivated Bahraminia et al. [25] to conduct a study to address this issue. Their research utilized a silica-gel-based solid desiccant dehydrator due to its ability to provide exceptionally low dew points. Their study presented the design analysis of a two-tower silica gel dehydration unit capable of dehydrating one million standard m^3 of natural gas per day and discussed the effects of various operating parameters on the unit's design. In addition, their study analyzed the regeneration of the weak desiccant bed based on some simplified assumptions and discovered that the higher the regeneration temperature, the less regeneration gas is required [26]. Zhang, L. et al. [27] investigated experimentally the mass-transfer characteristics and regeneration processes of a structured packing dehumidifier/regenerator that employs lithium chloride as a desiccant material under conventional air conditioning operating conditions. According to their findings, the overall mass transfer coefficient in the structured packaging of the dehumidifier/regenerator system varied with air velocity and solution temperature. In addition, they revealed that higher air velocity resulted in greater overall mass-transfer coefficients, while higher solution temperatures resulted in lower coefficients. In addition, correlations were derived for the dimensionless overall mass-transfer coefficients of the dehumidifier and regenerator, and predicted values were within 20% of the experimental values. Gao et al. [28] examined the impact of desiccant and air inlet parameters on the performance of a cross-flow dehumidifier in a liquid desiccant air conditioning system using LiCl solution and Celdek structured packaging. In their study, they evaluated the performance using enthalpy and moisture efficiency. They concluded that increasing dimensions simultaneously could improve performance without increasing pressure loss. Their work provided insights into the factors that affect dehumidifier performance in such systems, which can be used to design more efficient systems. In their recent work, Huang-Xi Fu et al. [29] provided valuable insights regarding the influence of liquid desiccant dehumidification on indoor air quality (IAQ). Although liquid desiccant dehumidification provides effective humidity control and energy savings, IAQ concerns have emerged. The authors' investigation focused on the ability of liquid desiccants to remove volatile organic compounds (VOCs), their effects on bacteria and viruses, their ability to capture particulate matter, and the problem of liquid desiccant carryover.

Sanaye and Taheri [30] modeled and optimized for cooling purposes a heat pump with hybrid liquid desiccant for hot and humid climates. The dehumidifying and cooling sections of the LD-HP system were evaluated based on energy, exergy, economic, and environmental factors. The system was optimized using a multi-objective genetic algorithm with two objective functions (total annual cost and exergy efficiency) and eight design parameters. Compared with a conventional HP system, the optimized LD-HP system reduces electricity consumption by 33.2% and CO_2 emissions by 1.855 kg/year. The COP of the LD-HP system is 4.83, compared with 2.74 for the conventional case. The payback period for the additional apparatus is 3.04 years.

Minaal Sahlot and Saffa B. [31] discussed the use of desiccant cooling systems as an efficient method to control moisture content in air supply without the use of ozone-depleting coolants and while consuming less energy than vapor compression systems. Their study provided a comprehensive analysis of all the components of a liquid desiccant system, including the dehumidifier, regenerator, packaging material, liquid desiccant properties, and energy storage capacities. The researchers also explored the combination of liquid desiccant systems with sensible cooling technologies and mathematical models to predict outlet parameters and current issues in liquid desiccants. Solid and advanced desiccants are briefly discussed, and successful case studies and economic evaluations of desiccant systems are summarized.

Khraisheh, M. et al. [32] reviewed volume reduction technologies as approaches to water production challenges. These technologies, which include freeze concentration, reverse osmosis, humidification, and dehumidification desalination systems, offer a cost-effective and environmentally friendly method for treating large quantities of water production. They concentrated on integrating humidification and dehumidification systems with refrigeration and power cycles for air conditioning and energy production. This review assesses the freshwater yield, GOR, and efficiencies of these integrated systems, as well as the innovation in the HDH desalination technology, particularly its incorporation with the MVC process. In contrast to conventional liquid desiccant air dehumidification, the membrane-based liquid desiccant air dehumidification (MLDAD) process employs semi-permeable membranes to separate water vapor molecules from the air and absorb them. This process eliminates solution droplet residuals in the air stream and removes vapor from the air stream. Liu, X. et al. [33] reviewed the characteristics of liquid desiccants and membranes, MLDAD modules and systems design, dehumidification performance evaluation and comparison, regeneration modules, and system-level energy analysis. In addition, the most recent research findings and future needs for this technology are presented and discussed in their review.

With the invention of gauze packings BX and CY in the early 1960s, Chemtech, S. [34] significantly advanced distillation technology, as depicted in Figure 4. These packings provided distinct benefits, successfully separating previously complicated complex mixtures. In addition, they allowed the separation of thermally sensitive substances via distillation for the first time.

P. Gandhidasan [35] introduced a new model for predicting the irrigated pressure drop in a desiccant–air contact system employing calcium chloride solution as the desiccant material. The model has been validated for various operating values and applies to structured and random packaging columns. Their study considered four distinct random packaging materials and three distinct structured packing materials. The results demonstrate that structured packing is superior to random packing in pressure reduction and capacity. Furthermore, they found that Mellapak 250Y sheets have the lowest pressure drop among structured packing materials, whereas Intalox saddles have the lowest pressure drop among random packing materials. In their review, Tu et al. [36] discussed the challenges and limitations of atmospheric water harvesting in arid and semi-arid regions. In addition, the current advancements in the discipline were reviewed, and its accomplishments and application barriers were discussed. It was determined that a cost-effective method for producing atmospheric water and predicting its efficacy in evaporative cooling for various applications must be identified. Ismael, L. et al. [37] designed and evaluated a new compact evaporative cooler (CCEC) with a desiccant dehumidifier. In their investigation, the air was cooled using thin-film evaporation and dry and moist channels. The study revealed that air flow rate significantly impacted efficiency, whereas air temperature at the inlet had a negligible influence. Leila Dehabadi and Lee D. Wilson [38] investigated the potential of linear and branched starch-based biopolymers, as well as their modified forms, for the fractionation of water and ethanol in binary mixtures, which is beneficial for food processing and biofuel production. Using 1H NMR spectroscopy, the fractionation properties of the materials that were cross-linked with epichlorohydrin at varying concentrations were compared with those of pure solvents. Depending on the Sips isotherm model, these materials have varying monolayer adsorption capacities for water and ethanol in binary mixtures. Depending on the properties of the polymer network, the fractionation selectivity of these materials ranges from 3.8 to 80, with unique solvent-selective absorption. Their results suggest that starch-based adsorbents are a promising and sustainable technology for the adsorptive fractionation of W-E binary mixtures.

