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# Sustainable solution for greenhouse cooling and dehumidification using high salinity bittern solution

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## ABSTRACT

Greenhouse cultivation, while offering year-round production, is often challenged by high temperatures and humidity, especially in arid and semi-arid regions. Traditional cooling and dehumidification techniques can be energy-intensive and environmentally unsustainable. This research explores a novel approach utilizing a high-salinity bittern solution as a desiccant to address these challenges. Bittern is a by-product of salt production. By leveraging the hygroscopic properties of salt solutions, this method offers a sustainable and energy-efficient alternative to conventional techniques. The proposed system aims to significantly reduce water consumption and minimize reliance on energy-intensive cooling technologies. A laboratory-scale dehumidifier column was employed to simulate both the dilution and regeneration processes of the desiccant. The performance of bittern was compared to a well-established desiccant lab-grade $CaCl_2$. The results indicate the potential of the by-product brine water as a promising solution for sustainable greenhouse agriculture. The bittern solution has proven to be a viable and effective alternative to traditional chemical desiccants. The experimental data show that bittern performs comparably to $CaCl_2$ in terms of its ability to extract moisture from humid air under controlled conditions. This finding is significant because bittern solution is more readily available, cost-effective, and environmentally friendly compared to synthetic desiccants.

**Keywords:** greenhouse cooling, sustainability, bittern solution, salt production.

## INTRODUCTION

Water scarcity poses a pressing challenge in Egypt, prompting the exploration of innovative technologies to conserve water, particularly in irrigation practices. With agriculture consuming a significant portion of Egypt's water resources, the adoption of new water-saving technologies is crucial for sustainable farming (Amer et al., 2017). Techniques such as drip irrigation, precision irrigation systems, and soil moisture sensors enable precise water delivery to crops, reducing waste and optimizing water usage. Furthermore, the integration of smart water management technologies and recycled water systems offers promising solutions to alleviate water scarcity pressures and promote efficient agricultural practices within arid environment (Siddique, 2021).

The evolution of irrigation methods from traditional surface irrigation to sprinkler systems, and eventually to drip irrigation, culminates in the sophisticated practices within greenhouses (Singh, 2012). Progressing through these irrigation techniques signifies a trajectory towards precision, efficiency, and sustainability in agriculture. Drip irrigation, particularly prevalent in greenhouse settings, allows for targeted water delivery directly to plant roots, minimizing water loss to evaporation and runoff (De Pascale et al., 2019). This transition underscores a commitment to optimizing water resources, enhancing crop yields, and reducing environmental impact.

Greenhouses offer substantial benefits in enhancing water use efficiency compared to traditional open-field cultivation methods (Nicola et al., 2020). The controlled environment within greenhouses allows for precise management of watering schedules, reducing water loss through evaporation and runoff. Techniques such as drip irrigation and hydroponics optimize water delivery directly to plant roots, minimizing wastage (Rajaseger et al., 2023). Additionally, greenhouse technologies like automated irrigation systems and climate control mechanisms enable tailored water utilization based on plant requirements, further enhancing efficiency. By conserving water resources and promoting sustainable practices, greenhouses play a vital role in increasing agricultural productivity while minimizing environmental impact (Singh et al., 2024).

Closed greenhouses offer distinct advantages over other greenhouse types due to their advanced design and control capabilities. Compared to traditional greenhouses, closed systems provide precise regulation of environmental factors such as temperature, humidity, and light intensity, optimizing conditions for plant growth. This level of control enhances crop productivity and quality while reducing energy consumption (De Gelder et al., 2012). Closed greenhouses also offer better protection against pests and diseases, leading to healthier crops and higher yields. Additionally, their efficient use of resources, including water and nutrients, contributes to sustainable agricultural practices.

Closed greenhouses in arid and semi-arid areas face significant challenges in maintaining optimal growing conditions. High temperatures and relative humidity can lead to plant stress and reduced yield. Dehumidification is crucial to prevent diseases and maintain proper plant development. Cooling systems are essential to regulate temperature and prevent heat stress. However, traditional cooling methods can be energy-intensive and unsustainable in these regions (Vadiee and Martin, 2012). Innovative solutions are needed to develop efficient and eco-friendly dehumidification and cooling technologies that minimize water and energy consumption, ensuring sustainable and productive greenhouse operations in challenging climatic conditions (Cuce et al., 2016; Soussi et al., 2022).

Desiccants offer a promising solution for greenhouse cooling and dehumidification, especially in arid and semi-arid regions (Al Sharif et al., 2025). These materials absorb moisture from the air, reducing humidity levels and creating a more favorable environment for plant growth. Desiccant-based systems offer several benefits, including energy efficiency, reduced water consumption, and precise control over humidity levels. By using renewable energy sources to power the regeneration process, desiccant systems can contribute to sustainable greenhouse operations (Lefers et al., 2016). Additionally, they can be integrated with other cooling technologies, such as evaporative cooling, to further optimize energy use and enhance overall greenhouse performance (Amani et al., 2020; Sultan et al., 2021).

One of the most promising concepts for improving resource efficiency in closed greenhouses is the Watergy system, which integrates energy and water management into a single cycle. The Watergy concept, when integrated with desiccant technology, offers a sustainable and efficient approach to greenhouse climate control (Buchholz et al., 2004; Janssen et al., 2005; Jochum et al., 2006). By combining solar energy, water, and desiccant materials, this innovative system can effectively manage temperature and humidity levels within the greenhouse. Solar energy can be used to power the desiccant regeneration process, while the recovered heat can be utilized to warm the greenhouse or other parts of the system (Nour et al., 2015). Additionally, the dehumidified air can be cooled using water-based technologies, such as evaporative cooling, further enhancing the system's energy efficiency. This integrated approach minimizes reliance on external energy sources and reduces the overall environmental impact of greenhouse operations.

Several types of commercial desiccants are commonly used in greenhouse cooling and dehumidification systems (Lefers et al., 2016). Solid desiccants, such as silica gel and activated alumina, are highly effective at absorbing moisture from the air. Liquid desiccants, like lithium chloride and calcium chloride solutions, offer flexibility and can be regenerated using heat or chemical processes. Solid desiccants generally have a higher capacity for moisture absorption but require careful handling and regeneration. Liquid desiccants, on the other hand, can be more easily regenerated but may have limitations in terms of capacity and operating temperature range (Misha et al., 2012). The choice of desiccant depends on various factors, including the specific requirements of the greenhouse, the available energy source, and the desired level of humidity control.

One of the challenges associated with using desiccants in greenhouse cooling and dehumidification systems is the gradual dilution of the desiccant's effectiveness throughout the day

(Mohammed et al., 2023). As plants undergo evapotranspiration, they release moisture into the air, which is then absorbed by the desiccant. This process leads to a decrease in the desiccant's concentration, reducing its ability to efficiently remove moisture from the greenhouse environment. To mitigate this issue, various strategies can be employed, such as periodic regeneration of the desiccant (Shukla and Modi, 2017), optimizing the airflow patterns within the greenhouse, and using desiccants with higher moisture absorption capacities (Soussi et al., 2022).

To restore the desiccant's moisture-absorbing capacity, a nighttime regeneration process can be implemented. This involves reversing the day cycle, where dry, cooler night air is drawn through the desiccant bed. As the cooler, dry air passes over the hot, diluted desiccant, it absorbs moisture from the desiccant, effectively concentrating it (Nour et al., 2015). This process not only regenerates the desiccant but also pre-cools the incoming air, reducing the energy demand for daytime cooling. By optimizing the airflow and temperature control during the nighttime regeneration, the desiccant's performance can be maintained throughout the day, leading to improved greenhouse climate control and energy efficiency (Almashharawi et al., 2024).

