Key factors of desiccant-based cooling systems: Materials

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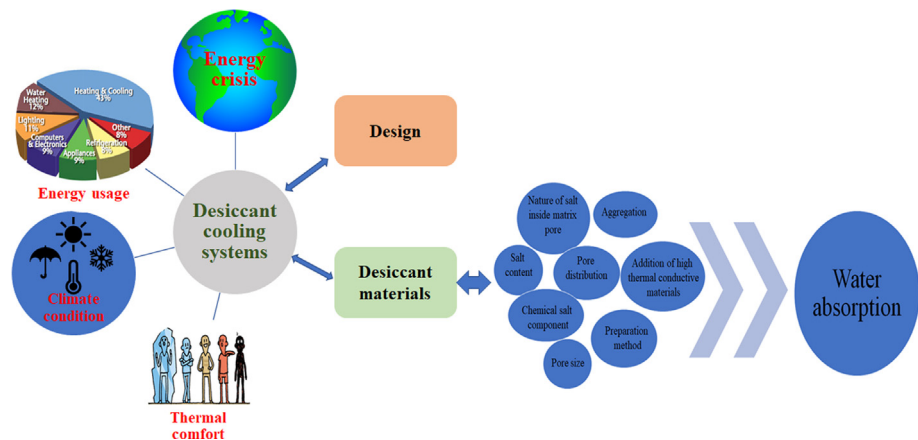[f] *Institute of Sustainable Energy, Universiti Tenaga Nasional (@The National Energy University), 43000 Kajang, Selangor, Malaysia*

HIGHLIGHTS

- To improve human comfort the desiccant cooling system has received much attention.
- Desiccant materials have crucial effect on performance of desiccant cooling systems.
- Composition, microstructure and preparation methods are most important parameters.
- Carbon based desiccant materials have a significant potential for future research.
- Limitations & recommendations towards developing desiccant materials are discussed.

GRAPHICAL ABSTRACT

ARTICLE INFO

ABSTRACT

A desiccant cooling system is among the best options to overcome future energy demand issues while considering human comfort by its ability to control both temperature and humidity. Although desiccant materials remarkably affect the performance of desiccant-based cooling systems, most studies focus on the design. This paper presents a review of the recent investigations on advanced desiccant materials regarding the improvement of the material properties for desiccant cooling application, emphasizing other important parameters, such as environmental conditions, cost, and design to achieve optimal performance. The preparation and performance of silica- and carbon-based desiccant materials are discussed. The current most suitable desiccant materials under different conditions for desiccant air conditioning systems and suggestions for future works are presented.

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1. Introduction

Modern lifestyle and industrialization come with the consumption of a huge amount of energy for cooling systems to provide thermal comfort in buildings and working places. Recent statistics from IEA claims triple demands on air conditioner system worldwide by the next 30 years [1], which means that almost three-fold energy usage and global warming will result if no significant changes will be made in modifying or replacing available air conditioner systems. This fact opens many research challenges for scientists and industries to study and develop eco-friendly and sustainable alternative for conventional vapor compression air conditioning systems. The desiccant cooling system is among these alternatives with very interesting concepts. Desiccant cooling system is not only energy efficient but also could effectively control the indoor humidity, which is another important factor for human comfort aside from temperature. The ability of separate control of latent and sensible loads, which removes the overcooling and reheating of process air, is an advantage of desiccant cooling system over conventional air conditioning systems, because of a huge decrease in energy consumption and increase in coefficient of performance (COP) [2]. The utilization of desiccant cooling system in industries such as pharmaceutical, food, laboratories, and chemical industries, which needs very dry air to maintain severe hygienic conditions constantly, is highly preferred because of its strong control for adjusting humidity and its cost-effectiveness.

This system could provide a better indoor air quality by avoiding condensed water formation which, decreases the growth of biological contaminants such as fungus and bacteria and improve the human health that spend more than 80%–90% of their time indoor [3]. These advantages accelerated the development and application of desiccant cooling system in both residential and industrial sectors [2]. Based on the type of desiccant (sorbent), the desiccant cooling system is divided into liquid, solid, and advanced desiccant systems [4]. Despite the different advantages of liquid desiccant materials, their disadvantages such as crystallization, carry-over issues, and corrosive nature [4] provide more interest and opportunities for development of solid and advanced desiccant (sorbent) materials.

Although some researchers have reviewed different desiccant materials for solid desiccant cooling systems in the past years [5–8], the following sections provide a review of newly developed desiccant materials as supplement. This study focuses on solid and advanced desiccant materials and state-of-the-art developments.

2. Desiccant cooling systems

Table 1 compares the three different classifications of solid desiccant dehumidification systems namely: fixed bed, rotary wheel, and desiccant coated heat exchanger (DCHE) [9]. Coating a desiccant material on the surface of a fin-tube heat exchanger could improve the performance of desiccant cooling systems by handling sensible and latent loads simultaneously within one component [10,11]. Vivekh et al. [9] reviewed recent developments in solid DCHEs. The importance of substrate in rotary and non-rotary solid desiccant systems has been

Table 2
Different sorption processes [14].

