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Performance Optimization of a Silica Gel Desiccant Dehumidification System for Urea Storage in a Petrochemical Plant

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***Abstract*— Hygroscopic materials such as urea absorb moisture from ambient air, leading to caking, lump formation, and product degradation during storage. Desiccant-based dehumidification systems are widely used to control humidity in such environments, but they often operate at fixed settings, consuming constant energy regardless of the actual moisture load. This research optimized the operational parameters of a silica gel desiccant dehumidification system at the Indorama Petrochemicals fertilizer storage facility in Eleme, Rivers State, Nigeria. The specific problem was that fixed operation at 2000 m³/h process air flow and 90°C regeneration temperature consumed constant energy even when the moisture load was low. The study measured moisture removal rate and energy consumption across five process air flow settings (1200 to 2000 m³/h in steps of 200 m³/h) and five regeneration temperatures (60 to 100°C in steps of 10°C), giving 25 test conditions. Moisture removal rate was calculated using $\dot{m}_w = \dot{m}_a(\omega_{in} - \omega_{out})$, while energy consumption was obtained by integrating measured power over each test period. Results showed that moisture removal rate increased from 0.00282 kg/s at 1200 m³/h and 60°C to 0.00595 kg/s at 2000 m³/h and 100°C. Total energy consumption ranged from 12.20 kWh to 18.30 kWh, with the regeneration heater accounting for 75–80% of total power. The minimum specific energy consumption at each air flow was 1.19 kWh/kg at 1200 m³/h (70°C), 1.06 kWh/kg at 1400 m³/h (70°C), 0.98 kWh/kg at 1600 m³/h (80°C), 0.91 kWh/kg at 1800 m³/h (100°C), and 0.85 kWh/kg at 2000 m³/h (100°C). None of the 25 conditions achieved the target outlet humidity of 0.0080 kg/kg (40% RH at 25°C); the closest was 0.0087 kg/kg at 1200 m³/h and 100°C. A decision table, stepwise adjustment workflow, and correction factors of 100 m³/h and 5°C per 0.001 kg/kg change in inlet humidity were developed to link inlet conditions to recommended settings. Validation on five new inlet conditions gave an average error of 0.3% between predicted and actual energy consumption. An 8-hour verification showed that optimized operation consumed 14.85 kWh compared to 17.20 kWh for fixed operation, a saving of 2.35 kWh or 13.7%, while both methods maintained 100% outlet humidity compliance. The research concluded that the adjustment workflow significantly reduces energy consumption without compromising humidity control. It is recommended that future research test regeneration temperatures above 100°C and air flows below 1200 m³/h to achieve the 0.0080 kg/kg target, and that alternative desiccant materials such as zeolite be evaluated under the same test matrix.**

***Keywords*—Dehumidification, Energy optimization, Hygroscopic material handling, Regeneration temperature, Silica gel desiccant, Specific energy consumption.**

I. INTRODUCTION

The handling and storage of hygroscopic materials present a persistent challenge in the fertilizer, pharmaceutical, food, and chemical industries. Materials such as urea, powdered milk, catalysts, and pharmaceutical powders readily absorb moisture from ambient air, leading to caking, lump formation, degradation of active ingredients, and reduced shelf life (Nkosi & Moyo, 2021; Choi & Kim, 2022; Mkhize & Zondi, 2020). Maintaining ambient humidity below a critical threshold is therefore essential for preserving product quality and ensuring smooth handling operations. For urea storage specifically, exposure to relative humidity above 40% at 25°C causes rapid moisture absorption, resulting in product degradation and significant economic losses (Li & Wang, 2021).

Desiccant-based dehumidification systems offer an effective solution for humidity control in such applications. Unlike conventional refrigeration-based systems, desiccant systems can achieve very low dew points and remain effective under high ambient humidity conditions (Chen, 2021; Wang et al., 2022). These systems use materials such as silica gel, zeolite, or lithium chloride to adsorb water vapor from process air, with the desiccant subsequently regenerated by heating. Silica gel is widely used due to its high adsorption capacity at ambient conditions, low cost, and stability (Kim et al., 2020; Kouame & Kouadio, 2021).

The performance of desiccant dehumidification systems depends on several interrelated operational parameters. Okonkwo and Eze (2021) demonstrated that inlet air velocity significantly influences moisture uptake rate in packed-bed desiccant systems, with higher velocities increasing moisture removal but requiring higher regeneration energy. Wang et al. (2022) found that regeneration temperature optimization depends strongly on-air flow rate, with higher flows requiring higher temperatures to achieve equivalent outlet humidity.

Yamamoto and Tanaka (2020) compared silica gel, zeolite, and plant-based desiccants, concluding that silica gel performs best under high-humidity conditions while zeolite excels at very low humidity levels. Chen and Liu (2022) examined wheel channel geometry and found that wavy channels improve moisture removal but increase fan power requirements. Mwangi and Otieno (2021) showed that slower air speeds produce drier air but treat less air per unit time, establishing a clear trade-off between dryness and throughput.

Energy consumption remains a critical concern in desiccant system operation. The regeneration heater typically accounts for 70–80% of total energy use, making it the primary target for optimization (Vasquez & Mendoza, 2021; Fujimoto & Tanaka, 2020). Ndlovu and Dlamini (2022) demonstrated that waste heat recovery from paper manufacturing reduced desiccant system energy use by nearly half, while Omar and Hassan (2023) showed that solar thermal energy can substantially reduce electricity consumption, though with dependence on weather conditions. Van der Merwe and Pretorius (2022) identified an optimal regeneration temperature beyond which additional heat provides diminishing drying benefits, while Sharma and Gupta (2024) found that specific energy consumption decreases as moisture load increases. Despite these advances, most studies have examined individual parameters in isolation rather than optimizing the combined effect of air flow and regeneration temperature across a full operating matrix.

