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Thermal performance analysis of a low-cost and eco-friendly rotary desiccant wheel dehumidification system with recycled materials

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ABSTRACT

Conventional rotary desiccant wheel dehumidification systems often present challenges regarding practicality, cost, size, and usability. This study experimentally investigates the performance of a novel, low-cost (~$100) dehumidification system featuring a 2 cm thick silica gel desiccant wheel. The system's optimal operating conditions are determined under various regeneration temperatures (40 °C, 50 °C, and 60 °C) and fan speeds (2 m/s and 4 m/s), establishing baseline parameters for traditional rotary desiccant systems. Experimental results demonstrated a maximum dehumidification coefficient of performance of 0.312 at 50 °C regeneration temperature and 2 m/s fan speed, decreasing to 0.254 at 60 °C and 4 m/s. Moisture removal and release rates were quantified across various operating conditions. At a regeneration temperature of 60 °C, moisture removal/release rates were 4.55/1.16 g/kg(d.a.) and 3.97/0.42 g/kg(d.a.) for fan speeds of 2 m/s and 4 m/s, respectively. Corresponding values at 50 °C were 3.48/0.54 g/kg(d.a.) and 2.77/0.28 g/kg(d.a.). Finally, at 40 °C, these rates were 1.53/0.09 g/kg(d.a.) and 0.59/0.05

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g/kg(d.a.) for 2 m/s and 4 m/s, respectively. These results indicate optimal operating conditions of 50 °C at 2 m/s and 60 °C at 4 m/s fan speed. Recognising that optimal conditions may vary with ambient humidity, this study provides valuable insights into the relationship between moisture removal and DCOP for each tested scenario. This innovative, cost-effective system demonstrates promising results for rotary desiccant dehumidification and offers the potential for integration with traditional air conditioning systems to enhance energy efficiency.

Nomenclature

Descriptions of symbols (Units)

W	Moisture content or amount of moisture (g/(kg(d.a.)))
M	Moisture flow rate (kg/h)
φ	Efficiency of the wheel
h_v	Latent heat of vaporisation of moisture (kJ/kg)
ω	Specific humidity (g/(kg(d.a.)))
$\dot{m}$	Mass flow rate (kg/s)

Abbreviations

DCOP	Dehumidification coefficient of performance

Subscripts

abs	Process air
reg	Regeneration air
in	Inlet
out	Outlet
env	Environment

1. Introduction

The building sector remains one of the largest consumers of global energy resources, with residential buildings comprising a substantial proportion of this overall consumption. Within the residential sector, a significant portion of the total energy usage is dedicated to heating, ventilation, and air conditioning (HVAC) systems, which play a crucial role in maintaining indoor thermal comfort. In the European Union, residential buildings allocate a considerable share of their total energy consumption to space heating, domestic hot water production, and electricity demand. The escalating energy demand in this sector is anticipated to increase further in the coming years due to multiple contributing factors, including the extended lifespan of buildings, the growing expectations of occupants for enhanced indoor comfort, and continuous population growth. This rising demand for energy-intensive climate control solutions has also led to increased environmental concerns, particularly with respect to carbon emissions and their impact on global warming. As a response to these challenges, significant research and technological advancements have been directed toward the development and implementation of alternative, more sustainable building technologies and energy-efficient practices [1,2].

The projected rise in energy demand can be attributed to various interrelated factors, including the longer service life of buildings, the heightened expectations of occupants for optimized thermal comfort, and the continued growth of the global population [3]. In this context, energy conservation strategies in heating, ventilation, and air conditioning (HVAC) systems have gained considerable attention, as researchers seek to replace traditional high-energy-consuming technologies with more sustainable and efficient alternatives. Improving energy efficiency in buildings, particularly within the HVAC sector, has become a key priority for environmentally conscious individuals, policymakers, and engineers alike [4]. Conventional air conditioning systems, which rely heavily on refrigerants with high global warming potential (GWP), have been identified as major contributors to greenhouse gas emissions, accounting for over 30 % of the emissions associated with building-related energy consumption. Consequently, there is a pressing need for the adoption of environmentally friendly cooling solutions that minimize reliance on high-GWP refrigerants while simultaneously improving energy efficiency and indoor air quality [5].

Among the emerging sustainable cooling technologies, rotary desiccant wheels (RDWs) have garnered significant attention due to their potential to enhance dehumidification efficiency and provide energy-saving benefits. These systems utilise a rotating wheel coated with a desiccant material that efficiently absorbs moisture from the process air stream. The continuous rotation of the wheel facilitates simultaneous dehumidification and regeneration processes, thereby ensuring a consistent supply of dry air within the conditioned space [6]. Unlike conventional vapor-compression refrigeration systems, which depend on synthetic refrigerants with high environmental impact, rotary desiccant wheels operate using air as the primary working fluid, making them a more environmentally friendly alternative. Furthermore, the potential integration of RDW systems with renewable energy sources, such as solar thermal energy, enhances their sustainability and viability for large-scale implementation in green building projects.

Rotary desiccant wheels have demonstrated substantial promise in energy-efficient dehumidification and climate control applications [7]. These systems employ a continuously rotating wheel that is coated with a desiccant material, enabling efficient moisture adsorption from the air stream [8]. As the wheel rotates, the absorbed moisture is expelled during the regeneration phase, which is typically driven by a low-grade heat source such as waste heat or solar energy. This dual-phase operational mechanism not only ensures a consistent supply of dehumidified air but also enables integration within passive design strategies, reducing reliance on active energy-consuming HVAC systems. By adhering to passive design principles, RDW systems offer significant advantages in terms of energy conservation and reduced environmental impact [9,10]. Compared to conventional vapor-compression refrigeration systems, which heavily depend on synthetic refrigerants with high GWP, rotary desiccant wheels offer an environmentally responsible alternative by utilizing water or air as the primary working fluid. Additionally, the possibility of integrating these systems with renewable energy sources, particularly solar energy, further enhances their sustainability and overall efficiency.

A growing body of experimental research has been dedicated to investigating the performance characteristics of RDW systems under diverse operating conditions and design configurations. Various studies have examined the influence of key parameters such as desiccant material composition, wheel rotation speed, airflow rate, and regeneration temperature on system efficiency, moisture removal capacity, and pressure drop characteristics. For instance, several researchers have analysed the effectiveness of different desiccant materials, including silica gel [11–13], molecular sieves, and newly developed composite materials, in achieving high moisture adsorption capacity and long-term operational stability. In a comparative study, Singh et al. [14] have evaluated the performance of enthalpy recovery wheels and dehumidification wheels, highlighting the distinct differences in their operational efficiency and system behaviour. Furthermore, Ma et al. [15] have investigated the impact of wheel rotation speed on dehumidification performance, identifying optimal operating conditions for maximizing system efficiency. Another noteworthy study has conducted by Hanifah et al. [16] explored the performance of a novel rotary desiccant wheel that lacked a conventional honeycomb matrix structure. Their experimental findings indicated a substantial reduction in the humidity ratio, decreasing from 0.0205 kg/kg to 0.0182 kg/kg, demonstrating the effectiveness of innovative design modifications.