	Physisorption	Chemisorption	Composite sorption
Sorption force	Intermolecular force	Chemical force	Intermolecular & chemical force
Sorption layer	Multilayer	Monomolecular	Multilayer
Water uptake	Low	High	Moderate
Sorption rate	High	Low	Moderate
Sorption heat	Low	High	Moderate
Cycle performance	Good	Poor	Good

studied by Wu et al. [12]. They proposed deeper study to understand the required match between the substrate and desiccant to improve their performance.

The performance of solid desiccant cooling system could be predicted using artificial neural network (ANN) based on input and output parameters such as humidity ratio, regeneration, and temperature [13].

Considering the vital role of desiccant materials in the performance of the desiccant cooling system because of their characteristics such as adsorption isotherms and regeneration temperature, many researchers have investigated the synthesis and modification of advanced and available desiccant materials to optimize water adsorption, regeneration, and stability [5].

3. Key factors for choosing desiccant materials in cooling systems

Desiccant (sorbent) materials could undergo different sorption process, such as physisorption, chemisorption, and composite sorption to absorb liquid and vapor. Table 2 shows the comparison of different sorption process [14]. The development of composite sorbent materials aims to overcome the limitations of standalone physical and chemical sorbent and increase their water absorption performance.

The high stability, eco-friendliness, and cost-effectiveness are other important parameters for ideal desiccant materials, which highly depend on the material composition, structures, and properties. Table 3 presents different parameters and their corresponding value for choosing desiccant materials.

3.1. Adsorption isotherm

Considering that the total performance of the desiccant cooling system is critically related to desiccant materials, their characteristics such as water absorbance and regeneration need vital attention. These characteristics could be monitored using their adsorption isotherm. The main types of adsorption isotherms based on the International Union of Pure and Applied Chemistry (IUPAC) are depicted in Fig. 1.

The adsorption isotherm of desiccant materials has an important role for choosing them for the specific application condition. Elementary theoretical investigations have proposed that materials with type V isotherm are the best candidate for desiccant materials, because materials with types I, II or IV absorption isotherm are more hydrophilic with high water absorbency at low P/P_o, which increases the difficulty in the regeneration process. In materials with type III

Table 1
Comparison between different solid desiccant dehumidification systems [9].

Properties	Fixed-bed Dehumidifiers	Rotary wheel dehumidifiers	DCHEs
Adsorption capacity	Low		High because of simultaneous cooling
Total cooling load	Total cooling load remains the same. The reduction in latent load of air is converted to an equivalent increase in sensible load		Reduction in cooling load is observed as the cooling water takes away a portion of sorption heat/latent heat
Heat transfer efficiency	Low, because of higher irreversibility associated with multiple heat transfer resistances		High, because of internal heating and high thermal conductivity of metallic fins
Continuous dehumidification	Possible with two beds	Possible using a single rotary wheel	Only possible with two DCHEs
Pressure drop	High	Low	Low
Desiccant material utilization	Low	High	High

Table 3
Weighing factors and figures of merit for desiccant selection [2,15].

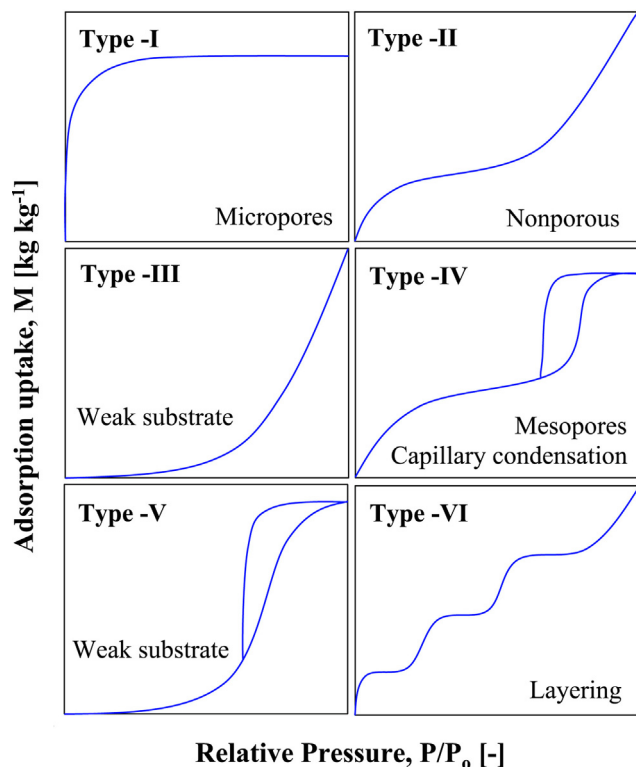| Characteristics	Weighting factor	Figure of merit
Safety	1.0	Lethal dose (LD50)
Corrosion	0.8	Corrosion rate
Mass transfer potential	0.8	Equilibrium vapor pressure
Heat of mixing	0.6	Energy/lb of absorbed water
Cost of desiccant	0.5	$/100 lbs of solution
Heat transfer potential	0.5	Thermal conductivity
Parasitic power losses	0.3	Viscosity

Fig. 1. Adsorption isotherm types based on IUPAC classification [16–18].

isotherm, water absorption occurs at too high P/P_o, which makes them non-ideal candidate as desiccants [5,19]. According to Zheng et al. [5], a combination of theory with practical process showed that ideal materials must exhibit saturated water absorption at medium P/P_o (≤ 0.5) during adsorption, while full desorption must occur at high P/P_o (≥ 0.6) during regeneration.