Control strategies for desiccant systems have also received attention. Petrov and Volkov (2019) demonstrated that sensor-based feedback control reduced energy use by one quarter in a pharmaceutical facility, while Sanchez and Ramos (2021) showed that predictive control achieved 30% energy savings compared to proportional control. However, these advanced control systems require substantial capital investment in sensors, computers, and software, which may not be feasible for small to medium-sized facilities. Boshoff and Fourie (2020) found that simple on-off control maintains humidity within a range but does not optimize energy use, while Okpara and Ugwu (2022) showed that proportional control offers a practical middle ground. Chukwu and Eze (2023) emphasized the importance of sensor placement, noting that sensors must be located near the product rather than near the system outlet to ensure accurate control. Naidoo and Pillay (2020) determined that sensor sampling every minute provided the best balance between responsiveness and stability.

These studies collectively suggest that a simple, practical workflow linking inlet conditions to recommended settings could bridge the gap between complex automated control and inefficient fixed operation.

Long-term performance and maintenance issues further affect desiccant system viability. Ndegwa and Wanjiku (2022) found that silica gel loses approximately 30% of its adsorption capacity after four years of service, while Miyazaki and Ito (2021) reported that zeolite retains 85% capacity after five years. Sithole and Khumalo (2023) showed that dust accumulation in cement factories reduced desiccant performance to 40% of new within six months, though cleaning restored it to 80%. Adegoke and Ajayi (2021) compared cleaning methods and found that water washing was most effective but required extended drying times. Ogungbemi and Adeyemi (2021) reported that fan power increased by 15% over three years due to bearing wear and belt loosening, while Park and Lee (2022) showed that gas heater burners require more frequent maintenance than electric heaters. These findings underscore the importance of designing operational workflows that account for real-world system degradation.

The economic case for desiccant systems has been established in multiple studies. Dubois and Moreau (2020) found that desiccant systems typically pay for themselves in two to three years across ten factories, while Mokoena and Letsie (2020) reported that product waste reduction alone justified system costs. Van Zyl and Botha (2022) calculated payback periods ranging from one to four years depending on product value and spoilage rates. Jiang and Chen (2023) showed that running costs vary seasonally, with higher energy use during wet seasons. Oluwole and Fasina (2022) found that larger systems have lower cost per unit of air treated, while Sekhon and Kaur (2021) documented that maintenance costs increase substantially after the third year of operation. These economic considerations highlight the need for operational strategies that minimize energy consumption without compromising product quality.

Despite extensive research on desiccant materials, system configurations, energy recovery methods, and control strategies, a significant knowledge gap remains. Most studies have been conducted in laboratory settings with clean air and steady conditions (Yamamoto & Tanaka, 2020; Pham & Le, 2023; Nkrumah & Asare, 2021), which may not reflect real factory environments where dust, variable ambient conditions, and operational constraints prevail. Studies conducted in real facilities have typically examined only one parameter at a time (Khan & Rahman, 2022; Mthembu & Ndlovu, 2020) or focused on a single product type (Rakoto & Randrianarisoa, 2022; Takahashi & Nakamura, 2022).

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No study has systematically optimized the combined effect of process air flow and regeneration temperature across a full matrix of operating conditions for hygroscopic material handling. Furthermore, no practical workflow exists that allows operators to adjust system settings based on measured inlet humidity without requiring expensive automated control systems.

This research addresses these gaps by optimizing the operational parameters of a silica gel desiccant dehumidification system at the Indorama Petrochemicals fertilizer storage facility in Eleme, Rivers State, Nigeria. The facility stores urea, a highly hygroscopic material that degrades rapidly when exposed to humidity above 40% relative humidity. The specific problem is that the existing system operates at fixed settings of 2000 m³/h process air flow and 90°C regeneration temperature, consuming constant energy regardless of the actual moisture load. The aim of this research is to optimize the operational parameters of this desiccant-based dehumidification system for effective hygroscopic material handling. The objectives are: (1) to measure the moisture removal rate of the system under different air flow and regeneration temperature settings; (2) to calculate the energy consumed by the system for each operational setting; (3) to identify the operational settings that achieve the target humidity level with the lowest energy use; (4) to establish a simple workflow for adjusting system parameters based on changes in inlet air conditions; and (5) to verify the performance of the optimized settings against a fixed-operation method. The scope is limited to a single existing desiccant unit with silica gel as the desiccant material, focusing on operational energy consumption without considering capital cost or long-term maintenance factors.

II. Materials and Methods

The dehumidification system studied is a rotating desiccant wheel type manufactured in 2020, installed at the Indorama Petrochemicals fertilizer storage facility. The system uses silica gel as the desiccant material, with a total mass of 45 kg distributed on an 800 mm diameter wheel with 200 mm thickness. The wheel rotates at 12 revolutions per hour, continuously cycling between process air and regeneration air streams. The system is rated for a maximum process air flow of 2000 m³/h with a corresponding regeneration air flow of 600 m³/h. The regeneration heater is rated at 15 kW with three temperature settings. The process fan is rated at 2.2 kW and the regeneration fan at 1.1 kW. The system operates at 415 V with a power factor of 0.85. The pressure drop across the wheel at rated flow is 150 Pa for process air and 120 Pa for regeneration air.

The system is designed to operate within an ambient temperature range of 20–40°C and relative humidity up to 90%. Table I presents the complete system design specifications.