Further research has been directed towards optimizing the design and operational characteristics of RDW systems to achieve maximum performance and energy efficiency. Ge et al. [17] have introduced a two-stage rotary desiccant cooling system, demonstrating its superior efficiency compared to single-stage configurations. Kara et al. [18] have conducted an in-depth analysis of the dehumidification and humidity removal process in desiccant wheels, offering valuable insights into the underlying thermodynamic mechanisms and performance-influencing factors. Additionally, Cheevitsopon and Cheevitsopon [19] have explored the application of RDW technology in hot air-drying processes, underscoring its effectiveness in enhancing overall drying efficiency while minimizing energy consumption.

The performance of a rotary desiccant wheel (RDW) system is significantly influenced by the airflow rate, which is driven by the fan speed. The optimal fan speed is a critical parameter that directly affects the system's dehumidification capacity, energy efficiency, and pressure drop characteristics. Generally, airflow velocities within the range of 2–4 m/s are considered ideal for most RDW applications, as they provide a balance between effective moisture adsorption and minimal resistance to airflow. Lower air velocities (1–2 m/s) allow for extended contact time between the air and the desiccant material, enhancing moisture removal efficiency; however, this can lead to a reduction in the overall air exchange rate, thereby limiting the system's capacity to handle large volumes of humid air. Conversely, higher airflow velocities (4–6 m/s) increase the rate of air exchange but may compromise dehumidification performance due to insufficient contact time with the desiccant surface. Therefore, the optimal fan speed must be carefully selected based on application-specific requirements, ensuring an efficient balance between airflow rate and moisture removal efficiency. Furthermore, integrating variable-speed fan controls can optimize RDW performance under varying environmental conditions, allowing for dynamic adjustment of airflow based on humidity levels and thermal load demands [14–17].

This study presents an innovative rotary desiccant wheel dehumidification system constructed entirely from recycled materials, distinguishing it from conventional RDW systems. Fabricated at a total cost of only $100, this system incorporates 100 % recycled components, highlighting the feasibility of achieving cost-effective dehumidification performance comparable to commercially available rotary desiccant wheels. As rotary desiccant wheels continue to gain recognition as a viable alternative to traditional air conditioning systems, this research underscores the importance of sustainable and low-cost solutions for climate control applications. Future research efforts will focus on evaluating the long-term energy efficiency and operational performance of this novel dehumidification system when integrated with a cooling system, further exploring its potential as a sustainable and economical solution for environmentally conscious climate control.

2. Research methodology

RDW systems are used in two ways: as dehumidification systems and dehumidification cooling systems. Although RDWSs are initially used for long-term drying of fruits vegetables, and fish products, as well as in storage areas and factories where systems needed to be kept moisture-free, they have recently been proposed as a strong alternative to traditional air conditioners for residential use [20]. The systems remove moisture from the air by passing it through a rotating wheel [21]. The air, dehumidified by a desiccant such as silica gel within the structure of the wheel, is directed into the indoor environment [22]. Desiccants that continuously remove moisture from the air will inevitably begin to lose their moisture-absorbing capacity over time; to prevent this, a regeneration process is carried out [23]. In the regeneration phase, stale air extracted from the indoor environment is heated and passed through the wheel; this process, based on thermodynamic principles, raises the temperature of the air while reducing its relative humidity, making it more suitable for absorbing moisture. As a result, the air physically captures some moisture through the wheel, allowing the desiccant to be used for a longer period [24]. These dehumidification systems are particularly noteworthy because they offer low maintenance costs, can utilise solar energy as a heat source, and, most importantly, do not have any greenhouse gas emissions, making them an environmentally friendly option [25]. Rotary desiccant wheel dehumidification systems can be categorised into two types based on their regeneration phase: those that utilise solar energy and those that rely upon electrical energy [26]. To effectively harness solar energy, systems typically utilise air collectors, which capture and transfer heat from the sun to enhance the efficiency of various applications [27] (see Fig. 1).

2.1. Description of the affordable and eco-friendly rotary desiccant wheel dehumidification system with recycled materials

In traditional rotary desiccant wheel dehumidification systems, the desiccant wheel typically features a honeycomb structure designed to maximise surface area for moisture absorption and improve overall system efficiency [28]. The newly developed system is designed with a metal sheet exterior to ensure cost efficiency and incorporate recycled materials. The desiccant is freely filled into a wheel structure, allowing for an effective and low-cost solution. Silica gel, a material commonly used in dehumidification applications due to its high efficiency and excellent performance in moisture absorption, has been chosen as the primary material for the desiccant wheel in the system. Two fans, each capable of transferring 275 cubic meters of air per hour, are used in this system to handle both regeneration and process air functions, ensuring efficient air circulation and optimal dehumidification performance throughout the operation. The direction of the air is controlled through the use of extractor ducts, which effectively guide the airflow throughout the system. Two humidity sensors are installed at the regeneration and dehumidification outlets to measure temperature and relative humidity values. The recorded temperature and relative humidity data are then used to calculate the specific humidity values by applying an iterative method within a computer environment. A data logger is used to read and record data from these humidity sensors. A slow yet powerful blender motor has been chosen to rotate the wheel. A rotary desiccant wheel system is designed around a wheel that is essentially divided into four equal sections. Two of these sections are dedicated to the regeneration process, while one section is utilised for the process air, where dehumidification takes place. The remaining section is intentionally left empty to facilitate a controlled heat loss from the desiccant wheel, thereby enhancing the system's overall efficiency. To ensure uniform air distribution and prevent stagnation, a 12W fan has been positioned at the furthest point of the aspirator pipes connected to the process air intake, as shown in Fig. 2. The airflow is facilitated through aspirator pipes with a thickness of 10 cm.

The desiccant wheel has been selected to be 2 cm thick in order to achieve the lowest possible cost. The desiccants poured inside are matrixed in two layers, ensuring that the layers do not align with each other. The airflow is designed to pass through the gaps between these layers in a cross-sectional manner. The desiccant wheel is divided into four sections, with each section containing 1 kg of silica gel moisture absorber. This wheel is designed to ensure the lowest possible pressure loss during operation. The wheel is segmented into four equal quarters. Two quarters are dedicated to regeneration, one quarter is designated for the process air, and the remaining quarter is left intentionally vacant to allow a portion of the air to bypass the desiccant material. This division facilitates a comparative analysis of the dehumidification process, enabling a clear graphical representation of the system's effectiveness in removing moisture from the air, as shown in Fig. 3.

2.2. Uncertainty analysis

The performance assessment of the novel low-cost, recycled, and energy-efficient solar air heater with waste beverage cans has been done with highly sensitive measurement systems. In order to give the readers a detailed explanation of the accuracy of the experiments, the equipment used in the experimental setup is shown in Table 1 with accuracy and measurement ranges.

2.3. Thermodynamic analysis

Alternatively, these equations, representing the moisture removal potential from the air and the moisture removal capacity from the wheel, can be expressed as Eq. (1) and Eq. (2), respectively [29,30].