Recently, Sultan et al. [16] investigated all different types of desiccant materials under different conditions for desiccant air conditioning systems. They found that for optimized energy effective desiccant air conditioner, when the relative humidity (RH) of the environment is very high (~ 80 to 100%), type III desiccant material is preferred while in medium–high RH (~ 60 to 80%), and type V desiccant is on priority. For places with moderate RH (~ 20 to 60%), type II or type-linear desiccant is preferred. Considering that type-linear desiccant could work equally in all different relative humid conditions, it could be utilized when other types are not working effectively. Type I materials could also work in all different RH, and their very high regeneration temperature limits their utilization for only very low RH condition ($< 20\%$).

3.2. Material composition and structure

Zhang et al. [5] classified the newly developed desiccant materials to three main groups (Fig. 2). However, for convenience, we presented the recent developments on advanced desiccant materials according to their main base component, such as silica-based and carbon-based desiccant.

The structure and composition of desiccant materials strongly affect their hydrophilicity, stability. and regeneration temperature. The recent development in the preparation of desiccant materials and their performance are presented below:

4. Advanced desiccant materials

The reason behind the preparation of composite materials, which mostly consist of porous host matrix and immersed hygroscopic salts, was to overcome on the low adsorption capacity of commonly used porous desiccant materials and the lyolysis effect of hygroscopic salts while keeping their high stability and water sorption [5]. The water absorbance of composite materials could be tailored by different parameters, such as pore size and its distribution in the matrix, chemical salt components, aggregation, and preparation method (Fig. 3) [5,14].

After Bu et al. [20] investigated the pore size effect on composite desiccant materials performance, further investigations have been conducted on this effect [21]. They proposed that pores with uniform size and porosity distribution are the preferred spatial structure. Furthermore, they proposed an optimum average porosity range of 0.4–0.6 for perturbation cycle period of 100–2000 s and volume- averaged pore diameter between 10 and 150 nm. Fig. 4 shows the water absorption steps on typical composite desiccant materials (selective water sorbents or SWS).

4.1. Silica-based desiccant materials

Silica gel is one of the most used desiccant materials in different applications. Impregnation of hygroscopic salt into silica gel pores is among the early research that has been made to improve water absorption [22]. These prepared composites exhibited higher sorption and dehumidification capacity, while regeneration temperature is lower compared with silica gel [5,11,20].

The developed composite by using silica gel and potassium formate as desiccant materials coated heat exchanger by Ge et al. [23] exhibited 20% higher moisture absorption capacity. Some studied used the sol–gel method or other aqueous procedure such as hydrolysis and condensation of the precursors instead of the direct impregnation of hygroscopic salts for a more uniform distribution and long-term retention of salts in the host [24].

Entezari et al. [25] tried to enhance the salt-silica gel composite performance by adding another salt to them (dual salt concept). They investigated the performance of different ratios of impregnated LiBr to LiCl–silica gel composite and vice versa. They found that the addition of small amount of LiBr to the LiCl composites could increase its sorption capacity up to 5.5%, whereas the addition of LiCl to LiBr composites reduced its sorption capacity by 12.7%. This result can be attributed to the reduced lattice parameter due to the smaller size of LiCl, which narrowed the spacing parameters and reduced the water vapor diffusion in LiCl–LiBr silica gel composite.

The concept of developing new adsorbent by the preparation of silica gel polymer composite or silica activated carbon has been studied by many researchers.

Fu et al. [26] have studied the micro-scale molecular dynamics (MD) sub-model for adsorbent material and macro-scale sub-model for heat and mass transfer in the matrix channels for the organic-inorganic hybrid adsorbent (HA3). The organic–inorganic hybrid adsorbent consists of silica gel B, LiCl, and polyvinyl alcohol (PVA). LiCl was utilized to improve the adsorption, while PVA used for mechanical durability enhancement. Fig. 5 shows the atomistic model for this hybrid [26] that PVA and LiCl were dispersed on silica gel B pores through van der Waals force and hydrogen bonding. The organic–inorganic hybrid
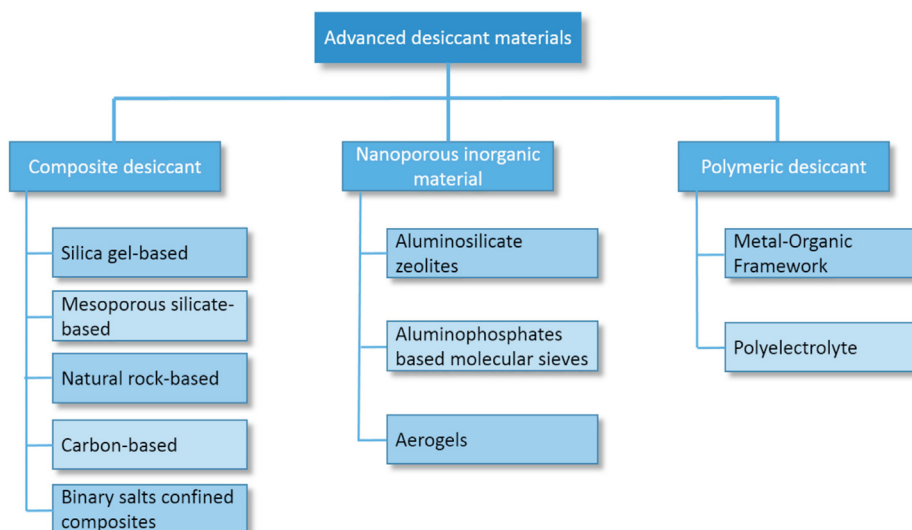
Fig. 2. Classification of advanced desiccant materials according to Zheng et al. [5].
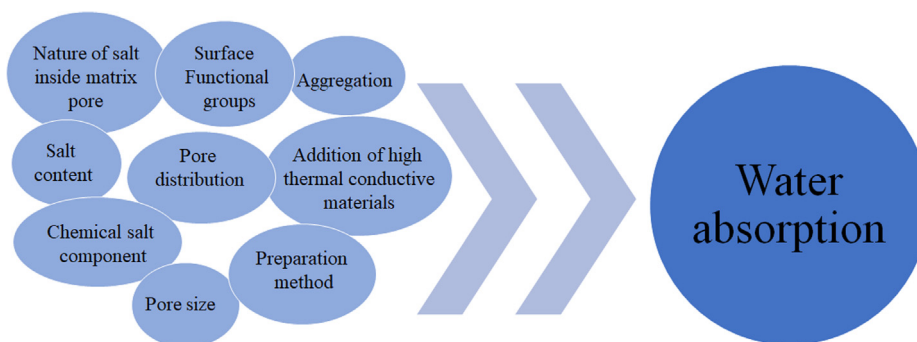