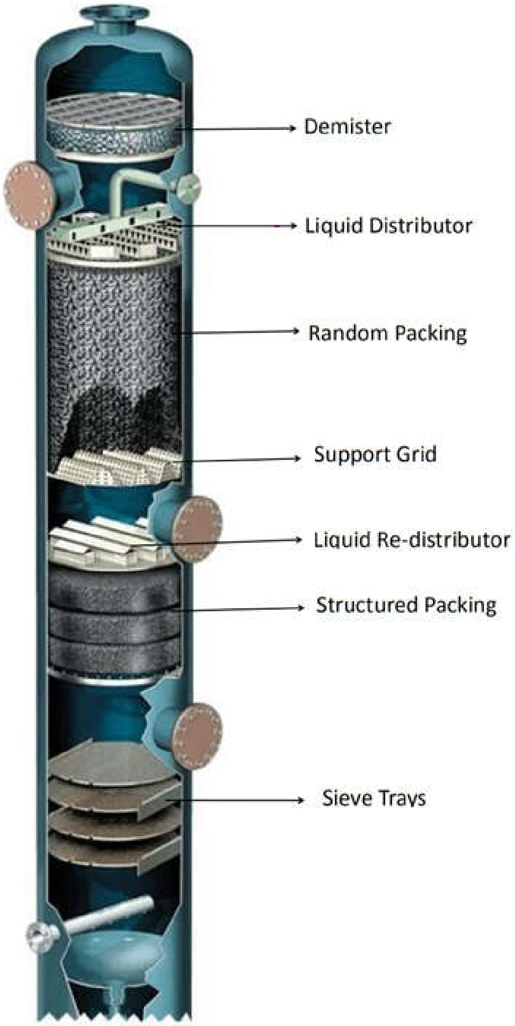

Figure 4. Distillation stuffed with gauze packings [34].

Farhad Fathieh et al. [39] attempted to evaluate the performance of a rotary desiccant wheel coated with mesoporous silica gel particles (55 µm in diameter and 77.5 angstroms in pore breadth) on an aluminum substrate. In their study, the physical and sorption properties of the silica gel were analyzed, and a test facility was designed to measure its exchanger transient response during the dehumidification process. Also, small-scale transient and cyclic tests involving dehumidification and regeneration cycles were conducted to determine the regenerator's latent effects. They found that the obtained latent effectiveness values from both tests exhibited high concordance. Moreover, it demonstrates the efficiency of mesoporous silica gel coatings for this application. Farhad Fathieh et al. [40] investigated the effect of silica gel's physical properties, including particle size, pore width, and specific surface area, on the moisture recovery efficiency of desiccant-coated energy wheels. Small-scale energy exchangers were coated with three silica gel samples with distinct properties, and their sorption performance was evaluated in their investigation. Their experimental results indicated that the pore size distribution, specific surface area, and coating mass of the desiccant were the most influential factors in the transient humidity response. Moreover, the exchanger with the smallest pore width had the highest latent effectiveness, and a 5% reduction in pore width led to a 5% increase in latent effectiveness. Furthermore, increasing particle size had a minor impact on latent efficacy. The outcomes corresponded with data from a correlated model. Fahid Riaz et al. [41] proposed a solar-powered desiccant evaporative cooling (DEC) system for air conditioning that employs thermochemical (TC) materials as a heat storage device, thereby presenting a promising technology for solar energy storage. The system is designed to meet the cooling demands of a subtropical climate bedroom in Lahore, Pakistan, which requires eight hours of nighttime cooling. Magnesium chloride ($MgCl_2 \bullet 6H_2O$) was also employed as a desiccant and a TC heat storage medium. According to the numerical results, 98.8% of July's cooling demand can be met with 57 kg of magnesium chloride even at the utmost cooling demand. Moreover, as heat exchanger efficiency increases, refrigeration output increases. This causes the solar fraction to increase from 70.4% to 82.44%. Further, the chilled air supplied by the system meets the requirements for fresh air essential for the building's ventilation. Using renewable solar energy, the proposed DEC system with TC materials for heat storage provides an efficient and effective solution for air conditioning in buildings located in subtropical climates. In arid regions, water scarcity is a major problem. Even though there is water in the air, it is difficult to extract it using modern technology, mainly when the relative humidity is minimal. However, atmospheric water generators that use sorbents are more efficient and can be powered by solar energy. In this investigation, a Metal–Organic Framework (MOF) called MOF-801 was shown to be capable of capturing water in extremely dry conditions (10–40% relative humidity) and low temperatures. The device is air-cooled and has a thermal efficiency of about 14%; it is anticipated to produce more than 0.25 L of water per kg of MOF per day [42]. Developing desiccant cooling systems, particularly environmentally favorable solar desiccant cooling systems, is discussed in [43]. The research proposed and evaluated the efficacy of a two-stage rotary desiccant wheel cooling/heating system. The results demonstrate that the proposed system performed effectively in both summer and winter, with a 6.68 and 14.43 g/kg moisture removal capacity and a refrigeration capacity of 21.7 and 26.7 kW. In chilling mode, the system's COP reaches approximately 1, and in heating mode, 0.45. Solar desiccant cooling systems' economic viability and energy-saving potential were analyzed, revealing a 45.41 percent and 49 percent reduction in operating costs and CO_2 emissions compared with conventional cooling systems.