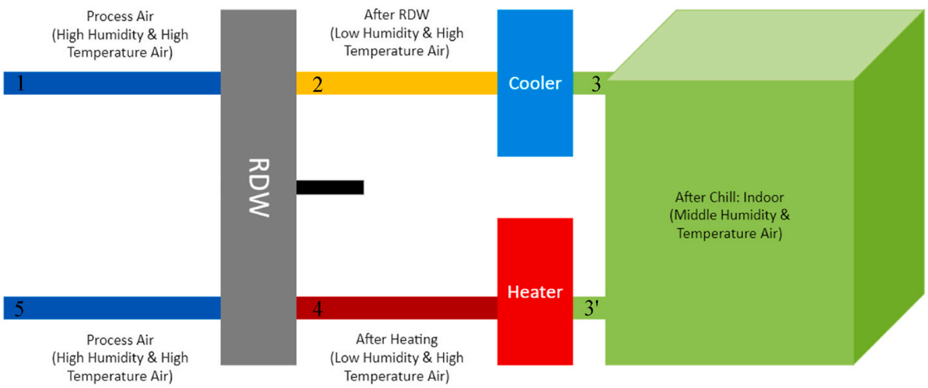

Fig. 1. Schematic image of rotary desiccant wheel system.

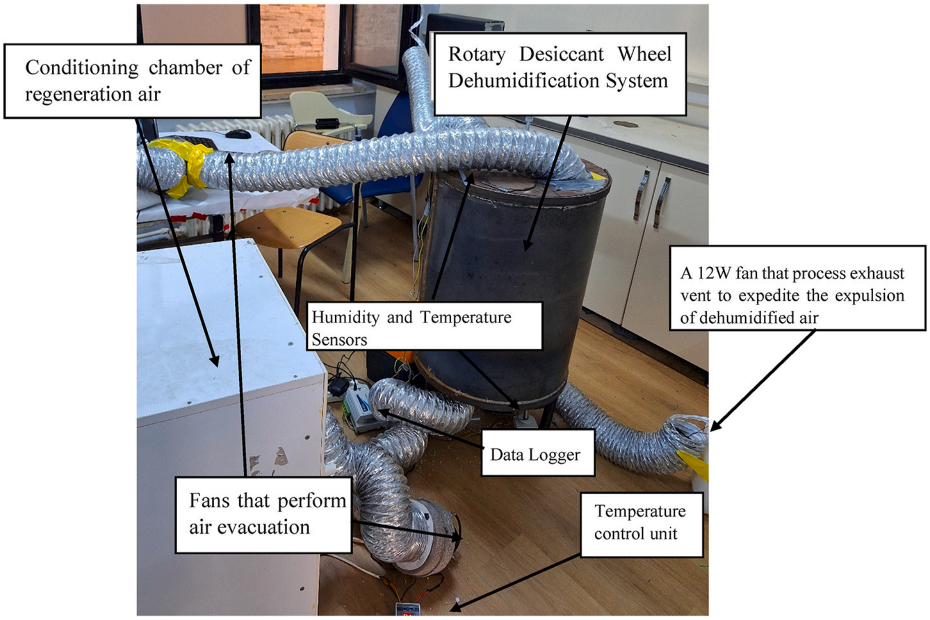

Fig. 2. Image of affordable and eco-friendly rotary desiccant wheel dehumidification system with recycled materials.

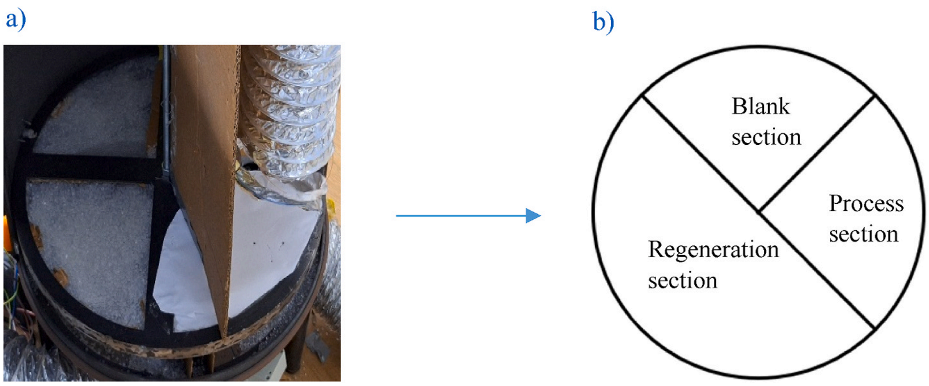

Fig. 3. a) The desiccant wheel b) and the Schematic representation of its separated parts.

Table 1
Accuracy and measurement ranges of the devices.

Device	Accuracy	Range
Thermocouple (K-type)	± 0.05 °C	0–400 °C
Humidity Sensor	±1 %	0–100 %

$$W_{abs} = \omega_1 - \omega_2 \quad (1)$$

$$W_{reg} = \omega_5 - \omega_4 \quad (2)$$

The quantification of both the dehumidification and regeneration capacities inherent to the rotary desiccant wheel system is meticulously delineated within the mathematical framework provided by Eq. (3) and Eq. (4), respectively [31].

$$M_{abs} = \dot{m}_{abs}(\omega_1 - \omega_2) \quad (3)$$

$$M_{reg} = \dot{m}_{reg}(\omega_5 - \omega_4) \quad (4)$$

The dehumidification and regeneration efficiencies are presented in Eq. (5) and Eq. (6), respectively [32].

$$\varphi_{abs} = \frac{\omega_1 - \omega_2}{\omega_1 - \omega_{2,ideal}}, \omega_{2,ideal} \rightarrow 0 \tag{5}$$

$$\varphi_{reg} = \frac{\omega_5 - \omega_4}{\omega_4} \tag{6}$$

Rotary Desiccant Wheel Dehumidification Systems, the determination of the Coefficient of Performance is achieved through the utilisation of the equation presented as Eq. (7) [33].

$$DCOP = \frac{\rho_a \times \dot{m}_{abs} \times h_v \times \Delta\omega_{abs}}{1000 \times q_{in}}, h_v \rightarrow 2250\ kJ \Big/ kg \tag{7}$$

The thermal energy consumption required for the DCOP calculation is determined using the equation presented in Eq. (8) [15].

$$q_{in} = \rho_a \times c_{abs,a} \times \dot{m}_{abs} \times \left(T_{reg,in} - T_{reg,env}\right) \tag{8}$$

3. Experimental results and discussion

An affordable and eco-friendly rotary desiccant wheel dehumidification system with recycled materials is tested in a room with dimensions of 10 × 20 × 3 m^3. The tests are conducted at regeneration temperatures of 40 °C, 50 °C, and 60 °C, respectively. For each regeneration temperature, the fan speeds are set at 2 m/s and 4 m/s. The rotation speed of the wheel is fixed at 1 rpm. The experimental test range covers the period until the system reaches a steady state. The duration of the test procedures typically spans a period of 20–40 min [15] (this study period is 25–55 min), allowing sufficient time for the system to achieve a state of stabilised operation and consistent performance.