Bittern solution, a concentrated salt solution that is available as a byproduct of table salt production, can be used as a desiccant in greenhouse cooling and dehumidification systems (Soussi et al., 2025). It is the concentrated liquid left after table salt (sodium chloride) has crystallized out of seawater and is mainly composed of magnesium chlorides and magnesium sulfates. It offers several advantages over traditional solid desiccants, including lower cost, easier handling, and potential for regeneration using renewable energy sources. However, bittern solution has limitations compared to commercial desiccants. The corrosive nature of bittern solution necessitates the use of specific materials for the system components. While bittern solution shows promise as a potential desiccant, further research and development are needed to optimize its performance and address its limitations. This research attempts to provide a comprehensive study of the use of bittern solution as a desiccant inside agricultural greenhouses and the extent to which it is possible to make agriculture sustainable inside greenhouses by regenerating it during the day and night cycles.

## MATERIAL AND METHODS

### Experiment setup

A laboratory experiment was designed using a cylindrical column that enables air to flow and interact with a cool desiccant (which resembles desiccant that has been cooled and regenerated during the night cycle in a greenhouse). The objective is to assess the desiccant's properties and its capacity to absorb heat and moisture from the air, comparing a high-salinity bittern solution with a known desiccant $CaCl_2$. The setup simulates the daytime cycle in closed greenhouses, where air enriched with heat and moisture is generated due to plant evapotranspiration. This air is drawn by fans inside the greenhouse and directed toward the desiccant to reduce its heat and moisture content, helping prevent excessive temperature and humidity levels that may harm plants.

The experimental model is a transparent cylindrical column, approximately 19 cm in diameter. It allows hot, moist air to enter from the bottom and flow upward, while the cooler desiccant moves from top to bottom within the sealed column. A middle section facilitates contact between air and desiccant, allowing heat and moisture transfer from the air to the desiccant. The column consists of three primary parts:

Lower part (air inlet) – this section has an opening with an extraction fan installed, pulling in hot, humid air into the column. A hot air source is placed in front of the fan. An outlet below this section lets the desiccant exit into a small tank. Middle part: Extending approximately 30 cm high, this part contains filler media to increase the surface area, enhancing contact between the air and desiccant for efficient heat and moisture transfer. Upper part: This part includes an outlet with an exhaust fan for releasing cooled, dehumidified air. A spray system at the top distributes the desiccant.

A small tank stores the desiccant, with a pump installed to circulate it throughout the system (Figure 1). The experiment begins by activating a water boiler that generates hot, humid air. Both column fans are turned on: the bottom one pulls in the moist air, and the upper one expels it. This continues for about five minutes until the column reaches the desired relative humidity. Then, the desiccant pump is switched on, allowing the solution to flow from the top down. The experiment runs for roughly one hour while measurements are taken. The short time (one hour) duration has been chosen as it isolates the effect of salinity while avoiding complications from dilution through the experiment. Also, it provides repeatable and controlled results, while the long-term performance has been assessed as the repeated cycles were used for the same desiccant.

This experimental setup simulates daytime greenhouse conditions, where desiccant removes heat and moisture from air affected by evapotranspiration. Over the day, the desiccant absorbs moisture and becomes diluted, reducing its effectiveness. Thus, regeneration is required at night to maintain long-term use and sustainability. Desiccant regeneration has been the focus of numerous studies, aiming to identify efficient and sustainable methods for restoring the drying capacity of desiccants after moisture absorption. Common regeneration systems include thermal regeneration (Oladosu et al., 2021), where external heat sources are used to evaporate the absorbed moisture; solar regeneration (Cheng and Zhang, 2013), which utilizes solar collectors or greenhouses to harness solar energy; and ventilation-based regeneration, which relies on ambient air movement, often during cooler periods, to remove moisture. Other techniques involve chemical or vacuum-based regeneration (Gurubalan and Simonson, 2021), which are more complex and typically used in industrial applications.

In the context of this experiment, the focus was on evaluating the feasibility of using the natural temperature difference between day and night, alongside the thermal energy retained in the desiccant during the day cycle. This passive regeneration approach offers a low-energy alternative by leveraging environmental conditions, particularly in closed greenhouse systems, where temperature fluctuations are common. Such a method could support sustainable, continuous operation without the need for external energy inputs, making it ideal for agricultural applications.

The same column has been reused in a second experiment with slight adjustments. The boiler has been removed, allowing ambient air to be drawn by the lower fan (Figure 2). The process is repeated, enabling this cooler air to interact with the saturated desiccant. The ability of the ambient air to extract moisture from the desiccant is evaluated, and measurements are recorded.

## Measuring tools

Various measurements were conducted throughout the experiment, encompassing data collection before, during, and after the experiment. These measurements were essential for assessing and analyzing the performance of the column and the desiccant. The key parameters that were measured include the following (salinity of desiccant before and after each experiment, the inlet and

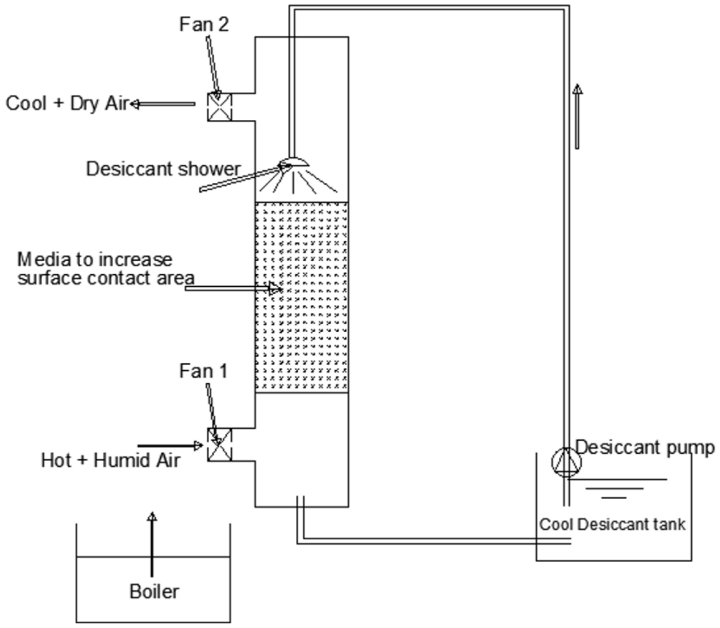

**Figure 1.** Experimental setup for the day cycle (desiccant dilution)

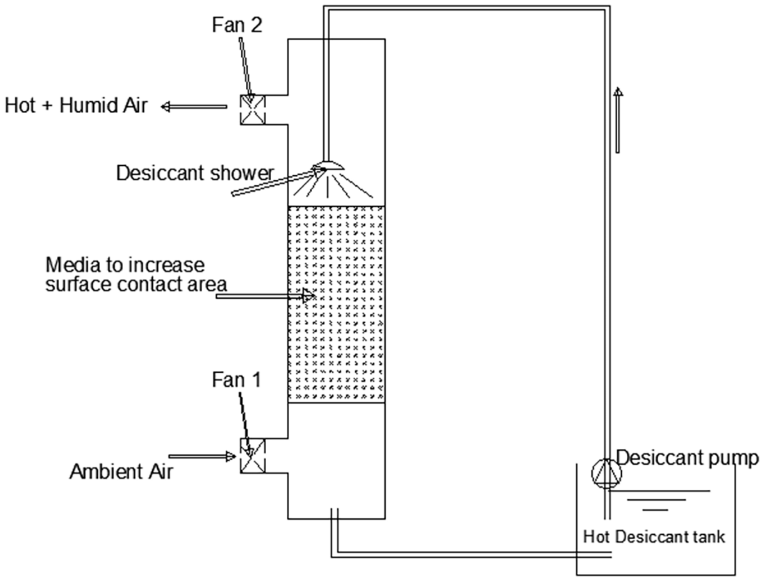

**Figure 2.** Experimental setup for the night cycle (desiccant regeneration)

outlet air temperature and humidity through the experiment, the flow rate of the desiccant, the flow rate of the air inlet and the initial desiccant volume in each experiment), while the duration of all experiments is fixed at one hour. Each parameter was quantified using specific methods and instruments to ensure accuracy and reliability.