Tafesse et al. [44] proposed a new liquid regeneration device, the solar air pretreatment collector/regenerator, which is more appropriate for liquid desiccant conditioning systems in South China's hot and humid climate. The apparatus permits liquid regeneration at reduced temperatures. They used theoretical calculations to determine the optimal Air-to-Salt Mass Ratio (ASMR*) that provides the greatest theoretical storage capacity (SC_{max}) when the air and solution states are matched in the collector or regenerator. It was discovered that when Yin decreases from 29 to 14 g/kg at Tr = 60 °C, and X_{in} = 2.33 kg/kg, the SC_{max} increases by 50% compared with when ASMR* is around 26–27. Additionally, two new concepts were introduced, the effective solution proportion (EPS) and the effective storage capacity (ESC), which were utilized in theoretical calculations to demonstrate that when the EPS decreases from 100% to 67%, the ESC increases slightly, and the liquid outlet concentration is Cstr. These results demonstrate that the liquid-from-air treatment regeneration procedure can improve the performance of liquid desiccant cooling systems.

Djaeni, M. et al. [45] discussed the difficulties and advantages of using dehumidified air at low temperatures in food processing to reduce moisture content and maintain product quality. The dehumidification potential of solid desiccants such as zeolite, silica-based materials, activated carbons, and biomass-based materials was investigated. In addition, the review covered the most recent advancements in effective adsorbent materials and the potential use of such substances in food drying applications. Furthermore, crucial parameters for enhancing systems of adsorptive dehumidification are discussed. Son et al. [46] used the gravimetric technique to determine the desorption isotherms of pure water vapor on zeolite 13X particles across a broad temperature and pressure range. The Sips, Toth, and multisite Langmuir models were modified with the Aranovich–Donohue model to fit the equilibrium of these pure-component systems. The A-D Sips isotherm was found to be the most applicable model for simulating water adsorption on zeolite 13X, as it best matched the experimental data.

Park, B. et al. [47] examined a compact desiccant-based external AC system that utilized heated desorption and chilled adsorption. On the basis of heat and mass transfer properties of the (ZCHE) system, a mathematical model was developed. The results demonstrate that the effectiveness of ZCHE's system depends on water temperature. It was possible to achieve humidification capacities of 25.0 g and 10.2 g at a heat capacity of 5 kW and a chilling capacity of 0.6 kW, respectively. The developed mathematical model corresponds well to the observed data. Xu, S.Z., et al. [48] presented a new design for a sorption thermal energy storage (TES) device for residential heating that employs a valveless adsorber system with a separate reservoir to reduce cost and enhance dependability. A newly developed composite sorbent of zeolite 13X/$MgSO_4$/ENG-TSA is used in the device, which an electric furnace charges. They found that under certain conditions, the results indicated that the TES device containing this sorbent has an energy storage density of 120.3 kWh m^3 and a high-temperature increase of 65–69 °C. In addition, imbued $MgSO_4$ increases the rate of temperature increase during the adsorption heat recovery process. M. Charidi [49] described a desiccant-assisted evaporative refrigeration system employing vermiculite–calcium chloride as the desiccant material. With an average cooling rate of 700 W and a cooling COP between 5 and 6, the system demonstrated a temperature decrease of 10 °C. The economic analysis revealed that the return on investment for summer operation only is three years, making it a viable option for building air conditioning in hot and humid climates such as North Cyprus. Crofoot L. [50] discussed a solar liquid desiccant AC system that conserves primary energy and reduces peak power demand. The system dehumidifies air using a liquid desiccant and can store solar energy. The Queen's University Solar Liquid Desiccant Cooling Demonstration Project was evaluated, which provides 9.2–17.2 kW of cooling power with a thermal Coefficient of Performance (COP) of 0.40 and an electrical COP of 2.40. The annual performance of the system in Toronto, Vancouver, and Miami was predicted using a TRNSYS model. They discovered that the system could be enhanced by replacing inefficient pumps and fans, adding desiccant storage, and enhancing the control scheme. Wu, Qiong [51] investigated Liquid Desiccant Dehumidification Systems (LDDS) to replace conventional air conditioning systems. The heat source for regeneration is typically centralized, whereas LDDS systems are typically distributed throughout a building. This study proposed a new buffer-integrated dehumidifier and a mathematical model describing the system's dynamic behavior. Also, they utilized a concentration regulation strategy and genetic algorithm to optimize energy consumption. Moreover, experimental studies were conducted to validate these strategies, and a fuzzy-PID controller was used to regulate the discharge of air humidity. Furthermore, the feasibility of the proposed method was validated on a test device using the distributed operating strategy. Zhang et al. [52] investigated liquid desiccant systems and their applications for reducing latent loads on air conditioning systems in humid climates. These systems consist of an absorber and a regenerator that use a heat source to remove water from the diluted liquid desiccant. To reduce ice formation on the surface of the evaporator, the localized removal of moisture from the air in low-temperature rooms, such as refrigerated facilities for the food industry, was investigated. Mathematical models of an adiabatic parallel-plate absorber for dehumidifying air have been developed in the cross-flow configuration. The numerical results obtained were compared with experimental data. Kadhim, B. J., et al. [53] discussed the use of Rigid Xanthan Gums (RXGs) as materials that reduce flow resistance. RXGs can enhance drag reduction rates by decreasing turbulence and, as a result, decreasing pressure decreases and increasing flow rates. However, the concentration and molecular weight of RXGs must be carefully chosen to obtain optimal results while minimizing undesirable side effects such as increased viscosity and operational expenses. D. B. Jani1 et al. [54] reviewed the different types and applications of thermally activated solid desiccant cooling systems. It has been demonstrated that solid desiccant dehumidification is an effective and energy-efficient method for removing moisture from the air. Compared with conventional cooling, solar-assisted solid desiccant cooling systems have remarkable performance. The review focuses on solid desiccant dehumidification techniques, system configurations, and advances in regenerator technology, a crucial system component. It was discovered that building air conditioning systems consume a considerable quantity of energy and that conventional air conditioning systems based on vapor compression refrigeration (VCR) are neither energy-efficient nor environmentally friendly. The use of liquid desiccant air conditioning (LDAS) is a promising alternative. Jani, D.B., et al. [55] provided an overview of recent developments in LDAS, including dehumidifier and regenerator design, desiccant material selection, and applications. In addition to discussing LDAS efficacy in various climates, the article also addresses indoor air quality. They provided insight into future research requirements for enhancing the efficacy of LDAS. Kumar, K. et al. [56] analyzed the isotherm mechanism of equilibrium water vapor adsorption on four different zeolites. The addition of exchangeable compensation cations such as Na^+, Li^+, K^+, Ba^{2+}, Mg^{2+}, and Ca^{2+} to the zeolite framework was discussed, as was their strong propensity to form bonds with water molecules. The significance of these cations in determining the zeolite's adsorptive properties was emphasized. It was suggested that the size, location, and type of exchangeable compensation actions substantially affected the adsorption process and zeolite cage capacity. Using environmental test chamber experiments, Cho, H.J., et al. [57] compared counter-flow and cross-flow dehumidifiers. Empirical models were developed to predict their performance under varying conditions of operation. Their experimental results show that increasing the inlet air humidity ratio enhanced the dehumidification efficiency of the counter-flow dehumidifier, whereas the cross-flow dehumidifier exhibited only modest improvement. Table 1 summarizes the dehumidification performances for various types of dehumidifiers according to the three flow patterns.