As depicted in Figs. 3–5, the moisture content at the process air inlets is precisely regulated and augmented using dedicated humidifiers, ensuring a controlled and elevated humidity level for the incoming air stream. Experimental investigations have unveiled a compelling interplay between the operational parameters of fan speed and regeneration temperature, underscoring their profound influence on the dehumidification efficacy of the system. Specifically, the findings demonstrate that reduced fan speeds correspond to a heightened moisture removal rate, indicating a more thorough dehumidification process. Conversely, elevated fan speeds, while potentially augmenting the airflow volume, appear to compromise the dehumidification efficiency, resulting in a diminished moisture extraction capability. This phenomenon can be attributed to the reduced contact time between the moist air stream and the desiccant material at higher flow velocities, thereby limiting the moisture absorption capacity.

Furthermore, the regeneration temperature emerges as a pivotal factor governing the system's dehumidification prowess. Elevated regeneration temperatures demonstrably enhance the moisture removal capacity, effectively revitalising the desiccant material and

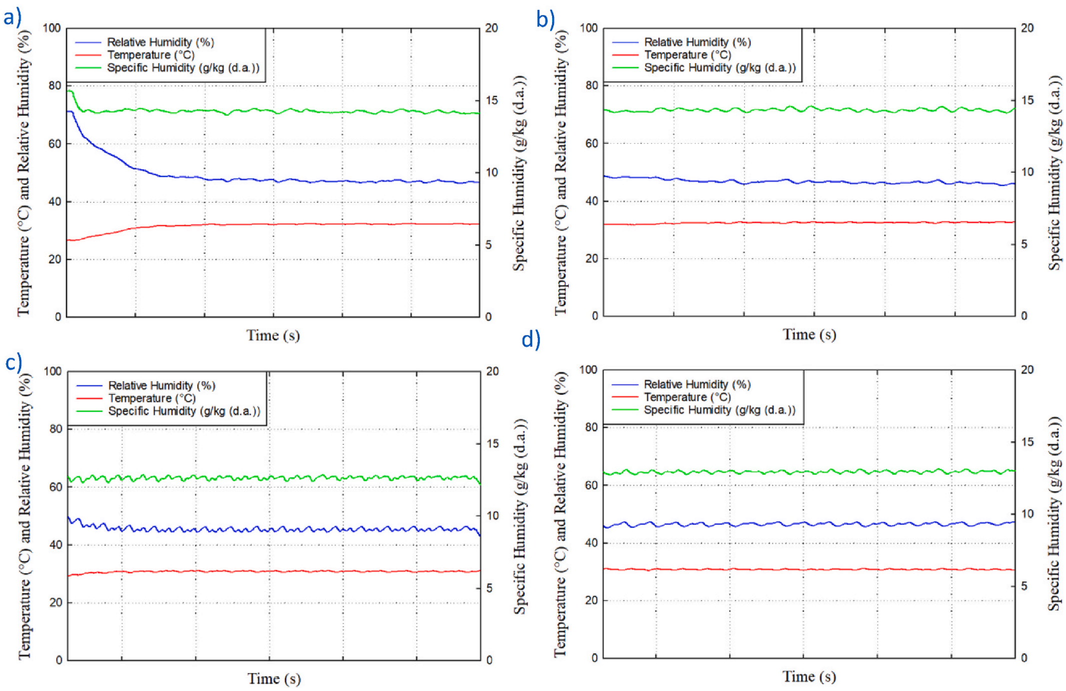

Fig. 4. a) Dehumidification and b) regeneration at 2 m/s fan speed and 40 °C regeneration temperature. c) dehumidification and d) regeneration at 4 m/s fan speed and 40 °C regeneration temperature.

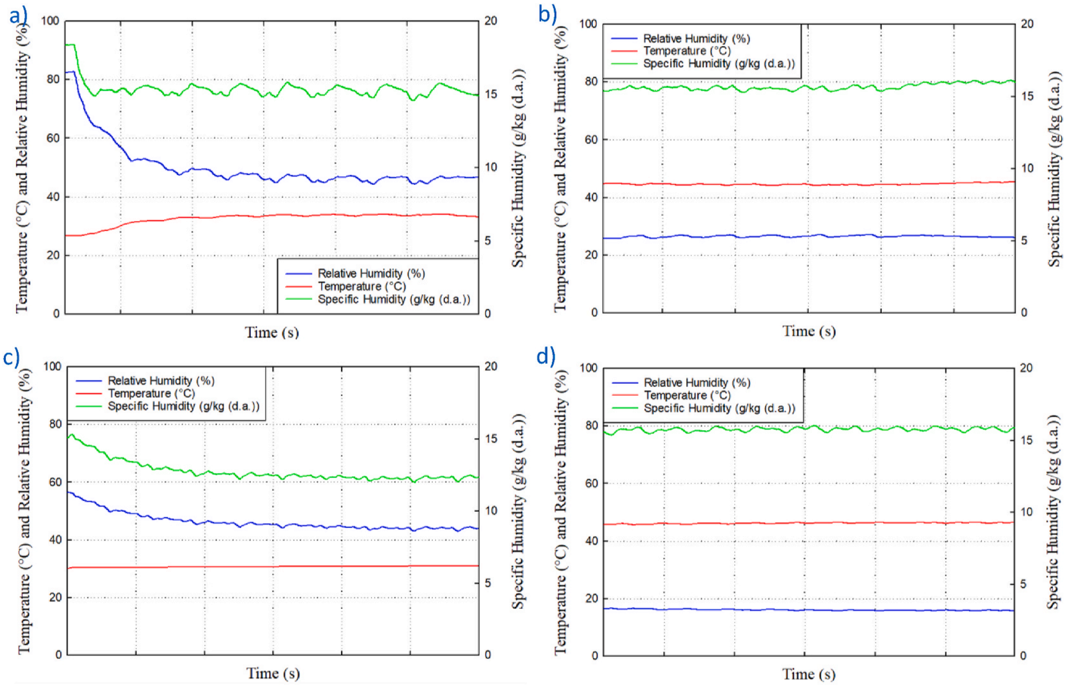

Fig. 5. a) Dehumidification and b) regeneration at 2 m/s fan speed and 50 °C regeneration temperature. c) dehumidification and d) regeneration at 4 m/s fan speed and 50 °C regeneration temperature.

restoring its adsorption potential. Conversely, lower regeneration temperatures hinder the desiccant's ability to release the absorbed moisture, thereby diminishing its overall dehumidification efficacy. These intricate and interconnected relationships underscore the critical importance of optimizing both fan speed and regeneration temperature to achieve the desired dehumidification performance. The observed trends are indicative of the delicate balance between mass transfer kinetics, heat transfer dynamics, and the inherent properties of the desiccant material, all of which contribute to the overall efficiency of the dehumidification process.

Fig. 4 a), b), c) and d) illustrates the significant impact of fan speed on the dehumidification process. At a fan speed of 2 m/s and a regeneration temperature of 40 °C, the process air experiences a decrease in specific humidity from 15.662 g/kg (d.a.) to 14.1324 g/kg (d.a.), accompanied by a temperature increase from 26.63 °C to 32.202 °C and a relative humidity reduction from 71.339 % to 46.807 % as shown in Fig. 4 a). Conversely, during regeneration at the same fan speed and temperature, the specific humidity of the air passing through the desiccant wheel exhibits a marginal increase from 14.3565 g/kg (d.a.) to 14.4469 g/kg (d.a.), with a corresponding temperature rise from 31.7750 °C to 32.8950 °C and a relative humidity decrease from 48.6940 % to 45.9960 % as shown in Fig. 4 b).