The salinity of the desiccant was measured using a Conductivity-TDS-TEMP Meter (AD-330). This versatile handheld device measures conductivity, total dissolved solids (TDS), and liquid temperature. It is widely used in environmental monitoring, water quality testing, and industrial fields. The salinity measuring range of the AD-330 is from 0 to 100 ppt. Since the desiccant used in the experiments can reach salinity levels up to 350 ppt, dilution before measurement is necessary. A sample is diluted using a 1:20 ratio (1 part desiccant to 20 parts water), and the salinity of the diluted sample is then measured. The actual salinity of the original desiccant can easily be calculated from this reading.

Temperature and relative humidity (RH%) were measured using the TM-305U device, which was set to record data at 1-minute intervals. This device provides high accuracy, with a temperature precision of 0.6 °C and a 3% accuracy for RH% readings. Continuous monitoring of these values allowed for a detailed analysis of temperature and humidity fluctuations over time, for both incoming and outgoing air in the system.

The desiccant flow rate was determined based on the specifications of the pump used and verified manually using a small container of known volume. The time required to fill the container with circulating desiccant was recorded, and the flow rate was then calculated. Efforts were made to maintain a consistent desiccant discharge of 0.05 L/s during all trials. The inlet air flow rate was estimated by knowing the fan's revolutions per minute (RPM) and its diameter. Throughout the experiment, the air flow rate was kept steady at approximately 4 $m^3/h$.

## Experimental plan

A large number of experiments have been conducted on both types of desiccants (Bittern solution and lab-grade $CaCl_2$), and the results have been compared. This comparison was done for both the day cycle (desiccant dilution) and the night cycle (desiccant regeneration) using the experimental column and taking all the necessary readings as explained above.

The experiments were conducted using desiccants with different salinity levels (0, 100, 150, 200, and 250 ppt) to investigate the influence of salinity on the desiccant's ability to remove heat and moisture from the air. The reason of choosing the range from (0 to 250 ppt) because the typical salinity of bittern solution ranges from about 250 to 300 ppt. Therefore, 250 ppt was selected as the upper limit in this study, while 0 ppt was used to represent fresh water. In this way, the selected range covers almost the entire practical range of bittern solution.

The objective was also to evaluate the performance of the saline industry by-product bittern solution as a potential replacement for a conventional lab-grade desiccant such as $CaCl_2$. All experimental conditions including desiccant flow rate, air flow rate, duration, column diameter, contact length within the column, and initial desiccant volume (10 L at the start of each test) were kept constant to ensure that the observed effects were solely due to variations in desiccant salinity for both bittern solution and $CaCl_2$.

The experiment was conducted in multiple stages. The initial stage focused on evaluating both desiccants at varying salinity levels to observe how salinity influences their efficiency in extracting moisture and heat from the air. A comparative analysis was performed between the bittern solution and the $CaCl_2$ solution.

## RESULTS

During each trial, the TM-305U was used to record temperature and humidity for both the air entering and exiting the column, helping to assess the variations in these parameters throughout the experiment. Some of the recorded data from this device are presented in Figures 3 to 4. These figures show the temperature and humidity at both the inlet and outlet locations during testing with a salinity level of 250 ppt for both desiccants – bittern solution and $CaCl_2$. Similar graphs were produced for each tested salinity level for both materials. The average values of inlet and outlet air temperature and humidity were then calculated and used for analysis.

After conducting tests at various salinity levels for both desiccants, the required readings were collected. Several graphs were generated to demonstrate how desiccant initial salinity influences temperature and humidity, as well as to highlight the degree of this impact throughout the experiment. Figures 5 and 6 illustrate the extent of this influence.

The figures highlight the effectiveness of both $CaCl_2$ solution and bittern solution in significantly reducing humidity at higher salinity levels, particularly around 250 ppt. This dehumidification capability steadily declines as salinity decreases. There is a sharp change in drying effectiveness for both solutions around a salinity of 150 ppt, and becomes nearly negligible when salinity drops to 100 ppt. The significant drop in efficiency below 150 ppt is attributed to the sharp reduction in vapor pressure. The solution approaches dilute conditions which leads to weaker hygroscopic behavior. This observation indicates the concentration at which regeneration would be most effective.