To summarize the above, this introduction concludes by highlighting the significant advancements and progress made in desiccant materials and their applications. The reviewed literature has cast light on the characteristics of various desiccants, membrane-based systems, dehumidification performance evaluation, regeneration modules, and energy analysis at the system level. Despite these accomplishments, there is still a need for additional research and investigation in this prospective field. Due to the identified research gaps and future orientations, researchers have exciting opportunities to contribute to developing innovative desiccant technologies and their integration with renewable energy sources. Researchers can pave the way for more sustainable and energy-efficient air conditioning solutions by concentrating on optimizing system performance, exploring new materials and designs, and implementing sophisticated control strategies. This field of study has the potential to resolve the growing environmental challenges we face today. Therefore, we encourage researchers to enter this field, collaborate, and conduct groundbreaking research to influence the future of desiccant-based air conditioning and contribute to a greener, more sustainable world.

Table 1. Dehumidification performances for various types of dehumidifiers.

Desiccant					Air				L/G	Remarks	Reference
Type	Temp. (°C)	Conc. (%)	Flow rate/flux (l/min)	Flow rate/flux (m^3/min)	Temp. (°C)	Humidity (g/kg)	ΔT (°C)	ΔW (g/kg)			
LiCI	25–27	35–40	3.76–5.01	4.9–6.4	n/a	n/a	n/a	n/a	n/a	SP, CF, COPhyb: 2.6–4.9	Ani et al. [58]
LiCI	n/a	40	n/a	40–96	30	18.9	−4.0	−7.2	n/a	SP, CF, COPhyb: 2.7–3.0	Fekadu and Subudhi [59]
TEG	29–35	92	1.7–2.2 [a]	0.94–2 [a]	n/a	17–26	n/a	−5.5 to −1.1	1.9–2.3	SP, CF, DP: 35–140 Pa/m	Kumar, K., and Singh, A. [60]
LiBr	n/a	n/a	n/a	n/a	n/a	n/a	−2 to −11	−2 to −8	n/a	Cooled FF, ST, PF	Indrawan, W. et. al. [61]
TEG	22.9	96.8	0.057 [b]	0.07 [b]	20.6	12.48	2.5	−8.1	0.81	Cooled FF, ST, CF, DP: 1736 Pa, drift: 5.6–9 g/min	Sanjeev, J. [62]
	20.5	95.2	0.058 [b]	0.07 [b]	19.4	8.71	2.1	−4.54	0.83		
	20.2	95.5	0.057 [b]	0.07 [b]	28.6	16.93	−4	−12.46	0.81		
	21.8	92.2	0.052 [b]	0.051 [b]	21	8.95	1.2	−4.21	1.02		
LiBr	20.1–29.5	42.6–54.8	0.3–0.64 [b]	0.31–0.47 [b]	24.7–33.9	10–21	n/a	n/a	n/a	SP, cross flow	Su, W., et al. [63]
LiCI	27–30	35	0.35–0.51 [b]	0.6–0.7 [b]	26–29	11.6–13.9	n/a	−2 to −4	n/a	RP, CF	Guo, Y. [64]
PG	n/a	n/a	n/a	n/a	4.4	3.12	−2.77	−1.4	n/a	Cooled spray type	LePree [65]
LiCI	27	43	1.67	3.3	26	11.6	5	−4.2	n/a	SP, cross flow	Pietruschka et al. [66]
$CaCl_2$	27	43	1.67	3.3	26	11.6	−1	−5.7	n/a	Cross-flow PHE, cooled	Pietruschka et al. [66]

Al, Aluminum; RP, random packing; SP, structured packing; COPhyb, hybrid COP; PHE, plate heat exchanger; CF, counter flow; FF, falling film/wetted wall; ST, shell and tube; PF, parallel flow; PG, propylene glycol; mw, water flow rate. [a] Measured in kg/m^2 s; [b] measured in kg/s.