Fig. 3. Some important parameters that affect water absorption in desiccant materials.

adsorbent showed two times higher moisture adsorption than silica gel B at high relative humidity (RH), and the system sensible and latent efficiency were enhanced by 12% and 30%, respectively.

Another organic–inorganic composite desiccant material consisting of 80% silica gel, 10% polyacrylic acid, and 10% polyacrylic sodium (SG8PS1PA1) has been developed for the evaluation in desiccant wheel combined with a heat pump for air-conditioning systems [27,28]. The developed composite materials showed high average adsorption rate, increased regenerative capacity and sorption in high RH, and low increase in average temperature of outlet air.
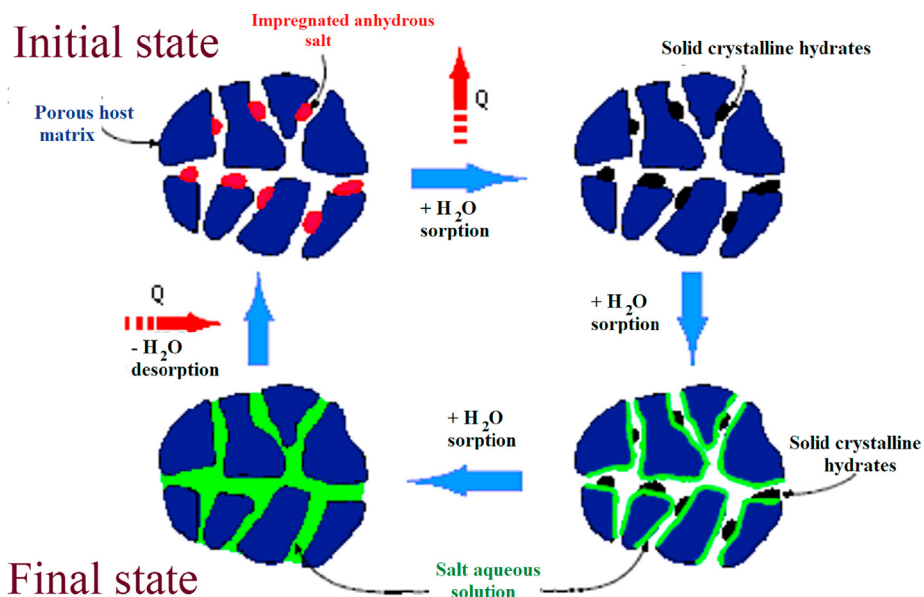

Fig. 4. Schematic of water absorption process on SWS-1L ($CaCl_2$ in mesoporous silica) [6,14].
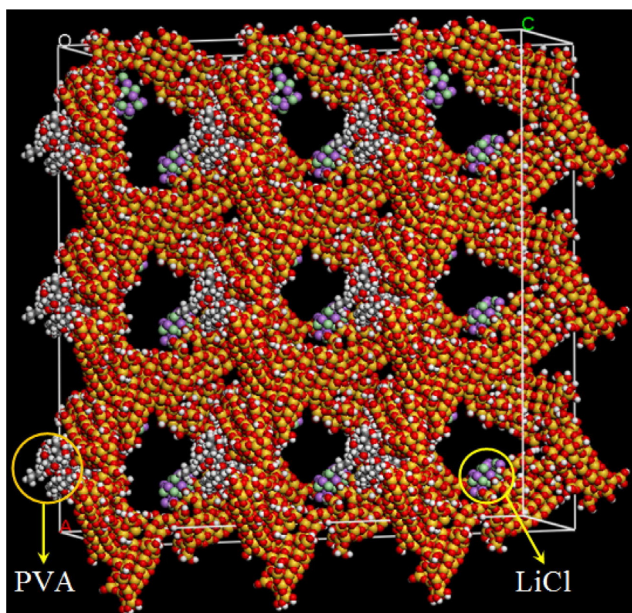
Fig. 5. Atomistic model of organic–inorganic hybrid adsorbent HA3 [26].