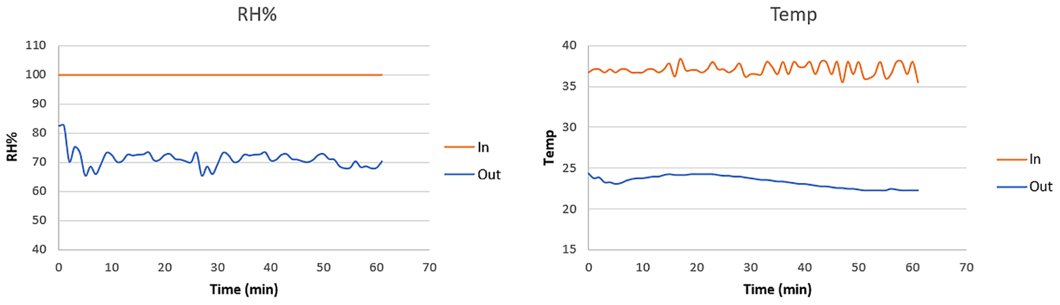

**Figure 3.** Inlet and outlet air RH% and temperature using $CaCl_2$ solution at salinity (250 ppt)

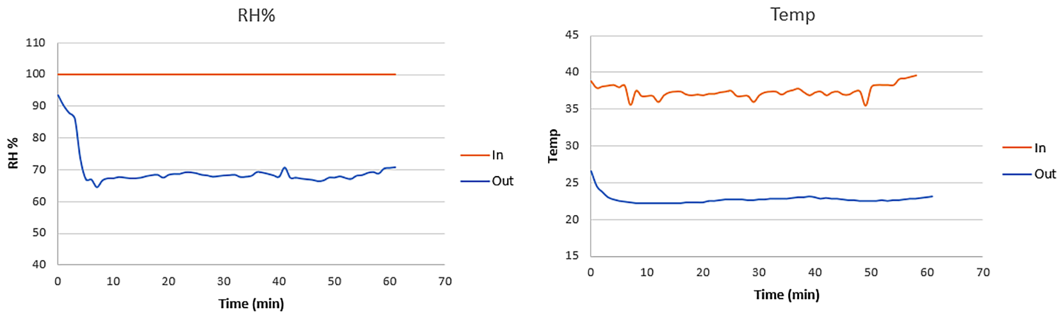

**Figure 4.** Inlet and outlet air RH% and temperature using bittern solution at salinity (250 ppt)

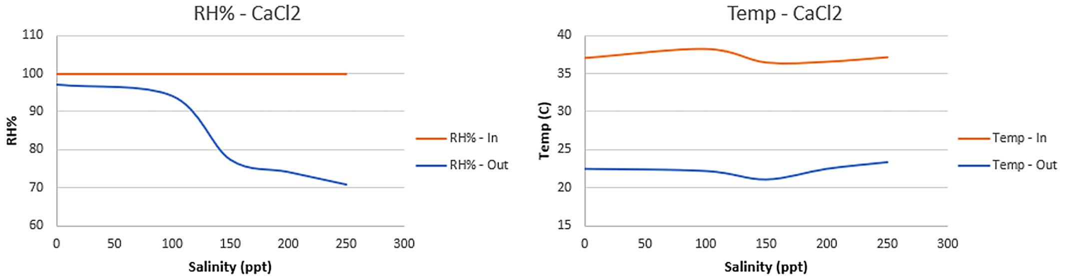

**Figure 5.** Average inlet air and outlet air RH% and temperature using $CaCl_2$ solution at different salinities

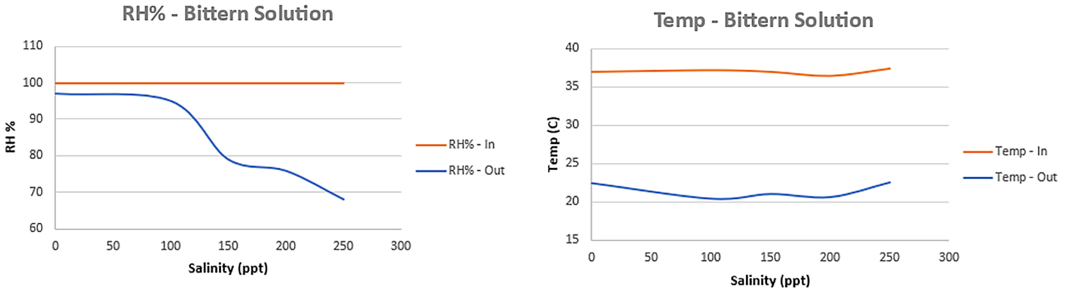

**Figure 6.** Average inlet air and outlet air RH% and temperature using bittern solution at different salinities

Additionally, the figures above show that variations in salinity have little effect on temperature reduction, as the difference between inlet and outlet air temperatures remains nearly constant at different salinity levels. This is because salinity mainly influences humidity by controlling moisture absorption (mass transfer), while its effect on air temperature is limited due to its weak influence on heat exchange (energy transfer).

These observations suggest that bittern solution performs comparably to CaCl₂ in reducing humidity, making it a viable alternative desiccant for use in greenhouse applications.

The same set of experiments was also used to monitor changes in salinity throughout the day cycle for both CaCl₂ solution and bittern solution. Results showed a significant drop in salinity during the experiment at higher initial salinities for both desiccants. However, this reduction gradually diminished as the starting salinity decreased, becoming almost unnoticeable at 100 ppt, as illustrated in Figures 7 and 8.

The experiment was conducted more than twenty times for both desiccants to simulate the night cycle to assess the potential for desiccant regeneration during nighttime conditions. Figure 9 presents a sample of the recorded data showing

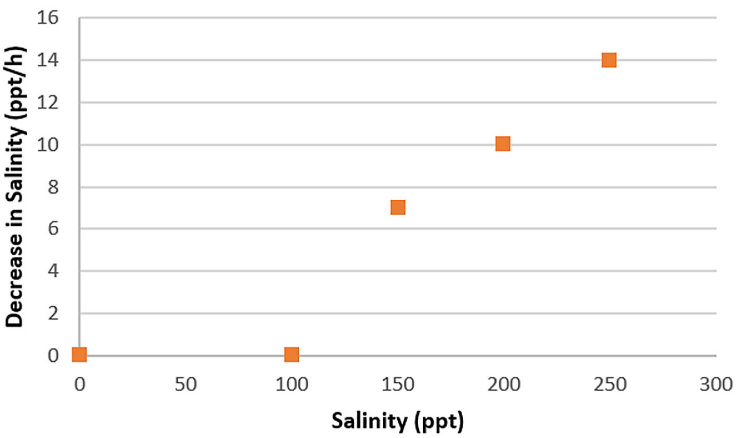

**Figure 7.** Rate of decrease in salinity for $CaCl_2$ solution at different salinities during day cycle

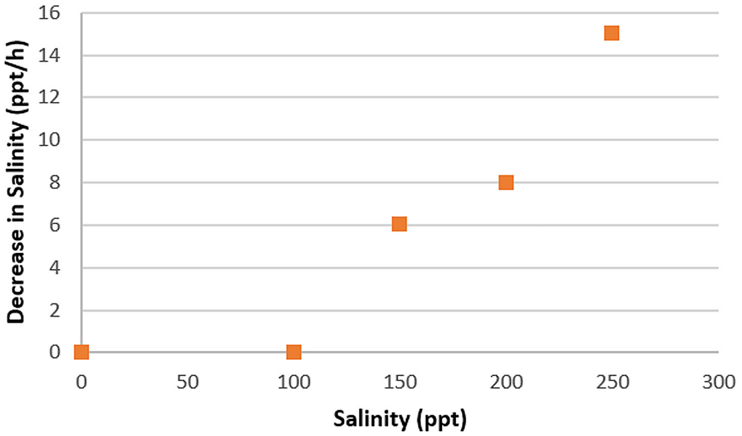

**Figure 8.** Rate of decrease in salinity for bittern solution at different salinities during day cycle

the characteristics of the air entering and exiting the column during the night cycle simulation. It was observed that the outlet air showed a slight increase in humidity compared to the inlet air, indicating that the air was able to absorb moisture from the diluted, moisture-laden desiccant.

This experiment was repeated at various salinity levels, and average temperature and humidity readings for both inlet and outlet air were collected during each trial. These results were compiled and illustrated graphically to analyze the regeneration effect across different salinities.

The experimental results demonstrate the effectiveness of the regeneration process for both bittern solution and $CaCl_2$ solution. As shown in Figure 10, the regeneration rate for $CaCl_2$ remains nearly consistent across various salinity levels. Similarly, Figure 11 shows that bittern solution also maintains a relatively steady regeneration rate at different salinities. However, a notable observation is that the regeneration rate for bittern solution is higher compared to that of $CaCl_2$.

The regeneration rate was also found to vary with desiccant temperature, increasing as the temperature of the desiccant rises. This effect was further investigated using the same experimental setup to study how temperature influences regeneration efficiency. Figures 12 and 13 illustrate that higher desiccant temperatures lead to improved regeneration rates for both $CaCl_2$ solution and bittern solution, even though the variations in temperature between experiments were relatively small.

## DISCUSSION

The following phase of the research concentrated on a more in-depth investigation of bittern solution. To achieve a clearer understanding of its performance during both the day and night cycles, the previous experiments were repeated using a wider range of salinity levels.

### Daytime cycle

To investigate this part, a wider range of bittern solution salinity levels was tested, aiming to create graphical representations and assess their influence. The day cycle experiment was repeated