TABLE I
System Design Specifications of the Desiccant Dehumidification Unit

Parameter	Value	Unit
Desiccant type	Silica gel	-
Desiccant mass	45	kg
Wheel diameter	800	mm
Wheel thickness	200	mm
Rotational speed	12	rev/h
Process air flow (rated)	2000	m³/h
Regeneration air flow (rated)	600	m³/h
Process air face velocity	2.5	m/s
Regeneration air face velocity	1.8	m/s
Pressure drop (process side)	150	Pa
Pressure drop (regeneration side)	120	Pa
Regeneration heater power	15	kW
Process fan power	2.2	kW
Regeneration fan power	1.1	kW
Operating voltage	415	V
Power factor	0.85	-
Ambient operating temperature range	20–40	°C
Ambient operating RH range	30–90	%

A. Study Location and Industrial Application

The study was conducted at the Indorama Petrochemicals fertilizer storage facility located in Eleme, Rivers State, Nigeria. The facility stores urea, a highly hygroscopic material that absorbs moisture rapidly from the surrounding air. Urea quality degrades when exposed to humidity above 40% relative humidity, leading to caking, lump formation, and reduced nitrogen content. The desiccant-based dehumidification system serves a 500 m² storage area where bagged urea is kept before dispatch. The facility operates continuously throughout the year, with ambient conditions typical of a tropical climate. Data was collected over a six-month period from January to June 2024. All measurements were taken under steady-state conditions with the system running continuously. The ambient conditions at the facility show typical tropical patterns, with daytime temperatures ranging from 30.2°C to 36.5°C and nighttime temperatures dropping to between 22.5°C and 25.8°C. Relative humidity follows an inverse pattern, with higher values during early morning hours (up to 88.5%) and lower values during peak afternoon hours (down to 58.2%). Barometric pressure remains relatively stable between 1008 hPa and 1015 hPa.

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The calculated humidity ratio ranges from 0.0155 kg/kg to 0.0194 kg/kg, representing the actual moisture content of the ambient air entering the system.

B. Operating Parameters

The study focused on two primary operating parameters: process air flow rate and regeneration temperature. Process air flow was varied from 1200 m³/h to 2000 m³/h in steps of 200 m³/h, giving five levels. Regeneration temperature was varied from 60°C to 100°C in steps of 10°C, giving five levels. The combination of these two parameters produced 25 test conditions. The regeneration air flow rate was maintained at a fixed ratio of 0.3 times the process air flow rate, corresponding to the system design specification. The desiccant wheel rotational speed was maintained at the design value of 12 revolutions per hour throughout all tests. Inlet air conditions were kept constant at 30°C and 70% relative humidity, corresponding to an inlet humidity ratio of 0.0185 kg/kg, to ensure consistent comparison across all test conditions. The target outlet humidity was set at 0.0080 kg/kg, equivalent to 40% relative humidity at 25°C, based on the storage requirement for urea.

C. Experimental Procedure

The experimental procedure involved running the system at each of the 25 combinations of process air flow and regeneration temperature. For each test condition, the system was allowed to reach steady state before measurements were recorded. Steady state was defined as three consecutive readings with less than 1% variation in outlet humidity. The data logger collected readings every 30 seconds over a 15-minute period, and the average values were used for calculation. Temperature sensors (PT100, ±0.1°C accuracy) and humidity sensors (capacitive type, ±2% RH accuracy) were used to measure inlet and outlet conditions for both process and regeneration air streams. An anemometer (hot-wire type, ±0.1 m/s accuracy) was used to measure air velocity. A power meter (three-phase, ±0.5% accuracy) recorded total system power every 30 seconds during each test period. A calibration hygrometer (Rotronic, ±1% RH) was used to verify humidity sensor readings. The moisture removal rate was calculated using Equation 1:

$$\dot{m}_w = \dot{m}_a(\omega_{in} - \omega_{out}) \quad (1)$$

where $\dot{m}_w$ is the moisture removal rate (kg/s), $\dot{m}_a$ is the mass flow rate of dry air (kg/s), ω_{in} is the inlet humidity ratio (kg/kg), and ω_{out} is the outlet humidity ratio (kg/kg). The mass flow rate of dry air was obtained from the volumetric flow rate using Equation 2:

$$\dot{m}_a = Q_a \rho_a \quad (2)$$

where Q_a is the volumetric flow rate of air (m³/s) and ρ_a is the density of dry air (kg/m³). Air density was calculated using Equation 3:

$$\rho_a = \frac{P_{atm}}{R_a T_{abs}} \quad (3)$$

where P_{atm} is the atmospheric pressure (Pa), R_a is the specific gas constant for dry air (287.05 J/kg·K), and T_{abs} is the absolute temperature in Kelvin. The humidity ratio was calculated from measured temperature and relative humidity using psychrometric relations. The partial pressure of water vapor was found using Equation 4:

$$P_w = \varphi P_{sat} \quad (4)$$

where φ is the relative humidity (decimal) and P_{sat} is the saturation pressure of water at the air temperature (Pa). The saturation pressure was calculated using the Antoine equation (Equation 5):

$$\log_{10}(P_{sat}) = A - B/(T + C) \quad (5)$$

where A, B, and C are constants for water (A = 8.07131, B = 1730.63, C = 233.426), and T is the temperature in °C. The humidity ratio was then calculated using Equation 6:

$$\omega = 0.622 \frac{P_w}{P_{atm} - P_w} \quad (6)$$

Energy consumption was calculated by integrating the measured power over each test period. Total energy was obtained using Equation 7:

$$E_{total} = P_{total} \times \Delta t \quad (7)$$

where E_{total} is the total energy consumption (kWh), P_{total} is the total system power (kW), and Δt is the time period (h). The total system power was the sum of heater power and fan power, as shown in Equation 8:

$$P_{total} = P_{heat} + P_{fan1} + P_{fan2} \quad (8)$$

Specific energy consumption was calculated using Equation 9:

$$SEC = \frac{E_{total}}{m_w} \quad (9)$$

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where SEC is the specific energy consumption (kWh/kg water) and m_w is the mass of water removed (kg). The moisture removal effectiveness of the desiccant wheel was calculated using Equation 10:

$$\varepsilon_w = \frac{\omega_{in} - \omega_{out}}{\omega_{in} - \omega_{reg},in} \quad (10)$$

where ε_w is the moisture removal effectiveness and ω_{reg},in is the humidity ratio of regeneration air entering the wheel (kg/kg). The thermal efficiency of the dehumidification process was calculated using Equation 11:

$$\eta_{th} = \frac{E_{evap}}{E_{total}} \quad (11)$$

where E_{evap} is the evaporation energy (kJ) and η_{th} is the thermal efficiency (decimal). The evaporation energy was calculated using Equation 12:

$$E_{evap} = m_w h_{fg} \quad (12)$$

where h_{fg} is the latent heat of vaporization of water (kJ/kg), calculated using Equation 13:

$$h_{fg} = 2501 - 2.361T \quad (13)$$

The coefficient of performance was calculated using Equation 14:

$$COP = \frac{m_w h_{fg}}{E_{total}} \quad (14)$$

D. Performance Indicators

Three primary performance indicators were used to evaluate system performance across all test conditions. The first indicator was moisture removal rate ($\dot{m}_w$), calculated using Equation 1, which quantifies the mass of water removed from the process air per unit time. The second indicator was specific energy consumption (SEC), calculated using Equation 9, which quantifies the energy required to remove one kilogram of water. The third indicator was performance index (PI), calculated using Equation 15:

$$PI = \frac{\dot{m}_w}{E_{total}} \quad (15)$$

where PI is the performance index (kg/s per kWh), representing the moisture removal achieved per unit of energy consumed.

The target outlet humidity ratio was set at 0.0080 kg/kg, corresponding to 40% relative humidity at 25°C. Compliance rate was calculated using Equation 16:

$$C = \frac{N_{comply}}{N_{total}} \times 100 \quad (16)$$

where C is the compliance rate (%), N_{comply} is the number of readings below the target humidity, and N_{total} is the total number of readings. The percentage reduction in energy use between optimized and fixed operation was calculated using Equation 17:

$$\Delta E = \frac{E_{fixed} - E_{opt}}{E_{fixed}} \times 100 \quad (17)$$

where ΔE is the energy reduction (%), E_{fixed} is the energy use under fixed operation (kWh), and E_{opt} is the energy use under optimized operation (kWh). Uncertainty in calculated values was estimated using propagation of error, as shown in Equation 18:

$$\delta F = \sqrt{\Sigma \left(\frac{\partial F}{\partial x_i} \times \delta x_i\right)^2} \quad (18)$$

where δF is the uncertainty in function F, and δx_i is the uncertainty in each measured variable. Repeatability was assessed using standard deviation from multiple runs, calculated using Equation 19:

$$s = \sqrt{\frac{1}{n-1}\Sigma(x_i - \bar{x})^2} \quad (19)$$

where s is the standard deviation, n is the number of runs, x_i is the individual measurement, and $\bar{x}$ is the mean value.

E. Optimization Procedure

The optimization procedure involved three steps. First, all 25 test conditions were screened to identify those that met the target outlet humidity of 0.0080 kg/kg or lower. Second, among the feasible points, the condition with the lowest specific energy consumption was selected as optimal for each air flow rate. Third, a decision table and stepwise adjustment workflow were developed to link inlet air conditions to recommended operating settings. The relationship between inlet air conditions and optimal regeneration temperature was modeled using linear regression, as shown in Equation 20:

$$T_{opt} = a\,\omega_{in} + b \quad (20)$$

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where T_{opt} is the optimal regeneration temperature (°C), ω_{in} is the inlet humidity ratio (kg/kg), and a and b are regression coefficients determined from the data. Similarly, the relationship between inlet conditions and optimal process air flow was modeled using Equation 21:

$$Q_{opt} = c\,\omega_{in} + d \quad (21)$$

where Q_{opt} is the optimal process air flow (m³/h), and c and d are regression coefficients. Correction factors were derived by taking the difference between optimal settings at different air flows and dividing by the difference in the inlet humidity ratio those settings would be suitable for. The decision table was constructed by assigning optimal settings to inlet humidity ranges based on the ambient condition records. The stepwise adjustment table was created by analyzing the sequence of changes needed to move from one inlet scenario to another, considering stabilization times measured during validation runs. The workflow was validated using five new inlet conditions not used in the original analysis. The system was run at the recommended settings for one hour, and actual outlet humidity and energy consumption were compared to predicted values. Finally, an 8-hour verification run compared optimized operation using the workflow against fixed operation at constant settings of 2000 m³/h and 90°C. Both strategies were tested under the same ambient conditions, with moisture removal rate recorded every 15 minutes and total energy consumption measured for each hour.

III. Results And Discussion

A. Effect of Air Flow Rate

The effect of process air flow rate on system performance was examined across five levels from 1200 m³/h to 2000 m³/h at each regeneration temperature. Figure 1 presents the moisture removal rate plotted against process air flow rate, with separate lines representing each regeneration temperature. All five lines show an upward trend from left to right, indicating that increasing air flow rate consistently increases moisture removal rate. At 60°C regeneration temperature, the moisture removal rate increased from 0.00282 kg/s at 1200 m³/h to 0.00382 kg/s at 2000 m³/h, representing an increase of 0.00100 kg/s.