2. Liquid Desiccant Agents (LDAs)

LDAs are frequently used in dehumidification and air conditioning systems to remove moisture from the air effectively. Numerous materials can be used as LDAs [5,10,11,25], each with distinct properties and suitability for various applications. The following are examples of common LDAs:

- Lithium Bromide (LiBr): This is one of the most commonly used liquid desiccants and is frequently used in industrial and commercial applications. LiBr has a strong affinity for water vapor and is effective at dehydrating the air.
- Calcium Chloride ($CaCl_2$): This is another popular liquid desiccant widely used in residential and small commercial applications. $CaCl_2$ is inexpensive and can absorb a substantial quantity of water vapor [67].
- Sodium Chloride (NaCl): NaCl can also be used as a liquid desiccant, although less frequently than LiBr or $CaCl_2$. Typically, it is less efficacious than LiBr or $CaCl_2$ but more affordable.
- Potassium Formate (KCOOH): This is a relatively new liquid desiccant that garners favor due to its low toxicity and biodegradability. It has a lower corrosion potential than other liquid desiccants and effectively removes moisture from the air, which makes it suitable for natural gas purification. In addition, there is a growing interest in developing novel desiccant materials and improving existing ones [1,68].

Effective desiccants should be efficient, economical, and environmentally favorable. As a result, extensive research and development have been conducted in this field, resulting in the discovery of new materials and the enhancement of existing ones. Metal–Organic Frameworks (MOFs), Natural Desiccants, Ionic Liquids, Graphene-based Materials, and Porous Carbon Materials are examples of recently discovered or evaluated desiccant materials. Triethylene glycol was among the first liquid desiccants to be utilized. Nonetheless, its applicability was limited due to its high viscosity, which caused system instability due to liquid residence. Although triethylene glycol has low toxicity and is compatible with most metals, its volatility is high due to its very low surface vapor pressure, causing some of it to vaporize into the conditioned space along with the air, rendering it unsuitable for use in air conditioning applications. It is suggested that a solution composed of 96% triethylene glycol and 4% water, with a LiCl solution concentration of 42% by weight, can help attain the dew point temperature of the air. Nevertheless, at the equilibrium point, the molar concentration of the glycol in the air is only about 1% of that of the water vapor, which implies that a substantial amount of triethylene glycol is lost annually in air conditioning applications [69]. The selection of a liquid desiccant will depend on the application's specific requirements, such as humidity levels, air flow rates, temperature ranges, cost, toxicity, and environmental impact [70]. By providing a comprehensive review of liquid desiccant agents, including standard options, recent advancements, and selection considerations, researchers can be better informed and encouraged to investigate this field further. Current research and development efforts on liquid desiccants emphasize the potential for advancements in efficient, cost-effective, and environmentally friendly dehumidification and air conditioning solutions.

3. Liquid Desiccant Characteristics

The various chemical and physical properties of the liquid desiccant used determine the overall performance of the LDAC system. For example, the vapor pressure of the desiccant needs to be low enough to ensure efficient operation, while the solubility in water should be high enough to enable regeneration. Additionally, the desiccant must have a high heat capacity to reduce the amount of energy needed for regeneration. Due to their hygroscopic properties, desiccant solutions are usually used because they are highly soluble in water vapor. Although this is one factor that impacts the dehumidification performance of the system, it is not the only one. The performance of the system is also impacted by other properties, such as density, dynamic viscosity, heat and mass transfer potential, and thermal energy storage potential. In addition, the design of the system plays a key role in determining the overall performance, as the system must be properly configured to achieve optimal dehumidification results. It is important to choose a desiccant that will improve both the performance of dehumidification and cooling as well as the economics of the system. Thus, it is crucial to ensure that the design and selection of the system components are well-thought-out to ensure the best possible output. It is therefore necessary to evaluate all the thermodynamic properties involved in the LDAC process. The organic liquid compound tri-ethylene glycol (TEG) is hygroscopic and has the ability to dehydrate natural gas. Due to its high viscosity and volatility, TEG exhibited serious drawbacks in the LDAC system, namely, stagnation and carryover of solution in the processed air [31]. The organic liquid compound tri-ethylene glycol (TEG) is hygroscopic and has the ability to dehydrate natural gas. Due to its high viscosity and volatility, TEG exhibited serious drawbacks in the LDAC system, namely, stagnation and carryover of solution in the processed air. To improve the performance of the LDAC process, it is important to consider the effect of TEG properties such as volatility, viscosity, and surface tension, amongst other thermodynamic properties. Additionally, the effects of other compounds, such as water, present in the processed air must be taken into account. Although there is no primary concern about the health of occupants, the TEG solution is still used in industrial dehumidification systems. Solutions containing metal halide salts (LiCl, LiBr, $CaCl_2$, $MgCl_2$, etc.) have been identified as being able to overcome the drawbacks of glycols (TEG). Due to their low equilibrium vapor pressure, these solutions ensure dehumidification. These solutions have a higher vapor pressure than water, which allows them to be effective at removing moisture from the air. They also have a higher boiling point than water, which prevents the solution from evaporating before it can be re-circulated through the dehumidification system. Furthermore, these solutions are non-flammable and have a higher heat transfer capacity than glycols, making them safer and more efficient. In addition, other thermodynamic properties of halide salt solutions, such as density and viscosity, make them the most popular choice for LDACs. The most common desiccant solution that is used worldwide is LiCl solution. This is due to its lower cost, high availability, and high thermal properties. Additionally, LiCl solutions have a higher boiling point than water, so they can be heated to higher temperatures without boiling and evaporating, making them ideal for use in LDACs [71]. In Table 2, a framework for evaluating fluids as liquid desiccants is provided.

Table 2. A framework for evaluating liquid desiccants [71].

Characteristics	Properties
Dehumidification ability	• Equilibrium vapor pressure and equilibrium moisture content. • Water activity, activity coefficient, chemical potential, osmotic. • Pressure.
Thermo-physical properties	• Density. • Viscosity. • Specific heat capacity. • Enthalpy of absorption; enthalpy of mixing.
Heat and mass transfer	• Thermal diffusivity. • Diffusion coefficient of water vapor in solution. • Henry's law constant. • Surface tension.
Other properties	• Thermo-chemical energy storage. • Health and safety requirements. • Corrosion to metals. • Economics. • Application and climatic conditions.