A study conducted showed a dramatic increase in heat and mass transfer performance of two new silica-based consolidated composite adsorbents compared with silica gel [29]. They used freeze-drying for the preparation of silica gel consolidated with carboxymethyl cellulose (CMC) and carbon fibre powder. The prepared samples had a better performance than the samples developed by heating-drying. The samples could be potential water adsorbent materials.

Chen et al. [27,28] studied the different combination of silica gel with polyacrylic acid and sodium polyacrylate, which could obtain a composite with higher dehumidification capacity at high RH compared with silica gel. Tso et al. [30,31] studied silica gel, activated carbon, and calcium chloride by using the impregnation method to prepare new adsorbent with higher water uptake and adsorption rate coefficient as the potential materials for the adsorption refrigeration system.

The synthesis of mesoporous silicas by using the sol–gel method and polyethylene glycol template and its impregnation by $CaCl_2$ was another attempt to increase the adsorption capacity of silica [32].

Although Srivastava et al. [33] investigated desiccant materials consisting of sand impregnated with LiCl, $CaCl_2$, and LiBr salts for water generation purpose, their promising water sorption performance makes them potential desiccant candidates for cooling purpose.

Periodic mesoporous organosilicas (PMOs) with high porosity and hydrothermal stability are another potential candidate for dehumidification. The chemical modification of their organic functionalities could increase their hydrophilicity. Ethylene-bridged PMOs with double bonds, which could be easily modified chemically, are very promising materials in different applications. Sanchez et al. [34] used the sulfonate groups to modify ethylene-bridged PMOs, which were evaluated as desiccant materials. The modified sample showed almost three times higher water sorption than the unmodified sample. However, different functionalizations and studies are needed to optimized desiccant materials based on PMOs.

Different zeolite (hydrated aluminium silicates) and zeotype materials with porous structure and hydrophilic sites are another interesting material, which could be utilized as desiccant materials. Zheng et al. [35] investigated SAPO-34 (silicoaluminophosphate) and FAPO-34 (ferro aluminophosphates) as desiccant-coated aluminium sheets for DCHEs. They found that the dehumidification performance of FAPO-34 is 2–3 times higher than that of SAPO-34 and silica gel at low regeneration temperatures.

4.2. Carbon-based composites dehumidifier materials

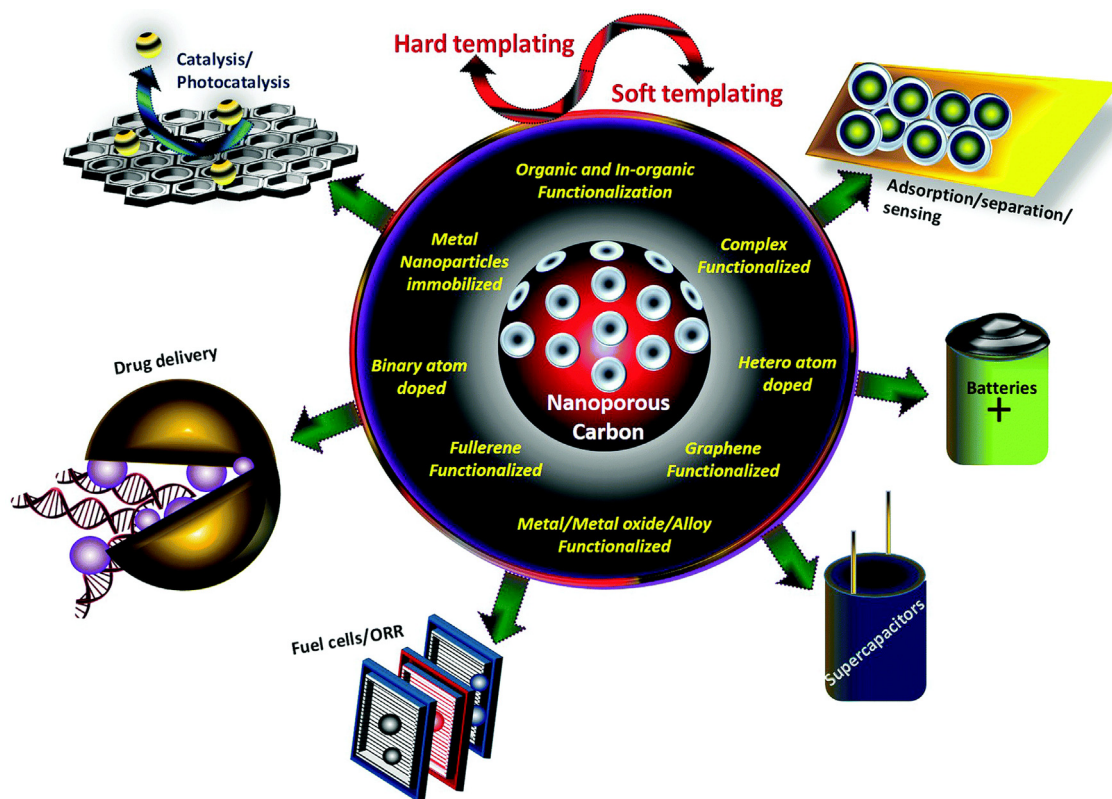Carbon-based materials with high porosity, surface area, and

Fig. 6. Schematic illustration of the synthesis, functionalization and applications of micro and mesoporous carbons [38].

different functional groups on their surface are good candidates as adsorbent materials for different applications.