Increasing the fan speed to 4 m/s while maintaining the regeneration temperature at 40 °C results in a smaller reduction in specific humidity during the process stage, from 12.7432 g/kg (d.a.) to 12.1518 g/kg (d.a.), along with a temperature increase from 29.37 °C to 31.1460 °C and a relative humidity decrease from 49.7120 % to 42.8620 % as shown in Fig. 4 c). Similarly, during regeneration at 4 m/s and 40 °C, the specific humidity of the air passing through the desiccant wheel shows a slight increase from 12.9475 g/kg (d.a.) to 13.0013 g/kg (d.a.), accompanied by a temperature decrease from 30.9790 °C to 30.605 °C and a relative humidity increase from 46.0470 % to 47.231 % as shown in Fig. 4 d).

Fan speeds significantly influence both dehumidification effectiveness and DCOP values. This DCOP variation is attributed to the balance between energy consumption and useful work output. At a regeneration temperature of 40 °C, DCOP values are observed to be 0.23 and 0.1 for fan speeds of 2 m/s and 4 m/s, respectively.

Fig. 5 illustrates the impact of varying fan speeds on dehumidification performance at a regeneration temperature of 50 °C. At a fan speed of 2 m/s, as shown in Fig. 5 a), the process air experiences a decrease in specific humidity from 18.412 g/kg (d.a.) to 14.93083 g/kg (d.a.), accompanied by a temperature increase from 26.997 °C to 31.678 °C and a relative humidity reduction from 81.772 % to 50.875 %. Conversely, during the regeneration phase at the same fan speed as shown in Fig. 5 b), the air passing through the desiccant wheel shows a slight increase in specific humidity from 14.4499 g/kg (d.a.) to 15.9891 g/kg (d.a.), with a corresponding temperature rise from 44.7650 °C to 45.3530 °C and a relative humidity increase from 25.9409 % to 26.6249 %.

Increasing the fan speed to 4 m/s at the same regeneration temperature as shown in Fig. 5 c) results in a smaller reduction in specific humidity during the process stage, from 15.1185 g/kg (d.a.) to 12.3453 g/kg (d.a.), along with a smaller temperature increase from 29.9810 °C to 30.9674 °C and a relative humidity decrease from 56.730 % to 43.9760 %. During regeneration at 4 m/s as shown in Fig. 5 d), the air exhibits a similar trend as in Fig. 5 b), with a slight increase in specific humidity from 15.6053 g/kg (d.a.) to 15.8852 g/kg (d.a.), accompanied by a temperature increase from 45.85 °C to 46.5970 °C and a negligible relative humidity increase from 25.9409 % to 26.0249 %.

At a regeneration temperature of 50 °C, DCOP values are observed to be 0.32 and 0.25 for fan speeds of 2 m/s and 4 m/s, respectively. The difference observed at 50 °C regeneration temperature is smaller compared to the difference between 2 m/s and 4 m/s at 40 °C, indicating a more pronounced effect of fan speed at the higher regeneration temperature.

Fig. 6 demonstrates the influence of fan speed on dehumidification performance at a regeneration temperature of 60 °C. At a fan speed of 2 m/s, as shown in Fig. 6 a), the process air experiences a significant reduction in specific humidity from 12.2193 g/kg (d.a.) to 7.6655 g/kg (d.a.), coupled with a slight temperature decrease from 32.6350 °C to 31.8170 °C and a notable decrease in relative humidity from 49.4859 % to 25.0313 %. Conversely, during regeneration at the same fan speed as shown in Fig. 6 b), the air passing through the desiccant wheel exhibits a small increase in specific humidity from 11.4024 g/kg (d.a.) to 12.5626 g/kg (d.a.), a temperature rise from 54 °C to 58.3650 °C, and a minor decrease in relative humidity from 12.1557 % to 10.8609 % (see Fig. 7).

Increasing the fan speed to 4 m/s while maintaining the regeneration temperature as shown in Fig. 6 c) leads to a smaller reduction in specific humidity during the process stage, from 11.1440 g/kg (d.a.) to 7.1749 g/kg (d.a.), a temperature increases from 25.6120 °C to 32.300 °C, and a relative humidity decrease from 54.2900 % to 23.8940 %. Similarly, during regeneration at 4 m/s, as shown in Fig. 6 d), the air shows a slight increase in specific humidity from 8.0913 g/kg (d.a.) to 8.5136 g/kg (d.a.), a temperature rises from 52.430 °C to 55.5330 °C, and a negligible increase in relative humidity from 9.3581 % to 8.4703 %.

At a regeneration temperature of 60 °C, DCOP values are observed to be 0.29 and 0.254 for fan speeds of 2 m/s and 4 m/s, respectively. The difference observed at 60 °C is smaller than the difference between 2 m/s and 4 m/s at 60 °C and even smaller than the difference between 40 °C and 50 °C, indicating a more pronounced effect of fan speed at higher regeneration temperatures. This finding suggests the existence of optimal fan speed values for each regeneration temperature. Table 2 provides a comparative analysis of DCOP variations at different regeneration temperatures for each fan speed.

Table 3 presents the test results of the newly designed, low-cost, recycled rotary desiccant wheel system.

Fig. 8 illustrates the ratio of both the moisture removal capacity of the supply air and the moisture added to the regeneration air, to their respective specific humidity values. In simpler terms, these values represent the rate of moisture removal from the air per second and the rate of moisture desorption from the wheel per second, respectively.

4. Conclusions

This study investigates the dehumidification performance of a low-cost, all-inclusive rotary desiccant wheel system, constructed from recycled materials at an approximate cost of $100, under real-world operating conditions. The primary objective of this experiment is to demonstrate the feasibility of integrating affordable systems into existing conventional air conditioning units.

Furthermore, the study aims to provide a detailed analysis of the dehumidification performance of a rotary desiccant wheel system utilizing a loosely packed, 2 cm thick desiccant wheel costing approximately $5, as opposed to a conventional monolithic desiccant wheel, across various process air and regeneration air speeds.