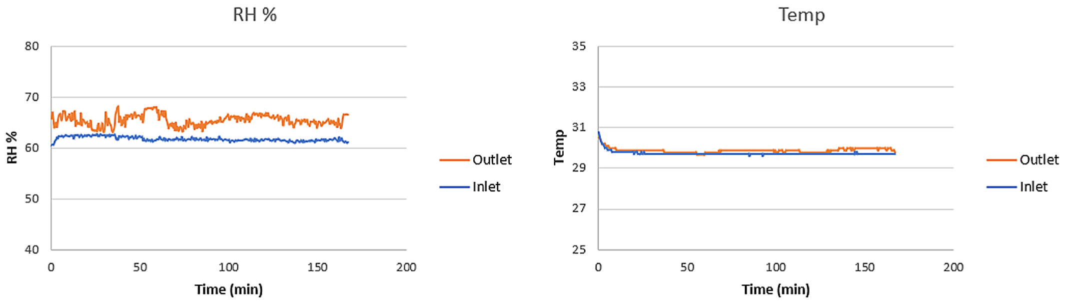

**Figure 9.** Inlet and outlet air RH% and temperature using bittern solution at salinity (150 ppt)

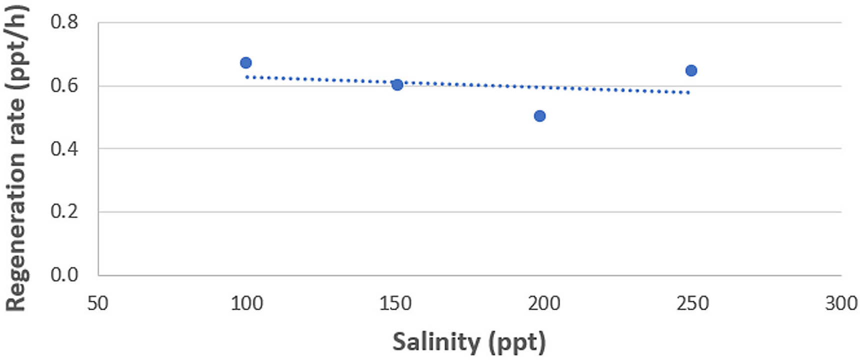

**Figure 10.** Rate of increase in salinity for CaCl$_2$ solution at different salinities during night cycle

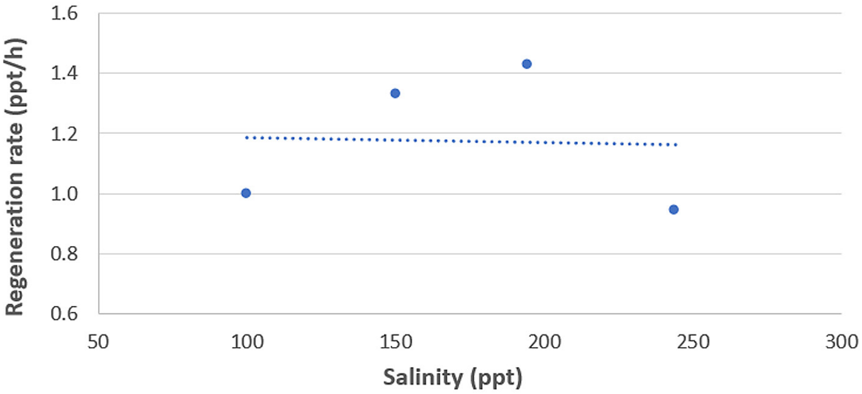

**Figure 11.** Rate of increase in salinity for bittern solution at different salinities during night cycle

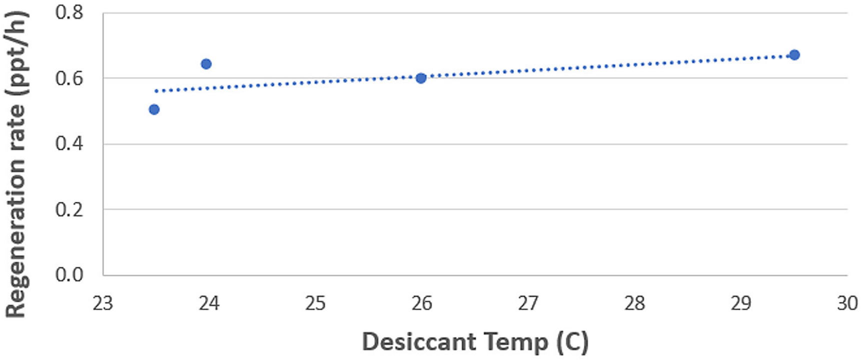

**Figure 12.** Rate of increase in salinity for CaCl$_2$ solution at different desiccant temperature

twenty times at different salinities, and the results are shown in Figure 14. These results reveal that the desiccant's ability to remove moisture from the air gradually declines as salinity decreases, with a noticeable drop in performance once salinity falls to around 150 ppt. This confirms the conclusions drawn from earlier experiments. Additionally, at higher concentrations nearing 350 ppt, the desiccant shows excellent efficiency in moisture removal. Throughout all experiments, the inlet air relative humidity was consistently maintained at 100%. It is interesting to note that there is a change in the rate of drop of effectiveness around a salinity of 300 ppt, and another, more gradual one, around a salinity of 150 ppt.

Changes in relative humidity (RH%) alone may not fully reflect the actual reduction in moisture content in the air. Therefore, calculating absolute humidity provides a clearer understanding of the desiccant's effectiveness in removing moisture.

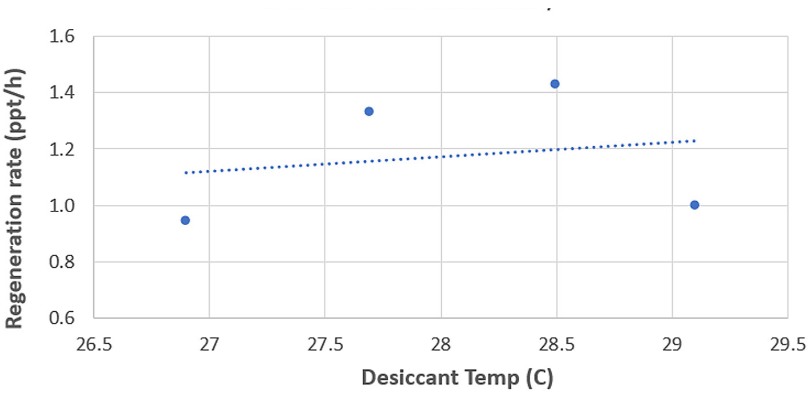

**Figure 13.** Rate of increase in salinity for bittern solution at different desiccant temperature

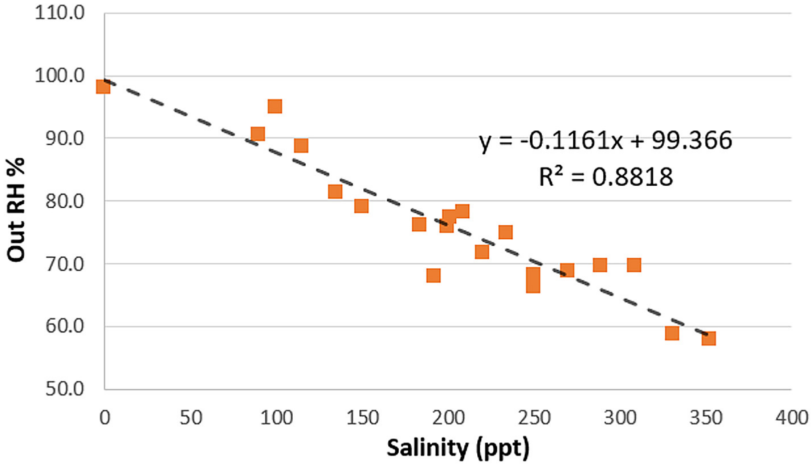

**Figure 14.** Average outlet air RH% using bittern solution at different salinities

To calculate absolute humidity, which represents the actual mass of water vapor in a given volume of air (typically expressed in grams per cubic meter), both temperature and relative humidity (RH%) are required. The calculation involves determining the saturation vapor pressure at a given temperature and then applying the relative humidity to find the actual vapor pressure. The absolute humidity (AH) can be calculated using the formula:

$$AH = 6.112\, e^{17.67\frac{T}{T+243.5}} \cdot RH \cdot \\ \cdot 2.1674 \,/\, (273.15 + T) \qquad (1)$$

where: $T$ – is the air temperature in degrees Celsius, $RH$ – is the relative humidity in percent (as a decimal, e.g., 60% = 0.60),

The constants are derived from the Clausius-Clapeyron equation and gas law relationships. This formula gives the absolute humidity in grams of water vapor per cubic meter of air (g/m³). By using this method during experiments, a more accurate and quantitative assessment of moisture removal by the desiccant can be obtained, as it directly reflects the amount of water removed from the air, regardless of temperature variations.

The variation in absolute humidity across different salinity levels was calculated and graphically represented to better define the active range of the desiccant. Figure 15 illustrates how absolute humidity changes with salinity. A significant drop in absolute humidity is observed at higher salinity levels, with the change gradually diminishing past 150 ppt and stabilizing around 100 ppt. The desiccant's ability to reduce absolute humidity increases noticeably from 100 ppt to around 250 ppt, but further increases beyond 250 ppt show only minimal improvement. The slight reduction in absolute humidity at low salinities (below 100 ppt) is mainly due to the temperature difference between the inlet and outlet air, as the desiccant's ability to lower RH% becomes negligible, as shown previously in Figure 14.