Activated carbon (AC) is one of the first carbon-based materials that is widely utilized as adsorbent material, especially for organic compounds, due to its porous structure and high surface area. Due to its almost nonpolar surface, different modifications are needed to optimize it for water absorption. Considering that the surface groups play a very important role in surface chemistry and the physical and chemical properties, functionalization is considered as an important process for tailoring the properties of carbon-based materials [36,37]. Benzigar et al. [38] extensively reviewed the different functionalization methods such as incorporation of metals, non-metal heteroatoms, multiple heteroatoms, and various surface functional groups for micro and mesoporous carbon materials (Fig. 6). The functionalization of carbon-based materials could completely change their properties and make them suitable for specified applications.

Functional groups containing oxygen have an important role in water adsorption process [39]. According to Brennan et al. [40], the first step for water vapor adsorption is the adsorption of water on the functionalized group on the surface, which proceeds by cluster formation and pore filling.

Liu et al. [39] reviewed the effect of functional groups, porous structure, and the temperature on water adsorption performance at different carbonaceous materials. The water adsorption process depends on both surface functionalities and the porous structure of carbon-based adsorbent materials. Fig. 7 shows that after the formation of primary clusters because of the interaction between water and the functional groups on carbon-based materials, increasing the pressure causes the primary water clusters to grow and coalesce to fill the pores, which highly depend on the porous structure.

Li et al. [41] studied the adsorption equilibrium and desorption activation energy of water vapor on modified AC by nitric acid oxidation and microwave-assisted reduction. They found out that these modifications not only increase the water adsorption at high RH but also significantly decrease the desorption activation energy of water on AC and increase its desiccant performance.

Xiao et al. [37] investigated the effect of S/O functionalization on water adsorption performance at a different RH for unmodified and mildly modified activated carbon fibre (ACF) and AC. They found that at low RH ($< 40\%$) $-COOH$ and $S=O$ functional groups control the water adsorption, while other oxygen functional groups such as $-OH$ contribute more in water adsorption in medium or high RH. However, at high RH (70%) the textural properties (such as pore volume) of carbon-based materials govern the water adsorption alongside with oxygen functional groups.

The surface oxidation of ACs introduces oxygen functionalities on the surface and the exchange of prepared H-ions by cations such as Li, Na, K, and Ca dramatically increase its moister absorption at low vapor pressure [36,42].

The introduction of hygroscopic salts to carbon-based porous host such as AC and their modification with other commonly used water adsorbent materials such as silica and zeolite are another effective methods to increase their water adsorption [5,37].

The prepared AC fibre cloth (ACFC) and $CaCl_2$ (15.2 and 22.8%) composites showed higher water adsorption than $CaCl_2$, which reached 90% equilibrium within only 2 min [43].

Zheng et al. [10] have been developed LiCl impregnated AC and ACF prepared from coal and coconut shell, respectively, for DCHE application, and the prepared composites showed improved water absorption of 1.0 and 1.1 $g\,g^{-1}$, respectively.

The comparison of water adsorption between the developed ACF–$CaCl_2$ and silica gel–$CaCl_2$ composites showed three times better performance for the ACF–$CaCl_2$ adsorbent [44].

Yu et al. [45] prepared AC from tobacco-stem by using $ZnCl_2$ activation. Its water vapou adsorption (563.4 mg/g) makes it a potential desiccant material.

Many types of research have been conducted to improve the porosity, surface area, and adsorption of AC for refrigeration application by preparing different consolidated composites containing AC, expanded graphite, expanded graphite treated with sulfuric acid (ENG–TSA), and binder. [46–48]. The developed composites could be evaluated as potential materials for solid desiccant cooling application.

Single-walled carbon nanotubes (SWNTs), multi-walled carbon nanotubes (MWNTs), and graphite are other potential carbon-based materials for adsorbent application due to their high surface area and stability [36]. However, most studies conducted for water adsorption application used them in composite form.

Consolidated MWCNT-embedded zeolite 13X/$CaCl_2$ composite adsorbents with different MWCNT mass ratios were synthesized [49]. The water uptake for the composite adsorbents is 0.5 kg/kg, which is five times better than that of zeolite 13X. It shows enhanced thermal conductivity compared with zeolite and the ability to improve the COP and specific cooling power (SCP) performance in the absorber by more than 20%.