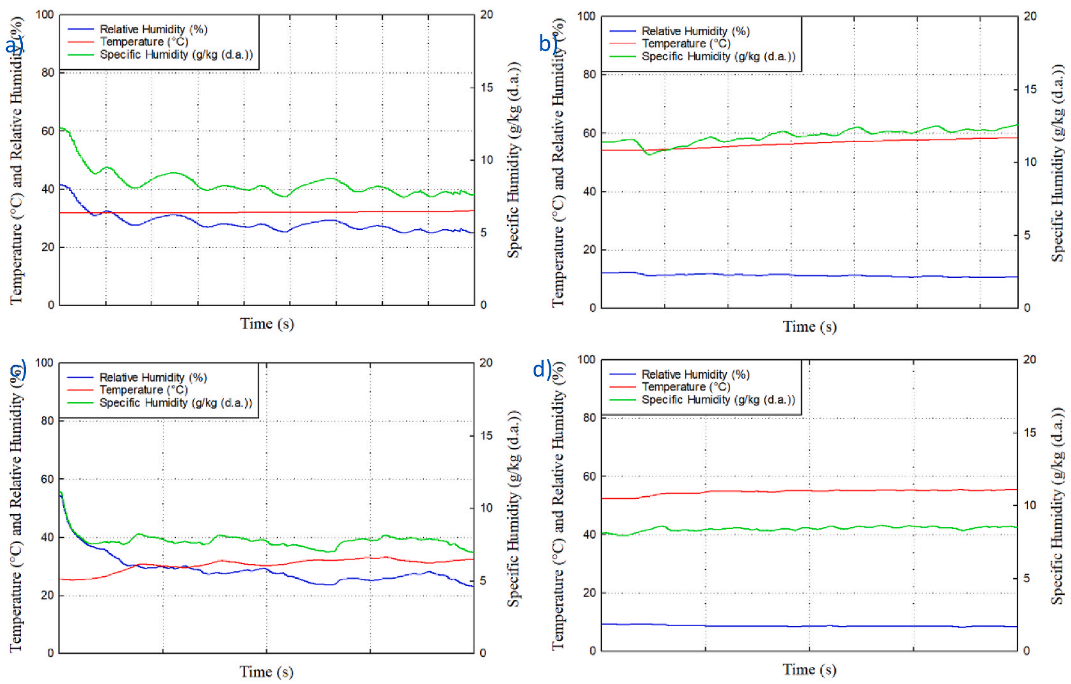

Fig. 6. a) Dehumidification and b) regeneration at 2 m/s fan speed and 60 °C regeneration temperature. c) dehumidification and d) regeneration at 4 m/s fan speed and 60 °C regeneration temperature.

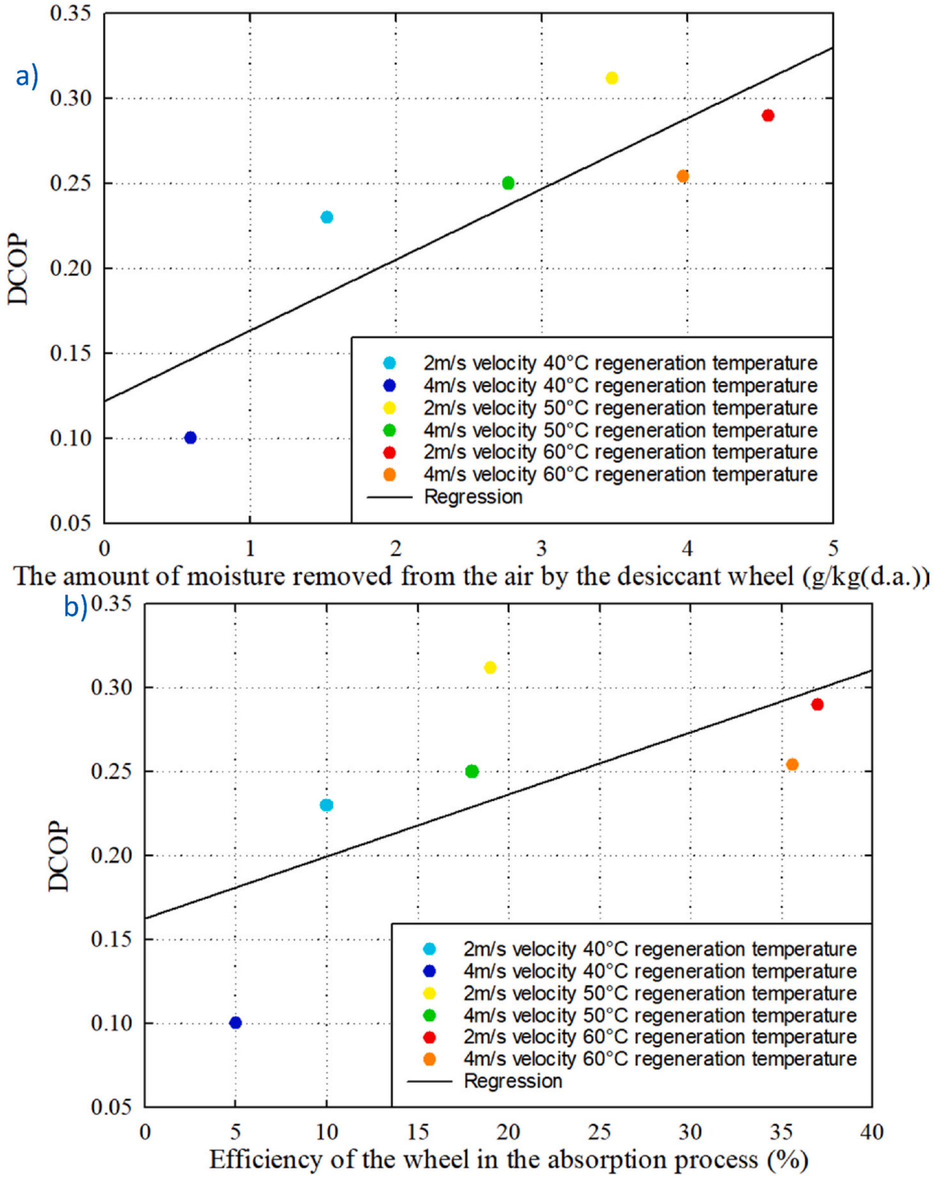

Fig. 7. a) DCOP values corresponding to the amount of specific moisture removal by the desiccant wheel, b) DCOP values correspond to the desiccant wheel efficiency for dehumidification.

Table 2
DCOP values of the results for each regeneration temperature and fan speed.

Regeneration Temperature (°C)	40		50		60	
V (m/s)	2	4	2	4	2	4
DCOP (–)	0.23	0.1	0.312	0.25	0.29	0.254

The key findings of the study are as follows:

(1) Regeneration temperature and fan speed are identified as the most influential parameters affecting system behaviour.
(2) At a regeneration temperature of 40 °C, the dehumidification and regeneration capacities are 1.5296 g/kg(d.a.) and 0.0904 g/kg(d.a.) respectively for an air velocity of 2 m/s, and 0.5914 g/kg(d.a.) and 0.0538 g/kg(d.a.) for an air velocity of 4 m/s. At 50 °C, these values are 3.48177 g/kg(d.a.) and 0.5392 g/kg(d.a.) for 2 m/s, and 2.7732 g/kg(d.a.) and 0.2799 g/kg(d.a.) for 4 m/s. Finally, at 60 °C, the values are 4.5538 g/kg(d.a.) and 1.1602 g/kg(d.a.) for 2 m/s, and 3.9691 g/kg(d.a.) and 0.421 g/kg

Table 3
Summary of experimental test results.