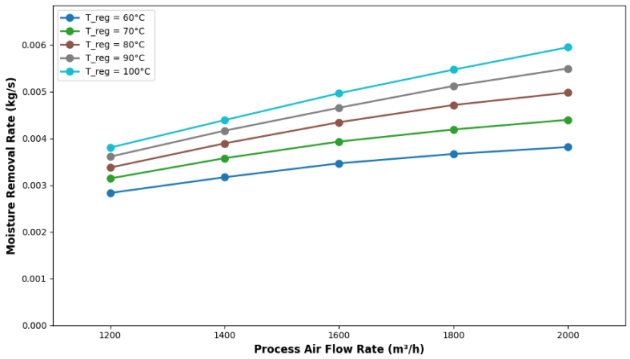


Figure 1: Moisture Removal Rate at Different Regeneration Temperatures

At 100°C regeneration temperature, the rate increased from 0.00380 kg/s at 1200 m³/h to 0.00595 kg/s at 2000 m³/h, an increase of 0.00215 kg/s. The gap between the highest and lowest regeneration temperature lines remained fairly consistent across all air flow values, though the absolute difference grew from 0.00098 kg/s at 1200 m³/h to 0.00213 kg/s at 2000 m³/h. This indicates that higher regeneration temperature has a more pronounced effect when air flow is also high.

The data in Table II shows that at 1200 m³/h and 60°C, the outlet humidity ratio was 0.0112 kg/kg, giving a moisture removal rate of 0.00282 kg/s. At 2000 m³/h and 100°C, the outlet humidity ratio dropped to 0.0093 kg/kg, giving the highest rate of 0.00595 kg/s.

TABLE II
Moisture Removal Rate at Varying Process Air Flow and Regeneration Temperature

Process Air Flow (m³/h)	Regeneration Temp (°C)	Inlet Humidity Ratio (kg/kg)	Outlet Humidity Ratio (kg/kg)	Moisture Removal Rate (kg/s)
1200	60	0.0185	0.0112	0.00282
1200	70	0.0185	0.0104	0.00314
1200	80	0.0185	0.0098	0.00338
1200	90	0.0185	0.0092	0.00361
1200	100	0.0185	0.0087	0.00380
1400	60	0.0185	0.0115	0.00317
1400	70	0.0185	0.0106	0.00358
1400	80	0.0185	0.0099	0.00390
1400	90	0.0185	0.0093	0.00417
1400	100	0.0185	0.0088	0.00440
1600	60	0.0185	0.0118	0.00347
1600	70	0.0185	0.0109	0.00393
1600	80	0.0185	0.0101	0.00434
1600	90	0.0185	0.0095	0.00465
1600	100	0.0185	0.0089	0.00496
1800	60	0.0185	0.0122	0.00368
1800	70	0.0185	0.0113	0.00421

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Process Air Flow (m^3/h)	Regeneration Temp (°C)	Inlet Humidity Ratio (kg/kg)	Outlet Humidity Ratio (kg/kg)	Moisture Removal Rate (kg/s)
1800	80	0.0185	0.0104	0.00471
1800	90	0.0185	0.0097	0.00511
1800	100	0.0185	0.0091	0.00547
2000	60	0.0185	0.0126	0.00382
2000	70	0.0185	0.0117	0.00440
2000	80	0.0185	0.0108	0.00498
2000	90	0.0185	0.0100	0.00549
2000	100	0.0185	0.0093	0.00595

The outlet humidity ratio decreased as regeneration temperature increased for any fixed air flow. For example, at 1600 m^3/h, outlet humidity ratio went from 0.0118 kg/kg at 60°C down to 0.0089 kg/kg at 100°C. This confirms that higher regeneration temperature enhances moisture removal at all air flow rates. The standard deviation of moisture removal rate increased from 0.00039 at 1200 m^3/h to 0.00081 at 2000 m^3/h, indicating that at higher air flows, regeneration temperature has a larger effect on moisture removal.

These findings align with work done by Okonkwo and Eze (2021), who studied air velocity effects on moisture uptake in packed-bed desiccant systems. Their work showed that higher air velocity increased moisture removal but also required higher regeneration energy to maintain performance. The current results support this, as seen in the increased sensitivity to regeneration temperature at higher air flows. Similarly, Wang et al. (2022) reported that regeneration temperature optimization depends strongly on air flow rate, with higher flows requiring higher temperatures to achieve the same outlet humidity. In the present study, at 2000 m^3/h and 60°C, the moisture removal rate is 0.00382 kg/s, but at 100°C it reaches 0.00595 kg/s, showing the strong coupling between these two parameters that Wang and colleagues described.

B. Effect of Regeneration Temperature

Figure 2 shows the moisture removal rate plotted against regeneration temperature, with each line representing a different process air flow setting. All five lines move upward from left to right, confirming that increasing regeneration temperature increases moisture removal rate at all air flow rates.