Metal-organic frameworks (MOFs) have been introduced as promising crystalline porous materials for sorption applications. Their high porosity, stable structures, and tailorable composition make them very attractive research area in different applications, such as heat transformation, proton conduction, air dehumidification, and water delivery process [50]. Some prepared MOFs such as MIL-101(Cr)–NH_2 (water sorption: 1.05 $g\,g^{-1}$), MIL-100(Fe) (water sorption: 0.87 $g\,g^{-1}$), and PIZOF-2 (water sorption: 0.68 $g\,g^{-1}$) have been employed for different applications [51–53]. Different modifications have been made to enhance their water absorption such as their combination with hygroscopic salts. Garzon et al. [50] combined UiO-66 and UiO-66-NH_2 as porous MOF matrices with $CaCl_2$ and LiCl as the inorganic salts by using the spray-drying continuous flow method. The prepared samples presented promising water sorption and COP.

In another modification attempt, Yan et al. [54] developed new adsorbent composite by using MIL-101 and graphite oxide (GO) with
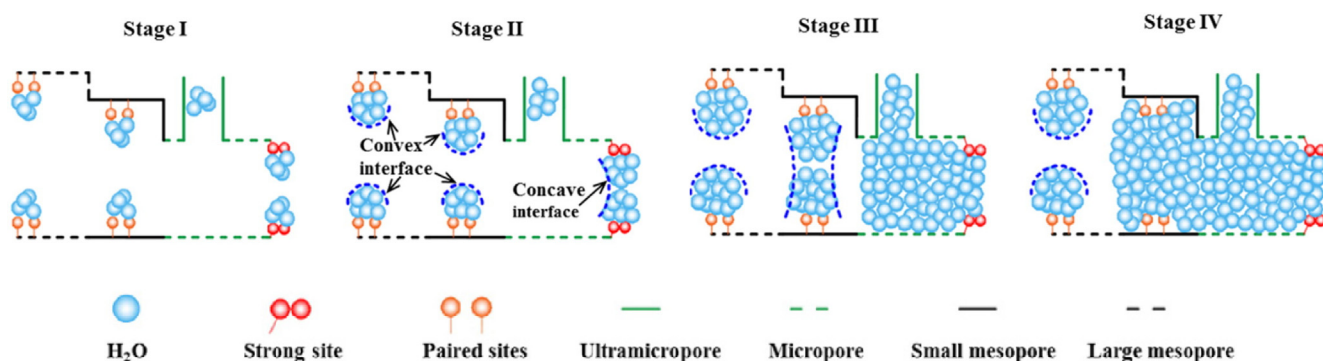

Fig. 7. Schematic description of the different stages of water adsorption in carbonaceous materials [39].

high water vapor sorption ($1.6 \, \text{g g}^{-1}$). The numerical study has been conducted to investigate the performance of the MOF (6%w/w GO dispersed in MIL101) as desiccant material in the desiccant based cooling system [55]. The study showed about six times higher water sorption and 30% increase in dehumidification performance compared with silica gel desiccant wheel under simulation conditions.

Qadir et al. [56,57] synthesized MOFs consisting of MWCNTs incorporated in a MIL-100(Fe) framework by using a molecular-level mixing process. They evaluated the performance of the prepared samples as a potential adsorbent for adsorption chiller by using water as a refrigerant. Due to their high-water absorption and cyclic stability, they could be practical substitute adsorbents for different cooling applications.

Polymers with high porosity and adsorption capacity attracted much research attention recently. Roy et al. [58] have investigated the poly(acrylamide-co-acrylic acid)-hydrophilized porous polypropylene composite membrane as a potential material for dehumidification applications. The water vapor adsorption on the developed membrane reached $1 \, \text{g g}^{-1}$ due to the abundance of hydrophilic groups, such as $-COOH$, $-C=O$, and $-NH_2$.

Some studies evaluated polyvinyl alcohol (PVA) composites with $CaCl_2$ and LiCl for dehumidification process [59–62].

The nanofibrous membrane of PVA–15 wt% LiCl, which was prepared by electrospinning, showed $1.04 \, \text{g g}^{-1}$ water intake at 25 °C and 90% RH (twice more than silica gel), which could regenerate at 40–60 °C [62].

Some studied polymer composites [60] and modified polymers such as crosslinked poly(acrylic acid) [63] showed good water adsorption, requiring a long time to reach the sorption equilibrium, which makes them non-ideal for cooling system application.

Recently, Fengjing et al. [64] synthesized polyamide 6-LiCl (20%w) electrospun nanofibrous membranes as new solid desiccant materials with $1.8 \, \text{g g}^{-1}$ water adsorption at 25 °C and 95% RH (approximately 4 times more than silica gels). Their high stability, sorption capacity, and low regeneration temperature (desorption of 85% of adsorbed water at about 50 °C) make them a very promising candidate for cooling systems.

Sultan et al. [65] demonstrated the promising performance of two various honeycomb-like cross-linked hydrophilic organic polymer desiccant, namely PS-I and PS-II (have 2–2.5 times higher water vapour adsorption compared to silica gel), in different air conditioning applications.

KOH4-PR and KOH6-PR are adsorbent materials, which were developed from spherical phenol resin treated with different mass ratios of KOH (carbonization of phenol resin and activation by KOH). They exhibited high adsorption capacity for ethanol ($1.43–2 \, \text{kg kg}^{-1}$) [66] and could be potential water adsorbent materials.