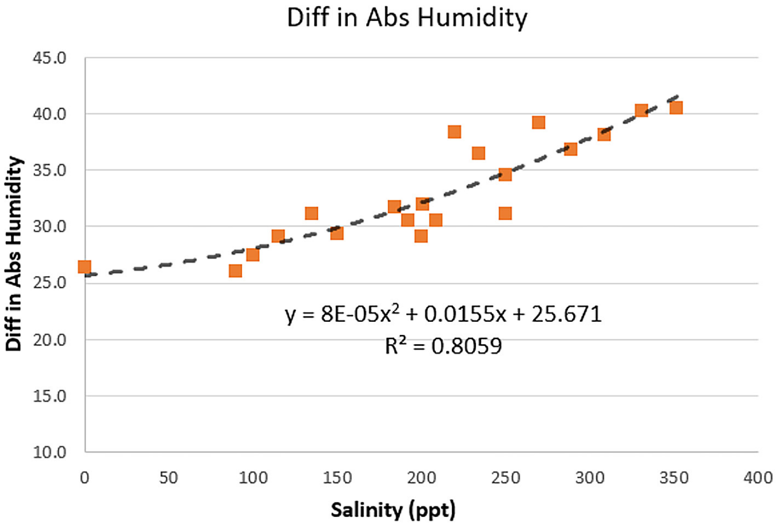

**Figure 15.** Reduction in abs. humidity between in & out air using bittern solution at different salinities

Based on Figures 14 and 15, the effective operating range of the desiccant appears to be between 150 and 250 ppt. Beyond 250 ppt, there is little added benefit in moisture removal. In contrast, from 150 to 100 ppt, there is a noticeable decline in desiccant performance, and at salinities below 100 ppt, the desiccant behaves similarly to fresh water in its ability to reduce air humidity.

The variation in desiccant salinity across different experiments is illustrated in Figure 16, providing clearer insight into how salinity decreases during the experiment at various starting levels. This information is particularly valuable for conducting a comprehensive feasibility study, as it helps estimate the expected salinity at the end of each day cycle and the corresponding regeneration required to maintain sustainable operation.

Figure 16 also highlights the rate of change in salinity when the same experiment is conducted at different initial salinities. It is evident that this rate is strongly influenced by the starting salinity of the desiccant. This is expected, as higher salinity levels enable the desiccant to absorb greater amounts of moisture, resulting in a more pronounced change in salinity. Conversely, as the salinity decreases, the desiccant's moisture absorption capacity diminishes, leading to a slower rate of salinity change. These findings are essential for informing the design of a regeneration strategy as part of a broader sustainability plan.

## Nighttime cycle

Additional experiments were carried out using desiccants at various salinity levels to examine how

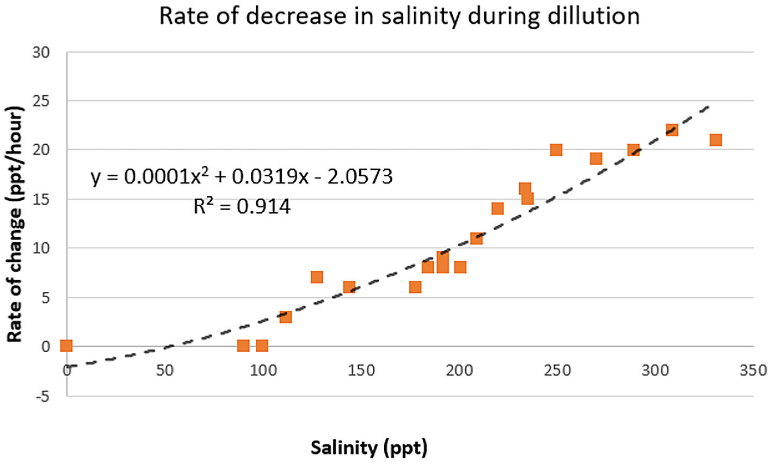

**Figure 16.** Reduction in bittern solution salinity at the day cycle

salinity influences the regeneration process. The results of these tests are presented in Figures 17 to 18.

Figure 17 indicates that increasing the salinity of the desiccant has little to no significant impact on the regeneration process. In contrast, Figure 18 demonstrates a clear relationship between desiccant temperature and regeneration efficiency, showing that the regeneration process improves as the desiccant temperature increases.

Therefore, the night cycle experiment was repeated at various desiccant temperatures to investigate the impact of temperature on the regeneration process. The average temperature of the desiccant was gradually increased throughout the trials.

The results, shown in Figure 19, reveal that the desiccant's ability to regenerate during the night cycle improves with rising temperature, up to around 45 °C. Beyond this point, the regeneration process tends to stabilize, showing little additional improvement with further temperature increases.

Additional experiments were carried out during the night cycle at desiccant temperatures near 45 °C to assess how salinity influences the regeneration process under these conditions. As shown in Figures 20 and 21, varying the salinity of the desiccant results in a slight improvement in regeneration performance. A modest increase in regeneration rate is also observed when desiccant temperatures exceed 45 °C. These results suggest that the optimal temperature for regeneration is around 45 °C.

The final conclusion indicates that the highest regeneration rate for bittern solution during the night cycle falls within the range of approximately 4.0 to 4.5 ppt/hour. This optimal rate is achievable when the bittern solution temperature is maintained at 45 °C or higher.

Based on the summarized experimental data, several practical conclusions can be drawn regarding the use of bittern solution as a desiccant in greenhouse environments.

The experimental column was scaled to model greenhouse conditions, where the bittern solution desiccant system included a fan capacity of 4.000 m³/h, a desiccant flow rate of 50 L/s, and a 10 m³ desiccant tank – scaling the lab model by a factor of 1.000. The greenhouse was