Some saturated salt solutions were evaluated for equilibrium relative humidity (ERH) at 25 °C by Eggert, G [72], as presented in Table 3. From the table, it appears that the caesium fluoride solution is the most effective salt solution at dehumidifying the air up to very dry conditions (about 3.4% RH). This is because it has the highest sorption capacity among the other solutions tested. This means that it can absorb the most moisture from the air, allowing it to reach the lowest relative humidity levels. The table shows that LiBr, LiCl, LiI, CH_3CO_2K, and $MgCl_2$ are possible liquid desiccants for air-conditioning use. This is because they have lower sorption capacities than caesium fluoride, but still higher than the other salts that were tested.

Table 3. ERH of some saturated salt solutions at 25 °C [72].

Salt	RH [%]	Saturation Concentration at 25 °C
Caesium Fluoride (CsF)	3.39 ± 0.94	0.851
Lithium Bromide (LiBr)	6.37 ± 0.52	0.644
Zinc Bromide (ZnBr)	7.75 ± 0.39	0.830
Potassium Hydroxide (KOH)	8.23 ± 0.72	0.547
Sodium Hydroxide (NaOH)	8.24 ± 2.1	0.500
Lithium Chloride (LiCl)	11.3 ± 0.27	0.458
Calcium Bromide ($CaBr_2$)	16.5 ± 0.2	0.610
Lithium Iodide (LiI)	17.56 ± 0.13	0.623
Potassium Acetate (CH_3CO_2K)	22.51 ± 0.32	0.722
Potassium Fluoride (KF)	30.85 ± 1.3	0.501
Magnesium Chloride ($MgCl_2$)	32.78 ± 0.16	0.359

4. Liquid Desiccant Systems

Figure 5 depicts the primary components of a fundamental Liquid Desiccant (LD) system. A variation in vapor pressure causes mass transfer in this process. In the dehumidifier, the liquid desiccant captures water vapor from the processed air and removes moisture from the incoming air. During this process, heat is released due to the condensation of water and heat exchange resulting from mixing. The dehumidified air is introduced into the space or cooled further with an evaporative cooler. The liquid desiccant that has been diluted is then returned to the regenerator for reuse. Before entering the regenerator, the diluted solution travels through a liquid–liquid sensible heat exchanger and a heating coil. This increases the solution's temperature. In the regenerator, the hot and concentrated solution is exposed to regenerative air, and due to the difference in vapor pressure, moisture is transferred from the weak solution to the air. Figure 6 illustrates that the concentrated solution is transmitted through a liquid–liquid heat exchanger and a cooling coil before re-entering the dehumidification unit. The liquid-to-liquid heat exchanger pre-cools the strong solution and pre-heats the weak solution [31,72].

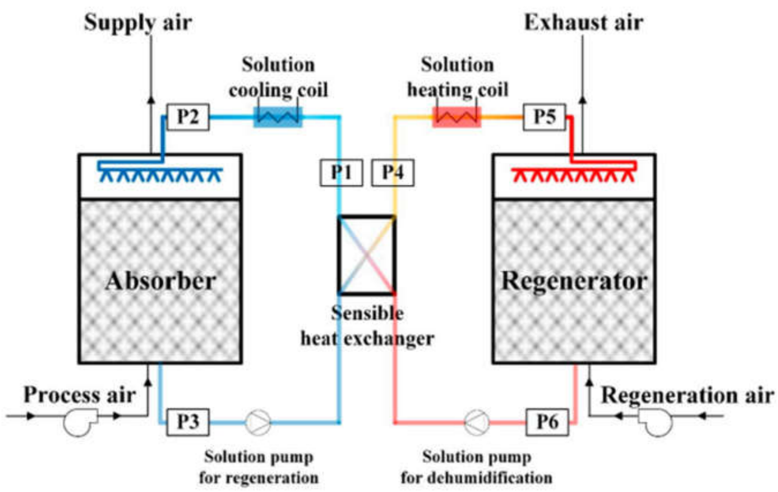

Figure 5. LD system schematic [73].

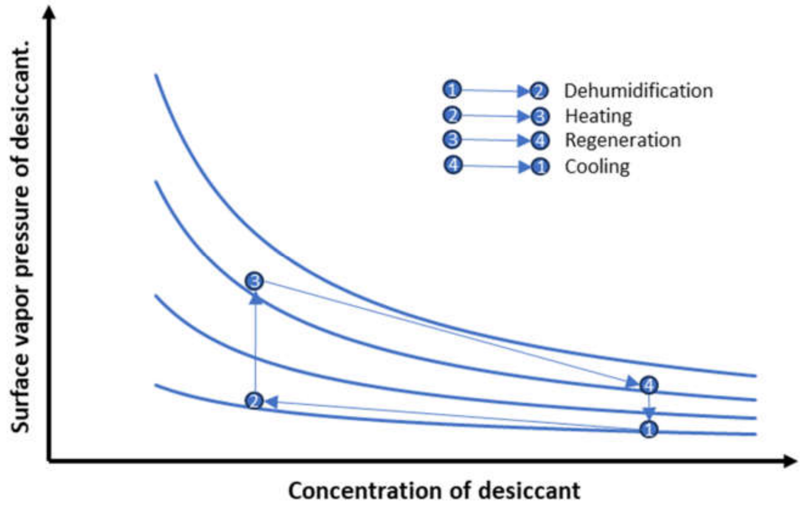

Figure 6. Variation in the desiccant cooling systems.

5. Liquid Desiccant Dehumidifiers

Desiccant dehumidification units are utilized to increase heat and mass transfer between the processed air and the desiccant solution [74]. For highly efficient LDs, LDDs must have the following characteristics [75]:

- Capable of rapid mass and thermal transfer.
- The minimum decrease in pressure.
- Offer minimal resistance to moisture diffusion in liquids.
- Have a large surface contact area per unit volume.
- Corrosion prevention requires compatibility with liquid desiccant.
- The air should not transport the liquid desiccant.