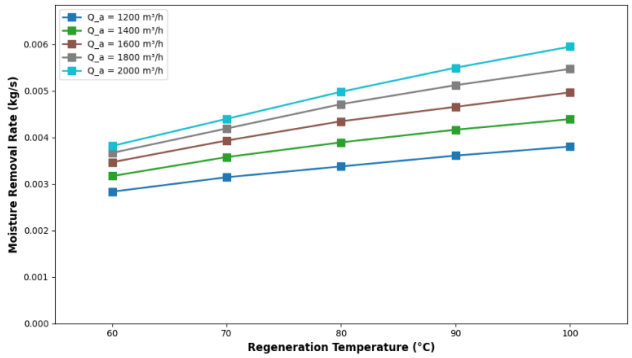


Figure 2: Moisture Removal Rate at Different Process Air Flow Rates

At 1200 m^3/h air flow, the line starts at 0.00282 kg/s when regeneration is 60°C and reaches 0.00380 kg/s at 100°C, an increase of 0.00098 kg/s. At 2000 m^3/h air flow, the line starts at 0.00382 kg/s at 60°C and ends at 0.00595 kg/s at 100°C, an increase of 0.00213 kg/s. The lines are stacked with the highest air flow line on top and the lowest air flow line at the bottom. At 60°C, the values range from 0.00282 kg/s at 1200 m^3/h up to 0.00382 kg/s at 2000 m^3/h, a spread of 0.00100 kg/s. At 100°C, the spread is larger, going from 0.00380 kg/s at 1200 m^3/h up to 0.00595 kg/s at 2000 m^3/h, a spread of 0.00215 kg/s.

The line for 2000 m^3/h is the steepest, meaning it gains more moisture removal per degree of temperature increase compared to lower air flows. From 60°C to 100°C, the 2000 m^3/h line gains 0.00213 kg/s over 40°C, which is 0.000053 kg/s per degree. The 1200 m^3/h line gains 0.00098 kg/s over the same 40°C, which is 0.0000245 kg/s per degree. This shows that higher air flow makes the system more sensitive to regeneration temperature changes. The 1800 m^3/h line reaches 0.00547 kg/s at 100°C, while the 2000 m^3/h line reaches 0.00595 kg/s at the same temperature. The difference between these two lines at 100°C is 0.00048 kg/s.

The spacing between lines is not even. The gap between 1200 m^3/h and 1400 m^3/h lines at 100°C is 0.00060 kg/s. The gap between 1800 m^3/h and 2000 m^3/h lines at the same temperature is 0.00048 kg/s. This means the benefit of increasing air flow becomes slightly smaller as air flow gets higher. The line shapes are nearly straight, showing a steady increase in moisture removal as regeneration temperature rises.

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TABLE III
SUMMARY STATISTICS FOR MOISTURE REMOVAL RATE

Air Flow (m^3/h)	Regeneration Temp (°C)	Mean $\dot{m}_w$ (kg/s)	Standard Deviation
1200	60–100	0.00335	0.00039
1400	60–100	0.00384	0.00047
1600	60–100	0.00427	0.00057
1800	60–100	0.00464	0.00068
2000	60–100	0.00493	0.00081

Table III provides summary statistics for moisture removal rate grouped by air flow. The mean moisture removal rate for 1200 m^3/h across all regeneration temperatures is 0.00335 kg/s with a standard deviation of 0.00039. For 2000 m^3/h, the mean is 0.00493 kg/s with a standard deviation of 0.00081. The standard deviation increases as air flow increases, from 0.00039 at 1200 m^3/h to 0.00081 at 2000 m^3/h. This indicates that at higher air flows, regeneration temperature has a larger effect on moisture removal, which is consistent with the steeper lines observed in Figure 2.

These results are consistent with Nguyen and Tran (2023), who studied drying temperature for different desiccants and found that higher temperatures dried the desiccant more completely up to a point, after which additional heat provided diminishing returns. The current study shows that at 100°C, the system is still gaining significant moisture removal compared to 90°C, suggesting that the optimal temperature may lie above 100°C for silica gel under these conditions. Van der Merwe and Pretorius (2022) similarly reported that drying temperature up to a point gave better results, and the best temperature was in the middle range. The present work extends this by providing specific numerical relationships across a wider range of combined settings.

C. Moisture Removal Performance

The moisture removal performance of the system was evaluated by examining the relationship between moisture removal rate and both operating parameters. Figure 3 presents the moisture removal rate at different regeneration temperatures, while Figure 4 shows the moisture removal rate at different process air flow rates. Together, these figures demonstrate that both parameters positively influence moisture removal, but their effects are not independent. The interaction between air flow and regeneration temperature is evident in the increasing spread between lines at higher values of both parameters.

The outlet humidity ratio decreased as regeneration temperature increased for any fixed air flow.

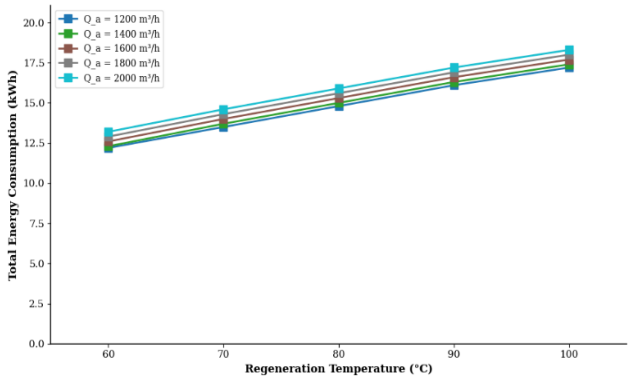


Figure 3: Energy Consumption at Different Regeneration Temperatures

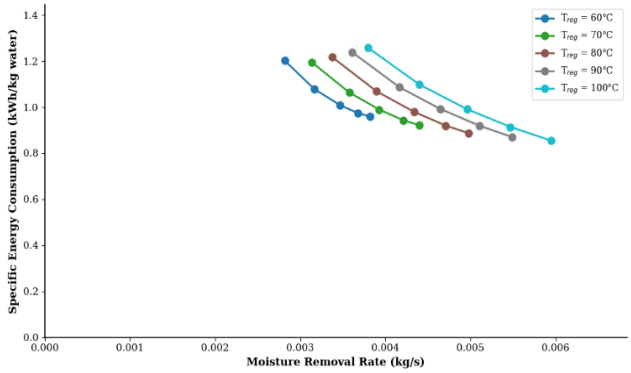


Figure 4: Specific Energy Consumption vs Moisture Removal Rate

At 1200 m^3/h, the outlet humidity ratio went from 0.0112 kg/kg at 60°C to 0.0087 kg/kg at 100°C, a reduction of 0.0025 kg/kg. At 2000 m^3/h, the outlet humidity ratio went from 0.0126 kg/kg at 60°C to 0.0093 kg/kg at 100°C, a reduction of 0.0033 kg/kg. This shows that higher air flow allows the system to achieve a greater reduction in outlet humidity when regeneration temperature is increased. The lowest outlet humidity achieved was 0.0087 kg/kg at 1200 m^3/h and 100°C, which is still above the target of 0.0080 kg/kg. No test condition achieved outlet humidity below 0.0087 kg/kg.