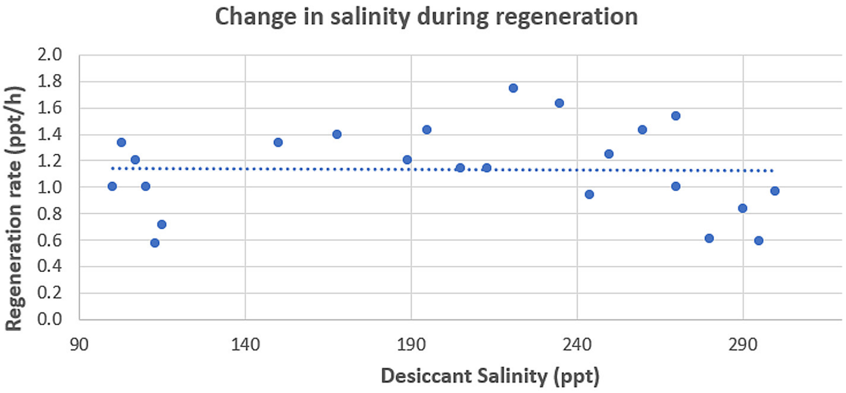

**Figure 17.** Rate of increase in salinity at different salinities during night cycle

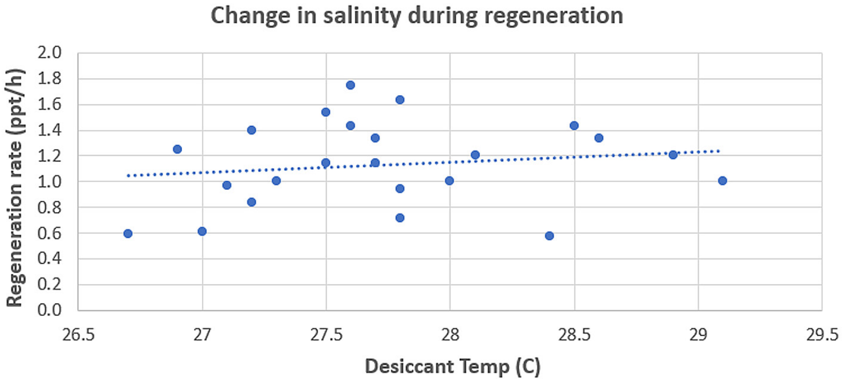

**Figure 18.** Rate of increase in salinity at different desiccant temperature

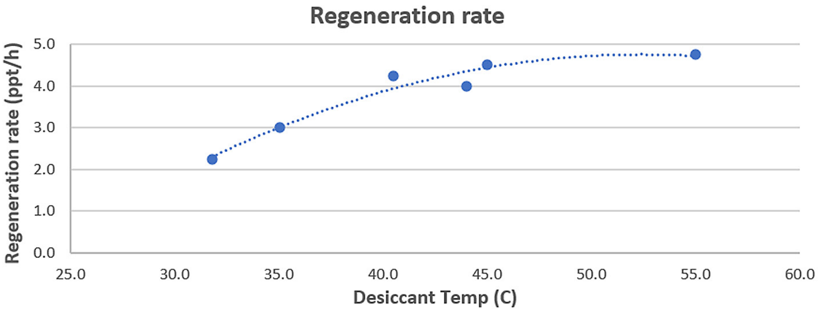

**Figure 19.** Rate of increase in salinity at different desiccant temperature

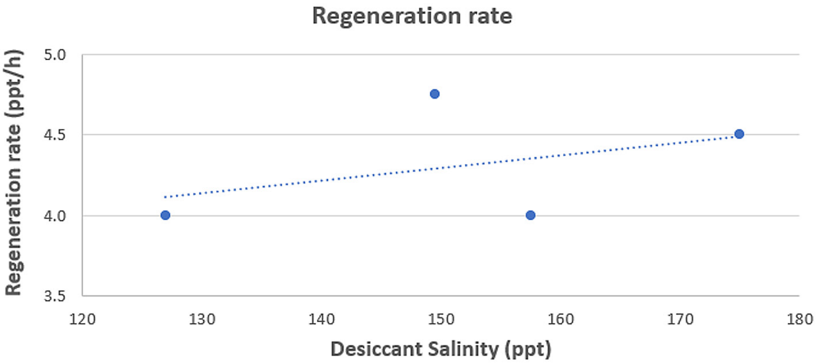

**Figure 20.** Rate of increase in salinity at different desiccant salinities

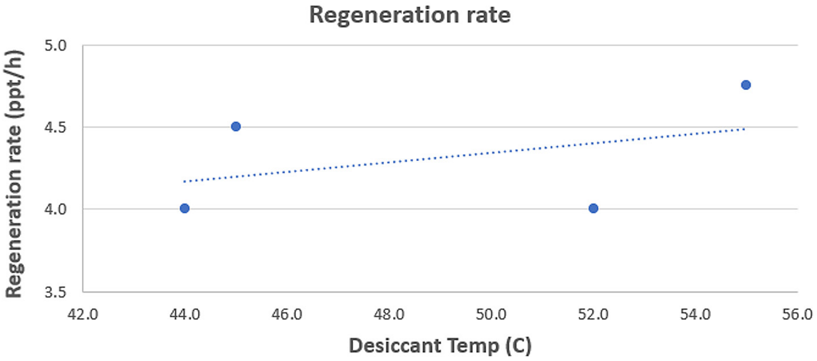

**Figure 21.** Rate of increase in salinity at different desiccant temperature

assumed to have a volume of 680 m³ (based on a width of 8 m, length of 20 m, and elevation area of 34 m²). The daily evapotranspiration (ET) from the plants was estimated at 960 liters over a 12-hour day, corresponding to 6 mm/day under Cairo climate conditions.

From the experiments, it was found that bittern solution at salinity levels of 150 to 300 ppt can effectively remove between 0.4 to 0.7 liters of water per 10 liters of desiccant per hour. Thus, 10 m³ of bittern solution is sufficient to remove the full 960 L of moisture generated in a typical greenhouse day. However, this dehumidification process dilutes the desiccant. For instance, using 10 m³ of desiccant at 300 ppt to extract 960 L of water reduces the salinity to about 273.7 ppt by the end of the day.

Regeneration of the desiccant is needed during the night before another day cycle start. According to experimental findings, ambient air at 20 °C can regenerate the desiccant at a rate of approximately 1.15 ppt/hour, while air at 45 °C can increase the regeneration rate to about 4.0 ppt/hour. Assuming equal 12-hour day and night cycles, desiccant at 20 °C would only recover to about 287.5 ppt overnight, leading to a gradual decline in efficiency over time. In contrast, if the desiccant temperature reaches 45 °C, it can be fully regenerated back to 300 ppt, ensuring continuous operation without needing replacement. While desiccant temperature increases naturally during the day, it is difficult to predict the exact end-of-day temperature due to variability in greenhouse conditions. To ensure sustainability, heating the desiccant to 45 °C after the day cycle may be needed. These findings show strong potential for closed-loop operation.

When applying these findings to a real greenhouse, results might vary slightly, and the desiccant may need replacement after a certain number of day and night cycles. This is where the use of high-saline bittern solution becomes highly advantageous. It offers nearly comparable drying capabilities to more expensive alternatives like $CaCl_2$, while being an extremely low-cost substitute as it's a by-product of desalination plants. Consequently, even if replacement is necessary after several cycles, high-saline bittern solution presents a sustainable and cost-effective solution for farming within closed greenhouses.

## CONCLUSIONS

Based on the results obtained from the series of experiments, several important findings have emerged that highlight the potential of bittern solution as a sustainable desiccant for use in closed agricultural environments such as greenhouses.

Firstly, bittern solution has proven to be a viable and effective alternative to traditional lab-gradw $CaCl_2$, one of the most widely used drying agents. The experimental data showed that bittern solution performs comparably to $CaCl_2$ in terms of its ability to extract moisture from humid air under controlled conditions. This finding is significant because bittern solution is more readily available, cost-effective, and environmentally friendly compared to synthetic desiccants.

One of the critical parameters affecting the performance of bittern solution is its salinity. The experiments clearly demonstrated that the desiccant is only effective when its salinity remains above 150 ppt. At salinity levels below this threshold, the moisture absorption capacity of the bittern solution begins to decline rapidly. By the time salinity drops to 100 ppt, the desiccant becomes almost completely ineffective, offering negligible reduction in humidity. This highlights the importance of monitoring salinity levels during operation to ensure optimal performance.

Keeping the bittern solution salinity of around 200 ppt is optimal, with a practical range between 180 and 220 ppt. Within this range, the desiccant provides good moisture absorption, while the reduction in salinity due to dilution is less significant compared to higher concentrations. In addition, this salinity level can be easily obtained as a by-product from brine solutions.

In terms of regeneration, bittern solution again shows favorable characteristics. The experiments indicated that it outperforms $CaCl_2$ in regeneration efficiency, especially at room temperature. This advantage could significantly reduce energy consumption and operational costs associated with desiccant regeneration in practical applications.

Furthermore, the study confirms that the night cycle can be utilized effectively for the regeneration process. When the desiccant temperature is increased to around 45 °C or higher, the regeneration rate improves notably. This suggests that passive or low-energy heating methods during the night, such as thermal storage from the daytime cycle, could be used to facilitate regeneration without requiring additional energy inputs.

The main limitations of using bittern solution in the real greenhouses are corrosion, scaling, and regeneration. These issues can be addressed as follows: for corrosion, suitable materials such as plastics and/or stainless steel can be used for pipes, pumps, and tanks to resist chemical attack. For scaling, the availability of bittern solution is not a major issue, especially in countries with natural or industrial sources such as salt pans and desalination plants (e.g., Egypt). In addition, an efficient regeneration process reduces the required amount of solution and allows repeated reuse. For regeneration, the manuscript presents a complete method for recycling the bittern solution without the need for replacement.