The composite adsorbent containing hygroscopic CMC graft copolymer (CMC-g-AA and CMC-g-AM) has been prepared by solution polymerization, which were prepared using CMC and acrylic acid (AA) or acrylamide (AM) as modifying monomers [67]. Afterwards, impregnation was carried out by using silica gel type B to obtain the CMC graft copolymer/silica gel composite adsorbents (CMC-g-AA/B, or CMC-g-AM/B). The evaluation of the prepared composite showed excellent adsorption performances compared with silica gel.

Superabsorbent resin (SAR) and superabsorbent polymers (SAP) or super porous hydrogels (SPH) [68,69] have been studied for different applications such as wastewater treatment [70], conducting hydrogel, coal dewatering, and slow-release fertilizer [71]. Their outstanding water absorption and retention capacity make them very promising material as desiccant and water reservoir for water management application. These functional polymers contain various hydrophilic groups and lightly crosslinked network structure [72] with high water absorptive capacity even under a certain pressure [73].

SARs have been prepared using petrochemical products and natural polysaccharides (PS) as resource materials. Zhang et al. [74] has

recently developed multi-functional SAR from blending waste plastics and AA. The prepared SAR showed not only very high water absorbency but also approximately 149% moisture absorptive capacity at 19 °C and RH of 100%, which is 3–5 times higher than that of commercial desiccants. These properties make it a very promising desiccant material. The addition of hygroscopic salt to these superabsorbent polymers could modify their properties [72,75].

Yang et al. [76] have developed new superabsorbent hydrogel composite (SHC) by impregnating LiCl in cross-linked sodium polyacrylate. Their very high absorption capacity ($2.76 \pm 0.2 \, \text{g/g}$ at 99% RH), low regeneration temperature (80 °C), and high stability make them very interesting candidate in desiccant cooling application.

Utilizing modified or unmodified natural fibres and agricultural wastes as desiccants materials have a long history [69,77–79]. These lignocellulosic materials have shown very promising results and capability to replace commonly used desiccant materials, although the study of some of their important characteristics is important for their performance evaluation [78]. Dehabadi et al. [80,81] have been studied different PS-based materials such as PS of cellulose, soluble, corn- and maize-derived starches with variable amylose/amylopectin content were cross-linked with variable EPI composition to prepare polymeric adsorbents. The prepared starch biopolymer with high amylose [82] has revealed high water vapor sorption rate and uptake capacity and higher latent effectiveness performance (2–13%) compared with silica gel materials.

Their sorption performance can be enhanced by the preparation of AC from raw carbonaceous materials and modification using hygroscopic salts [5,83–85]. Zhao et al. [86] have investigated various consolidated AC with expanded natural graphite treated with sulfuric acid (ENG–TSA) as adsorbents for refrigeration, and the results showed improved performance by 30%.

4.3. Other materials

Rajamani et al. [24] employed single step sol–gel synthesis method at room temperature to prepare bundled-firewood-like ALOOH–$CaCl_2$ nanocomposite by using chitosan as biopolymer template at ambient condition as an alternative method for the conventional impregnation technique to improve the uniform distribution and long-term retention of lyophilic salt ($CaCl_2$) in the host matrix (boehmite). The prepared nanocomposite desiccant exhibits 5–7 times higher water sorption from air compared with silica gel ($> 2.0 \, \text{g/g}$). In another attempt, they developed chitosan–boehmite nanocomposite without lyophilic salts as desiccant material. Chitosan was not only used as biopolymer template but also as a reinforcing agent to improve the boehmite performance. The highly stable and reusable prepared nanocomposite showed high moisture absorbency ($> 1.5 \, \text{g/g}$) at high humidity (55–65%RH) and low regeneration temperature (80 °C).

The composites of burnt natural clay with sawdust, horse dung, and $CaCl_2$ were prepared at different temperatures and investigated experimentally and numerically as desiccant material [87]. Results showed different water sorption performance for the prepared composites at different temperatures.

5. Discussion and future works

As mentioned earlier, the determination of optimized desiccant materials for cooling systems depends on environmental RH, desiccant cooling system design, adsorption isotherm, stability, regeneration temperature, safety, and cost. The use of some program such as ANN is beneficial for estimating the performance but for reliable results, performance evaluation in a holistic approach is necessary.

However, a study on silica-based porous materials and their modification as primary desiccant materials are extensive. The modified carbon-based porous materials and their composites with silica-based materials and hygroscopic salts open very promising research area. The

stability, cost-effectiveness, eco-friendly potential (possibility to synthesise them using waste materials), and tailorable properties of carbon-based desiccant by functionalization and composite preparation provide their potential as desiccant materials for cooling systems.

However, more research on PMO, MOF, SAR, SAP, SPH, consolidated composites with AC, MWNT, etc. for an improved performance and application in the desiccant cooling system as new desiccant generation is essential.

6. Conclusion

To develop an optimized desiccant-based cooling system at different conditions (RHs, temperature, etc.), the selection of proper desiccant materials alongside with system design is very crucial. Many parameters affect the adsorption performance of desiccant materials, such as adsorption isotherm, structure, and composition. This study provides a review of the recent progress made on solid desiccant materials for desiccant-based cooling systems. Despite the great progress in developing new desiccant materials, carbon-based desiccant materials show huge opportunities for more development. Their capability for functionalization and making composites, making them a very interesting research topic and proposing them as future generation desiccant for desiccant based cooling systems.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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