There are two varieties of desiccant dehumidifiers for liquids: adiabatic and internally cooled. Adiabatic dehumidifiers enable the air to come into direct contact with the desiccant solution. In contrast, internally cooled dehumidifiers additionally cool the desiccant solution using a cooling medium to improve the system's performance [76].

Researchers and engineers can create more efficient and effective dehumidification systems by incorporating these characteristics and considering the various types of liquid desiccant dehumidifiers. Further advancements in liquid desiccant dehumidifiers will increase energy efficiency, improve indoor air quality, and expand their applications across various industries and contexts.

6. Liquid Desiccant Cooling (LDC)

Indoor air temperature and humidity must be regulated for human comfort. The cooling load of any building can be either latent or sensible. Traditional compressor-based air conditioning systems are effective at controlling the sensible load. However, they waste energy by overcooling the air below its dew point to remove moisture through condensation and then reheating it to the desired temperature. This process also promotes the development of molds and bacteria, which can negatively impact indoor air quality and cause health problems. More effective solutions are required to address this issue, particularly in hot and humid climates where the latent load predominates. LDC units provide a viable and cost-effective alternative by absorbing and desorbing moisture from the air during the absorption and regeneration processes, as shown in Figure 7. Heat and mass are transmitted simultaneously in LDC systems, and mass transfer theories, such as the penetration, film, and surface renewable theories, are utilized to control the latent load by transferring moisture from the humid air to the LD surface. The film theory is the most prevalent approach to mass transfer, and it implies the presence of mass transfer resistance in a small region close to the interference of two streams [77–80].

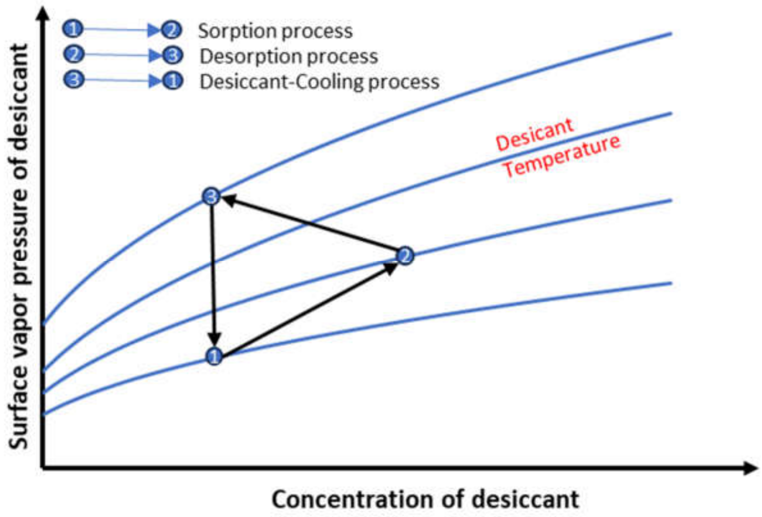

Figure 7. Process of desiccant regeneration and dehumidification [78].

7. Solid Desiccants (SDs)

SDs are frequently employed in solid desiccant systems, typically consisting of a desiccant wheel or a cross-flow wheel containing a solid desiccant. SDs are economical, non-flammable, non-corrosive, and eco-friendly. They have a higher dehydrating capacity than liquid desiccants [81] and do not react chemically with moisture in the processed air. Additionally, they are simple to clean. However, solid desiccant regeneration temperatures are greater than liquid desiccant regeneration temperatures. A desiccant wheel used for dehumidifying processed air and regenerating solid desiccant is depicted in Figure 8.

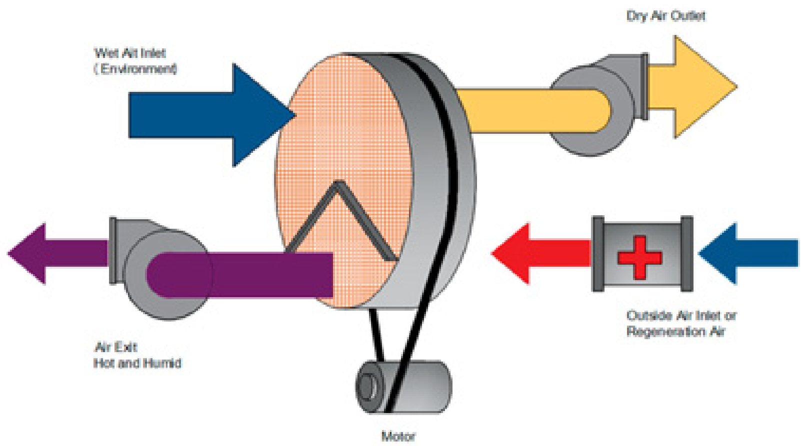

Figure 8. SD wheel schematic [82].

In contrast to liquid desiccants, the dehumidification and regeneration processes occur simultaneously in solid desiccant systems. The desiccant wheel is separated into two distinct sections by a barrier. Humid air is dehumidified in one portion by passing through the desiccant wheel. In the other part, hot air is transmitted through the solid desiccant to remove the added water [82]. Although both solid and liquid desiccants have several benefits, they also have some disadvantages. For instance, silica gel has a low adsorption capacity and requires a high temperature for regeneration, whereas desiccants containing chloride compounds like lithium chloride and calcium chloride can cause corrosion [83]. Zeolites have low water capacities and high regeneration expenses [84]. To address these limitations, researchers are examining the possibility of developing new and innovative desiccants with enhanced performance. Several new desiccants, including bio-desiccants, composite desiccants, and polymeric desiccants, have been developed with modified properties compared with traditional desiccants. These new desiccants have the potential to outperform conventional desiccants. Jia and associates, for instance, created a high-performance desiccant cooling system utilizing a compound desiccant. They discovered that a compound desiccant could enhance the overall performance of a desiccant wheel by 20 to 30 percent when compared with a wheel containing only silica gel. Tests demonstrated that the system's coefficient of performance could reach 1.28, which is 35% higher than the desiccant wheel containing only silica gel [85].