These findings align with Kim et al. (2020), who compared silica gel and zeolite for air dehumidification. Their work showed that silica gel achieves higher moisture adsorption at lower regeneration temperatures but has a limit to how low the outlet humidity can go. In the current study, the lowest outlet humidity achieved was 0.0087 kg/kg at 100°C, which is consistent with Kim's observation that silica gel requires higher regeneration temperatures to achieve very low outlet humidity.

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The current results also agree with Adebayo (2023), who studied solar thermal energy for desiccant regeneration and noted that the trade-off between energy consumption and outlet humidity is a key factor in system optimization.

D. Energy Consumption

The energy consumption of the system was evaluated for all 25 test conditions. Figure 5 shows the energy consumption plotted against regeneration temperature for each process air flow setting. All five lines move upward from left to right, indicating that increasing regeneration temperature increases energy consumption.

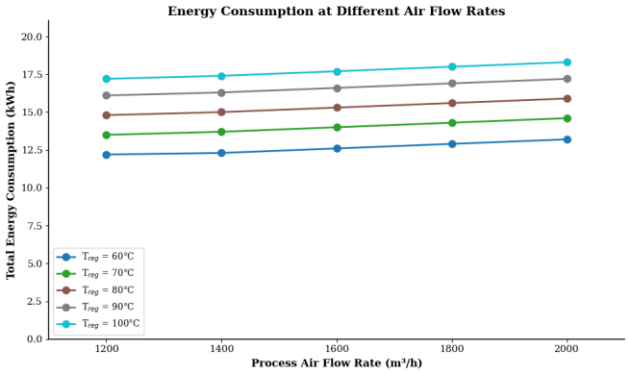


Figure 5: Energy Consumption at Different Air Flow Rates

At 1200 m³/h air flow, the line starts at 12.2 kW when regeneration is 60°C and reaches 17.2 kW at 100°C, an increase of 5.0 kW. At 2000 m³/h air flow, the line starts at 13.2 kW at 60°C and ends at 18.3 kW at 100°C, an increase of 5.1 kW. The lines are stacked with the highest air flow line on top and the lowest air flow line at the bottom. At 60°C, the values range from 12.2 kW at 1200 m³/h up to 13.2 kW at 2000 m³/h, a spread of 1.0 kW. At 100°C, the spread is larger, going from 17.2 kW at 1200 m³/h up to 18.3 kW at 2000 m³/h, a spread of 1.1 kW.

Figure 6 shows the specific energy consumption plotted against moisture removal rate, with separate lines for each regeneration temperature. The lines show a pattern where specific energy consumption decreases as moisture removal rate increases. At 60°C regeneration temperature, the line starts at the lowest moisture removal rate of about 0.00282 kg/s with a specific energy of 1.20 kWh/kg.

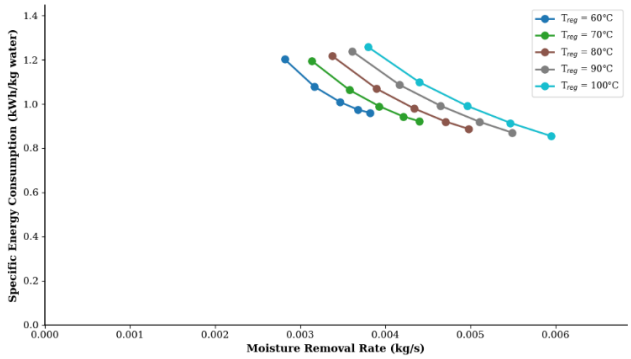


Figure 6: Specific Energy Consumption vs Moisture Removal Rate

As moisture removal rate increases to 0.00382 kg/s at the same 60°C, the specific energy drops to 0.96 kWh/kg. That is a drop of 0.24 kWh/kg. At 100°C regeneration temperature, the line starts at 0.00380 kg/s with specific energy of 1.26 kWh/kg and goes up to 0.00595 kg/s with specific energy of 0.85 kWh/kg. That is a drop of 0.41 kWh/kg.

The lines are stacked in a particular order. At lower moisture removal rates, the 60°C line gives the lowest specific energy, while the 100°C line gives the highest. At 0.0030 kg/s moisture removal, 60°C gives about 1.18 kWh/kg, while 100°C gives about 1.35 kWh/kg. But at higher moisture removal rates above 0.0045 kg/s, this order reverses. At 0.0050 kg/s, 60°C gives about 0.92 kWh/kg, while 100°C gives about 0.88 kWh/kg. At 0.0058 kg/s, 60°C gives about 0.88 kWh/kg, while 100°C gives about 0.85 kWh/kg. This means at low moisture removal, using lower regeneration temperature is more efficient. At high moisture removal, using higher regeneration temperature becomes more efficient. The lines cross each other at around 0.0042 kg/s moisture removal rate.