$T_{process}$ = 40 °C		Fan speed (m/s)			
		2		4	
		VoP		VoP	
Dehumidification	Relative humidity (%)	71.339	46.807	49.712	42.862
	Temperature (°C)	26.63	32.202	29.37	31.146
	Specific humidity (g/kg (d.a))	15.662	14.132	12.7432	12.1518
Regeneration	Relative humidity (%)	48.6940	45.9960	46.0470	47.231
	Temperature (°C)	31.7750	32.8950	30.979	30.605
	Specific humidity (g/kg (d.a))	14.3565	14.4469	12.9475	13.0013
$T_{process}$ = 50 °C		Fun speed (m/s)			
		2		4	
		VoP		VoP	
Dehumidification	Relative humidity (%)	71.772	50.875	56.73	43.976
	Temperature (°C)	26.997	31.678	29.981	30.9674
	Specific humidity (g/kg (d.a))	18.412	14.9308	15.1185	12.3453
Regeneration	Relative humidity (%)	25.9409	26.6249	25.9409	26.0249
	Temperature (°C)	44.765	45.353	45.85	46.597
	Specific humidity (g/kg (d.a))	14.4499	15.9891	25.9409	26.0249
$T_{process}$ = 60 °C		Fun speed (m/s)			
		2		4	
		VoP		VoP	
Dehumidification	Relative humidity (%)	49.4859	25.0313	54.29	23.894
	Temperature (°C)	32.635	31.817	25.612	32.3
	Specific humidity (g/kg (d.a))	12.2193	7.6655	11.144	7.1749
Regeneration	Relative humidity (%)	12.1557	10.8609	9.3581	8.4703
	Temperature (°C)	54	58.365	52.43	55.533
	Specific humidity (g/kg (d.a))	11.4024	12.5626	8.0913	8.5136

VoP: Variation of the parameter.

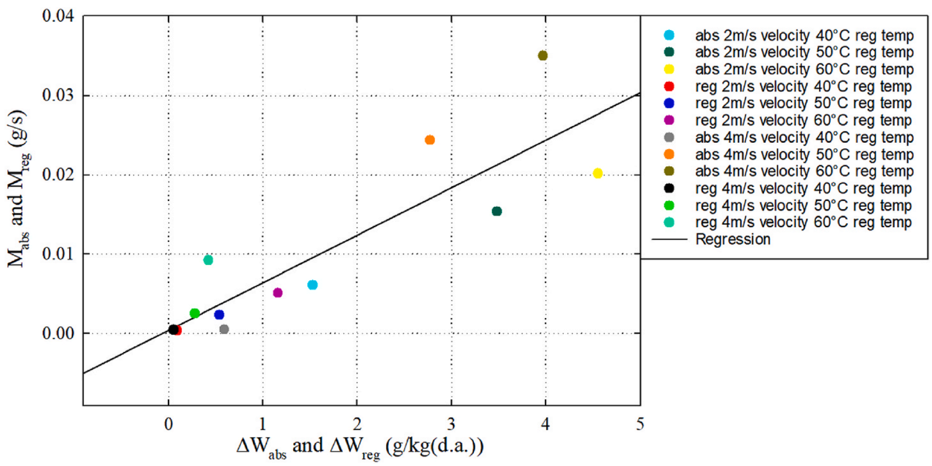

Fig. 8. The moisture removal capacity of supply air and the amount of moisture added to the air in the regeneration section.

(d.a.) for 4 m/s. These results demonstrate that while the amount of moisture removed by the desiccant wheel and the amount of moisture desorbed from the wheel increase with increasing regeneration temperature, the opposite is observed with increasing fan speed.

(3) The dehumidification and regeneration efficiencies are 9.8 % and ~1 % respectively for 2 m/s, and ~5 % and ~0.5 % for 4 m/s at a regeneration temperature of 40 °C. At 50 °C, these values are ~19 % and ~3.5 % for 2 m/s, and 18 % and ~2 % for 4 m/s. Lastly, at 60 °C, the values are 37 % and 10 % for 2 m/s, and 35.6 % and 5 % for 4 m/s. These findings indicate that while the dehumidification and regeneration efficiency coefficients increase with increasing regeneration temperature, they decrease with increasing fan speed.

(4) The DCOP value at a regeneration temperature of 50 °C and a fan speed of 2 m/s is higher than the DCOP value at 60 °C and the same fan speed. Conversely, for a fan speed of 4 m/s, the DCOP value is higher at 60 °C than at 50 °C. Additionally, at a fan speed of 4 m/s, the DCOP value at 50 °C is higher than that at 40 °C. These observations suggest the existence of optimal operating conditions for the system. While higher regeneration temperatures are favoured at higher fan speeds, this does not hold true at lower fan speeds, indicating that an optimal fan speed exists for each regeneration temperature to maximise energy efficiency.

(5) Comparing the three regeneration temperatures at two different fan speeds, a clear trend emerges: higher initial moisture content in the air leads to greater moisture removal. Furthermore, both the dehumidification coefficient of performance and wheel efficiency vary depending on the initial humidity level. This conclusion is supported by the observed changes in specific humidity values before and after dehumidification at regeneration temperatures of 40 °C, 50 °C, and 60 °C, and fan speeds of 2 m/s and 4 m/s. In summary, for regions with high relative and specific humidity, higher regeneration temperatures and correspondingly optimal fan speeds may be more suitable. Conversely, in regions with lower humidity, lower regeneration temperatures and optimal fan speeds are likely more suitable.
(6) Integrating this novel, low-cost system into conventional air conditioners can lead to significant energy savings, as evidenced by the amount of moisture removed.
(7) In further works, rotary desiccant wheels (RDWs) are planned to be designed by taking inspiration from nature through biomimetic techniques for fast and effective mass transfer performance [34]. In addition, heat and mass transfer enhancement can be achieved through micro fin configurations [35] for improved DCOP figures.