8. Mixed and Composite Desiccant

Recent years have witnessed a developing interest in studying mixed solvent desiccants. Although certain desiccants, such as LiCl, have a low vapor pressure and greater stability, they are more expensive than others, such as $CaCl_2$. Combining these desiccants can improve dehumidification performance and substantially reduce costs and energy usage [86]. Both Salikandi, M. et al. and Al-Farayedhi [87,88] have examined the performance of numerous two-solvent combinations. In the majority of applications, the mixed solvent must possess characteristics such as a high boiling point elevation, a high latent heat of condensation and dilution, a low-vapor pressure, a low crystallization point, simple handling at low temperatures, a low viscosity, a high density, and a low price. Bouzenada, S., et al. [89] examined the effects of varying concentrations and temperatures on a mixture solution. Their results indicated that adding LiCl to $CaCl_2$ caused a nonlinear decrease in vapor pressure across the temperature range. Chen et al. and Tsai, et al. [90,91] studied the densities and vapor pressures of mixed solvent desiccants at temperatures spanning from 30 °C to 70 °C. The researchers chose six combinations of organic solvents (T4EG, DEG, and DPG) and salts (LiCl and LiBr), with salts ratios ranging from 4% to 25% and glycol ratios from 50% to 80%.

The experiment results demonstrate that the selected system of combined organic salts had a lower vapor pressure than commonly used desiccants. Gonzalez et al. [92] introduced a novel desiccant that combines the hydrophilic and fibrous properties of sepiolite with the hydrophobic properties of activated carbon. This combination of characteristics renders sepiolite a versatile material suitable for various applications. In addition, using a sepiolite-$CaCl_2$ composite enhances sepiolite's adsorption capacity. In Australia's warm, sunny climate, where air conditioning is in high demand, the reliance on electricity for HVAC systems significantly impacts the environment. Baniyounes et al. [93] examined the conceptual foundations of these technologies, including open and closed-cycle cooling methods and their capacities and limitations.

9. LD Applications

Various applications utilize liquid desiccants to remove moisture from the air. There are common uses for liquid desiccants, including [70,94–96]:

1. LDs are used in air conditioning systems to eliminate moisture from the air. Consequently, mold and mildew prevention, humidity reduction, and air quality enhancement can maintain a comfortable and healthy indoor environment.
2. LDs are also utilized for dehumidification. This is especially essential in humid climates, where excess moisture can cause damage to structures, equipment, and goods.
3. LDs may also be used in industrial drying procedures to remove moisture from paper, textiles, and food products.
4. LDs have been utilized in energy recovery systems to remove moisture from the air and transfer it to a distinct air stream for reuse. Consequently, energy consumption and the efficiency of air conditioning and dehumidification systems are decreased.

10. Conclusions

Numerous recent studies have focused on incorporating liquid desiccant dehumidification with other systems. This review provides an overview of the advancements and developments in this research field. The benefits and drawbacks of commonly used liquid desiccant materials are contrasted and discussed in depth. The main conclusions drawn from the review are as follows:

1. Single salts such as LiCl, LiBr, and $CaCl_2$ are frequently used in dehumidification. Due to its superior dehumidification ability, LiCl has become the preferred option in approximately 85 percent of reported studies. However, LiBr and $CaCl_2$, despite being less expensive, exhibit inferior stability and dehumidification performance. Exploring the potential of potassium formate solution (KCOOH) and blended solvents requires additional research.
2. Packaging material selection, arrangement, and flow pattern within a desiccant dehumidifier substantially affect system performance. These factors must be optimized for optimal dehumidification efficacy.
3. Additional fieldwork is necessary to design liquid desiccant (LD) systems that supplant conventional air conditioning (AC) systems. Applications in the real world and performance evaluations are required to validate theoretical findings.
4. Composite-based desiccants have the potential to optimize absorption capacity and reduce regeneration temperature compared with single-component desiccants. However, potential limitations associated with scalability and compatibility with different operating conditions must be addressed.
5. The core component of LD cooling systems is the desiccant dehumidifier. There has been extensive research on adiabatic and inner-cooled configurations. Inner-cooled dehumidifiers are advantageous because they do not require desiccant conveyance or high flow rates for complete surface saturation. Desiccant carryover can be prevented by rotary LD dehumidifiers constructed from porous materials, such as dense cloth.
6. The combination of liquid desiccant systems with solar collectors, heat exchangers, and hybrid heat and power systems has the potential to improve performance. However, more experimental research is required to validate theoretical findings in this field.
7. Due to varying solar radiation, liquid desiccant systems powered by solar energy have advantages but encounter practical limitations. Incorporating energy storage systems into solar-powered liquid desiccant systems will improve their efficacy.

In conclusion, liquid desiccant dehumidification research and its integration with other systems have significantly progressed. By addressing the factors mentioned earlier, further progress can be made in this field, resulting in more efficient and sustainable cooling solutions for various applications. This study contributes to sustainability as it accurately highlights the current issues and future obstacles that accompany developments in the use of desiccant agents (DAs) and studies their applications in various industries because these agents contribute significantly to reducing the environmental impact and controlling humidity in an environmentally friendly manner. Thus, it is far superior to other traditional options currently available. In doing so, this review advances knowledge of DAs and their potential to transform humidity control systems towards sustainability and energy efficiency. It emerges from the study that there is a need to develop a more comprehensive review of empirical models for performance prediction of liquid desiccant dehumidifiers. Further, a review of standardized testing procedures needs to be conducted to enable easier comparison of different dehumidifier designs.

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