These findings point to the feasibility of using both the day and night cycles in tandem to maintain the efficiency and sustainability of desiccant use in closed greenhouses. However, to fully implement this approach, further studies in actual greenhouse environments are necessary. These would help determine the best strategies to balance the moisture removal and regeneration processes and identify when the desiccant should be replaced or re-concentrated. As a guideline, it is recommended to replace or regenerate the desiccant when its salinity drops below 150 ppt, as it loses its effectiveness at that point.

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## REFERENCES

1. Al Sharif, M., Jaradat, M., Alshoubaki, A. Y., Abdelhay, A., Sandri, S., Alshyab, N., Jum'a, L., Abushaikha, I., Hayajneh, A. (2025). Enhancing greenhouse efficiency in semi-arid climates: Humidity control and water recovery using liquid desiccant systems. *Sustainable Science and Technology.*
2. Almashharawi, A., Bamasag, A., Abulkhair, H., Lefers, R. (2024). Pilot study on liquid desiccant systems in greenhouse for water saving and climate control. *Case Studies in Thermal Engineering*, *61*, 105165. https://doi.org/10.1016/j.csite.2024.105165
3. Amani, M., Foroushani, S., Sultan, M., Bahrami, M. (2020). Comprehensive review on dehumidification strategies for agricultural greenhouse applications. *Applied Thermal Engineering*, *181*. https://doi.org/10.1016/j.applthermaleng.2020.115979
4. Amer, M. H., Abd El Hafez, S. A., Abd El Ghany, M. B. (2017). Water Saving in irrigated agriculture in Egypt. *LAP LAMBERT Academic Publishing: Saarbrücken, Germany*.
5. Buchholz, M., Jochum, P., Zaragoza, G. (2004). Concept for water, heat and food supply from a closed greenhouse-the watergy project. *International Conference on Sustainable Greenhouse Systems-Greensys2004 691*, 509–516.
6. Cheng, Q., Zhang, X. (2013). Review of solar regeneration methods for liquid desiccant air-conditioning system. *Energy and Buildings*, *67*, 426–433. https://doi.org/10.1016/j.enbuild.2013.08.033
7. Cuce, E., Harjunowibowo, D., Cuce, P. M. (2016). Renewable and sustainable energy saving strategies for greenhouse systems: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *64*, 34–59. https://doi.org/10.1016/j.rser.2016.06.004
8. De Gelder, A., Dieleman, J. A., Bot, G. P. A., Marcelis, L. F. M. (2012). An overview of climate and crop yield in closed greenhouses. *Journal of Horticultural Science and Biotechnology*, *87*(3), 193–202. https://doi.org/10.1080/14620316.2012.11512852
9. De Pascale, S., Incrocci, L., Massa, D., Rouphael, Y., Pardossi, A. (2019). Advances in irrigation management in greenhouse cultivation. In *Achieving sustainable greenhouse cultivation* (pp. 241–284). Burleigh Dodds Science Publishing.
10. Gurubalan, A., Simonson, C. J. (2021). A comprehensive review of dehumidifiers and regenerators for liquid desiccant air conditioning system. *Energy Conversion and Management*, *240*, 114234. https://doi.org/10.1016/j.enconman.2021.114234
11. Janssen, H. J. J., Gieling, T. H., Speetjens, S. L., Stigter, J. D., Van Straten, G. (2005). Watergy: Infrastructure for process control in a closed greenhouse in semi-arid regions. *Acta Horticulturae*, *691*, 821–828. https://doi.org/10.17660/ActaHortic.2005.691.101
12. Jochum, P., Zaragoza, G., Pérez-Parra, J., Buchholz, M., Buchholz, R. (2006). Temperature and humidity control in the watergy greenhouse. *International Symposium on Greenhouse Cooling 719*, 401–408.
13. Lefers, R., Bettahalli, N. M. S., Nunes, S. P., Fedoroff, N., Davies, P. A., Leiknes, T. (2016). Liquid desiccant dehumidification and regeneration process to meet cooling and freshwater needs of desert greenhouses. *Desalination and Water Treatment*, *57*(48–49), 23430–23442. https://doi.org/10.1080/19443994.2016.1173381
14. Misha, S., Mat, S., Ruslan, M. H., Sopian, K. (2012). Review of solid/liquid desiccant in the drying applications and its regeneration methods. *Renewable and Sustainable Energy Reviews*, *16*(7), 4686–4707. https://doi.org/10.1016/j.rser.2012.04.052
15. Mohammed, R. H., Ahmadi, M., Ma, H., Bigham, S. (2023). Desiccants enabling energy-efficient buildings: A review. *Renewable and Sustainable Energy Reviews*, *183*, 113418. https://doi.org/10.1016/j.rser.2023.113418
16. Nicola, S., Pignata, G., Ferrante, A., Bulgari, R., Cocetta, G., Ertani, A. (2020). Water use efficiency in greenhouse systems and its application in horticulture. *AgroLife Scientific Journal*, *9*(1).
17. Nour, M. H., Ghanem, A., Buchholz, M., Nassar, A. (2015). Greenhouse based desalination for brackish water management using bittern evaporative cooling technique. *Water Science and Technology: Water Supply*, *15*(4), 709–717. https://doi.org/10.2166/ws.2015.025
18. Oladosu, T. L., Baheta, A. T., Oumer, A. N. (2021). Desiccant solutions, membrane technologies, and regeneration techniques in liquid desiccant air conditioning system. *International Journal of Energy Research*, *45*(6), 8420–8447. https://doi.org/10.1002/er.6449
19. Rajaseger, G., Chan, K. L., Tan, K. Y., Ramasamy, S., Khin, M. C., Amaladoss, A., Haribhai, P. K. (2023). Hydroponics: current trends in sustainable crop production. *Bioinformation*, *19*(9), 925. https://

doi.org/10.6026/97320630019925

20. Shukla, D. L., Modi, K. V. (2017). A technical review on regeneration of liquid desiccant using solar energy. *Renewable and Sustainable Energy Reviews*, *78*, 517–529. https://doi.org/10.1016/j.rser.2017.05.041
21. Siddique, I. (2021). Sustainable water management in urban areas: Integrating innovative technologies and practices to address water scarcity and pollution. *The Pharmaceutical and Chemical Journal*, *8*(1), 172–178.
22. Singh, K. A. P., Goutam, P. K., Panotra, N., Rajesh, G. M. (2024). The role of greenhouse technology in streamlining crop production. *Journal of Experimental Agriculture International*, *46*(6), 776–798.
23. Singh, P. K. (2012). Irrigation techniques for protected cultivation. *Centre of Advanced Faculty Training in Plant Pathology*.
24. Soussi, M., Chaibi, M. T., Buchholz, M., Saghrouni, Z. (2022). Comprehensive review on climate control and cooling systems in greenhouses under hot and arid conditions. *Agronomy*, *12*(3), 626. https://doi.org/10.3390/agronomy12030626
25. Soussi, M., Chouk, G., Chaibi, M. T., Buchholz, M., Buchholz, R. (2025). Performance assessment of brine-based liquid-desiccant system for greenhouse air conditioning. *Applied Thermal Engineering*, *271*, 126310. https://doi.org/10.1016/j.applthermaleng.2025.126310
26. Sultan, M., Ashraf, H., Miyazaki, T., Shamshiri, R. R., Hameed, I. A. (2021). *Temperature and humidity control for the next generation greenhouses: Overview of desiccant and evaporative cooling systems*. Intech Open. https://doi.org/10.5772/intechopen.93905
27. Vadiee, A., Martin, V. (2012). Energy management in horticultural applications through the closed greenhouse concept, state of the art. *Renewable and Sustainable Energy Reviews, 16*(7), 5087–5100. https://doi.org/10.1016/j.rser.2012.04.022