CRediT authorship contribution statement

Pinar Mert Cuce: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Erdem Cuce:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Ali Ahmed Alqahtani:** Writing – review & editing, Methodology, Funding acquisition. **Saad Alshahrani:** Writing – review & editing, Funding acquisition. **Manzoore Elahi M. Soudagar:** Writing – review & editing, Writing – original draft. **Jingyu Cao:** Writing – review & editing, Writing – original draft. **Abdallah Bouabidi:** Supervision, Writing – review & editing. **Mohammed El Hadi Attia:** Supervision, Writing – review & editing. **Yusuf Nadir Yilmaz:** Writing – original draft, Software, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] E. Alvur, M. Anac, P.M. Cuce, E. Cuce, The potential and challenges of bim in enhancing energy efficiency in existing buildings: a comprehensive review, Sustain. Clean Build. 1 (1) (2024) 42–65.
[2] E. Cuce, P.M. Cuce, E. Alvur, Y.N. Yilmaz, S. Saboor, I. Ustabas, E. Linul, M. Asif, Experimental performance assessment of a novel insulation plaster as an energy-efficient retrofit solution for external walls: a key building material towards low/zero carbon buildings, Case Stud. Therm. Eng. 49 (2023) 103350.
[3] M.W. Akram, M. Hasanuzzaman, E. Cuce, P.M. Cuce, Global technological advancement and challenges of glazed window, facade system and vertical greenery-based energy savings in buildings: a comprehensive review, Energy Built Environ. 4 (2) (2023) 206–226.
[4] P.M. Cuce, S. Riffat, A novel moist airflow heating system for low/zero carbon buildings: a numerical study, Sustain. Clean Build. 1 (1) (2024) 23–41.
[5] P.M. Cuce, S. Riffat, A state of the art review of evaporative cooling systems for building applications, Renew. Sustain. Energy Rev. 54 (2016) 1240–1249.
[6] P.M. Cuce, S. Riffat, A comprehensive review of heat recovery systems for building applications, Renew. Sustain. Energy Rev. 47 (2015) 665–682.
[7] S. Abdullah, M.N.B.M. Zubir, M.R.B. Muhamad, K.M.S. Newaz, H.F. Oztop, M.S. Alam, K. Shaikh, Technological development of evaporative cooling systems and its integration with air dehumidification processes: a review, Energy Build. 283 (2023) 112805.
[8] U.H. Kumar, S.I. Hussain, S. Kalaiselvam, Energy-efficient low-temperature activated desiccant wheels with nano-desiccant-coated fiber matrix, J. Therm. Anal. Calorim. 148 (21) (2023) 11511–11533.
[9] M.M. Abd-Elhady, M.S. Salem, A.M. Hamed, I.I. El-Sharkawy, Solid desiccant-based dehumidification systems: a critical review on configurations, techniques, and current trends, Int. J. Refrig. 133 (2022) 337–352.
[10] A.A. Fajar, K. Tokimatsu, Building performance simulation of near zero energy building design in Indonesia, Sustain. Clean Build. 1 (1) (2024) 79–97.
[11] Y. Zhang, W. Wang, X. Zheng, J. Cai, Recent progress on composite desiccants for adsorption-based dehumidification, Energy 302 (2024) 131824.
[12] H. Liu, S. Sundarrajan, G.V. Kumar, S. Ramakrishna, Review on polymer materials for solid desiccant cooling system, Macromol. Mater. Eng. 308 (12) (2023) 2300176.
[13] R.H. Mohammed, M. Ahmadi, H. Ma, S. Bigham, Desiccants enabling energy-efficient buildings: a review, Renew. Sustain. Energy Rev. 183 (2023) 113418.
[14] G. Singh, R. Das, Performance analysis of evaporation and heat wheel-based building air conditioning systems, J. Energy Resour. Technol. 145 (3) (2023) 032101.
[15] Z. Ma, X. Liu, T. Zhang, Experimental investigation and effectiveness analysis of a desiccant wheel dehumidification system with low air humidity, Appl. Therm. Eng. 226 (2023) 120279.
[16] U. Hanifah, M.A. Karim, A. Haryanto, R. Alfiyah, A. Taufan, Experimental performance of A rotary desiccant wheel without honeycomb matrix structure: a preliminary study, IOP Conf. Ser. Mater. Sci. Eng. 1096 (1) (2021) 012043.
[17] T.S. Ge, Y. Li, R.Z. Wang, Y.J. Dai, Experimental study on a two-stage rotary desiccant cooling system, Int. J. Refrig. 32 (3) (2009) 498–508.
[18] O. Kara, E. Hurdogan, O. Buyukalaca, Analysis of dehumidification and humidity removal process of desiccant wheel, Euro. Mech. Sci. 1 (1) (2017) 9–14.
[19] E. Cheevitsopon, J.S. Jongyingcharoen, Drying in a desiccant wheel dehumidification system-assisted hot air dryer: desiccant wheel effectiveness and carrot drying, IOP Conf. Ser. Earth Environ. Sci. 301 (1) (2019) 012046.

[20] D. La, Y.J. Dai, Y. Li, R.Z. Wang, T.S. Ge, Technical development of rotary desiccant dehumidification and air conditioning: a review, Renew. Sustain. Energy Rev. 14 (1) (2010) 130–147.
[21] K.S. Rumbhad, P.V. Walke, V.P. Kalbande, M.A. Kumbhalkar, W. Khandv, Y. Nandanwar, M. Mohan, R. Jibhakate, Experimental investigation of desiccant dehumidification with four different combinations of silica gel desiccant wheel on indoor air quality, SN Appl. Sci. 5 (11) (2023) 277.
[22] Su X, Geng Y, Huang L, Li S, Wang Q, Xu Z, Tian S. Review on dehumidification technology in low and extremely low humidity industrial environments. Energy, 131793..
[23] S.S. Salins, S.K. Reddy, S. Kumar, Assessment of process parameters in a dehumidification process using biomass-based wood shoving as a packing material, Indoor Built Environ. 31 (2) (2022) 496–509, 2024.
[24] P.M. Cuce, Thermal performance assessment of a novel liquid desiccant-based evaporative cooling system: an experimental investigation, Energy Build. 138 (2017) 88–95.
[25] U.H. Kumar, S.I. Hussain, S. Kalaiselvam, Energy-efficient low-temperature activated desiccant wheels with nano-desiccant-coated fiber matrix, J. Therm. Anal. Colorim. 148 (21) (2023) 11511–11533.
[26] E. Cuce, P.M. Cuce, Y.N. Yılmaz, E. Alvur, Rotary desiccant wheel systems: a review, Turkish Journal of Electromechanics and Energy 8 (2) (2023) 56–65.
[27] R.P. Singh, R.K. Das, Progressive development and challenges faced by solar Rotary Desiccant-Based Air-Conditioning Systems: a review, Processes 9 (10) (2021) 1785.
[28] D. O'Connor, J.K. Coloutit, B.R. HuTurkish J. Electromech. Energyghes, A novel design of a desiccant rotary wheel for passive ventilation applications, Appl. Energy 179 (2016) 99–109.
[29] I.P. Koronaki, E. Rogdakis, T. Kakatsiou, Experimental assessment and thermodynamic analysis of a solar desiccant cooling system, Int. J. Sustain. Energy 32 (2) (2013) 121–136.
[30] M. Su, X. Han, D. Chong, J. Wang, J. Liu, J. Yan, Experimental study on the performance of an improved dehumidification system integrated with precooling and recirculated regenerative rotary desiccant wheel, Appl. Therm. Eng. 199 (2021) 117608.
[31] N. Subramanyam, M.P. Maiya, S.S. Murthy, Application of desiccant wheel to control humidity in air-conditioning systems, Appl. Therm. Eng. 24 (17–18) (2004) 2777–2788.
[32] M.A. Mandegari, H. Pahlavanzadeh, Introduction of a new definition for effectiveness of desiccant wheels, Energy 34 (6) (2009) 797–803.
[33] Y. Xue, Q. Li, R. Wang, T. Ge, Performance analysis of a rotary desiccant wheel using polymer material with high water uptake and low regeneration temperature, Int. J. Refrig. 158 (2024) 385–392.
[34] E. Cuce, Z. Nachan, P.M. Cuce, F. Sher, G.B. Neighbour, Strategies for ideal indoor environments towards low/zero carbon buildings through a biomimetic approach, Int. J. Ambient Energy 40 (1) (2019) 86–95.
[35] E. Cuce, P.M. Cuce, Homotopy perturbation method for temperature distribution, fin efficiency and fin effectiveness of convective straight fins with temperature-dependent thermal conductivity, Proc. IME C J. Mech. Eng. Sci. 227 (8) (2013) 1754–1760.