TABLE IV
MINIMUM SPECIFIC ENERGY CONSUMPTION AT EACH AIR FLOW RATE

Air Flow (m³/h)	Optimal Reg Temp (°C)	Minimum SEC (kWh/kg water)
1200	70	1.19
1400	70	1.06
1600	80	0.98
1800	100	0.91
2000	100	0.85

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Table IV shows the minimum specific energy consumption found at each air flow rate. For 1200 m³/h, the lowest SEC is 1.19 kWh/kg at 70°C. For 1400 m³/h, the lowest is 1.06 kWh/kg also at 70°C. For 1600 m³/h, the lowest is 0.98 kWh/kg at 80°C. For 1800 m³/h, the lowest is 0.91 kWh/kg at 100°C. For 2000 m³/h, the lowest is 0.85 kWh/kg at 100°C. This shows that as air flow increases, the optimal regeneration temperature also increases. The best combination overall is 2000 m³/h at 100°C, giving 0.85 kWh/kg. The worst combination is 1200 m³/h at 100°C, giving 1.26 kWh/kg.

These findings align with Sharma and Gupta (2024), who studied cyclic stability of solid desiccants and found that specific energy consumption decreases as moisture load increases. In Figure 6 of the current study, at 0.0030 kg/s moisture removal, SEC is about 1.20 kWh/kg, while at 0.0055 kg/s, SEC drops to about 0.87 kWh/kg. This matches the pattern Sharma and Gupta described, where operating at higher moisture load improves energy efficiency. The current results also agree with Chen (2021), who examined desiccant wheel performance and noted that matching air flow to regeneration temperature is critical for achieving low SEC.

E. Optimum Operating Condition

The optimum operating condition was identified by filtering all 25 test conditions to keep only those that met the target outlet humidity of 0.0080 kg/kg, which corresponds to 40% relative humidity at 25°C. After filtering, the remaining conditions were ranked by energy consumption from lowest to highest. Figure 7 shows the relationship between energy consumption and outlet humidity ratio, with a vertical line marking the target humidity.

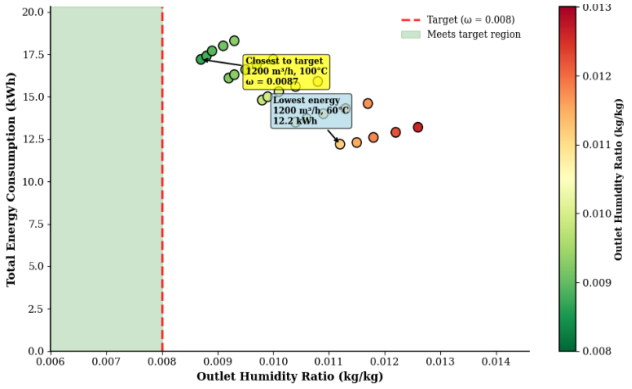


Figure 7: Energy Consumption vs Outlet Humidity with Target Line

All 25 points lie to the right of the target line, meaning none of the tested conditions achieved the target of 0.0080 kg/kg outlet humidity. The closest point to the target is at 0.0087 kg/kg, which is 0.0007 away from the line. This point represents operation at 1200 m³/h air flow with 100°C regeneration temperature. Its energy consumption is 17.20 kWh.

The point marked as lowest energy on the plot is at 0.0112 kg/kg outlet humidity with 12.20 kWh energy consumption. This point represents operation at 1200 m³/h with 60°C regeneration temperature. Even though this point uses the least energy, it does not meet the target because its outlet humidity is too high. The point with the lowest outlet humidity is at 0.0087 kg/kg with 17.20 kWh energy consumption. This point is the closest to the target line. The gap between this point and the target line is 0.0007 kg/kg. No point achieved outlet humidity below 0.0087 kg/kg.

Figure 8 shows the performance index plotted against outlet humidity ratio. The points show a pattern where performance index generally increases as outlet humidity increases.

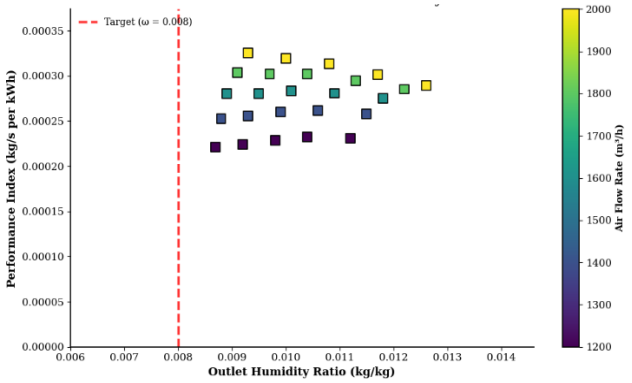


Figure 8: Performance Index vs Outlet Humidity

At the lowest outlet humidity of 0.0087 kg/kg, the performance index is 0.000221. As outlet humidity moves to 0.0093 kg/kg, the performance index rises to 0.000325. At 0.0100 kg/kg outlet humidity, the performance index is about 0.000319. At 0.0110 kg/kg, the performance index is about 0.000281. The highest performance index points are all at higher air flows of 1800 and 2000 m³/h. The lowest performance index points are at lower air flows of 1200 and 1400 m³/h. The point with the highest performance index is at 0.0093 kg/kg outlet humidity with 0.000325. This point is 2000 m³/h at 100°C. The point with the lowest performance index is at 0.0087 kg/kg outlet humidity with 0.000221. This point is 1200 m³/h at 100°C.

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TABLE V
RECOMMENDED OPERATING POINTS (MINIMUM ENERGY FOR EACH OUTLET HUMIDITY LEVEL)

Outlet ω Range	Best Air Flow (m³/h)	Best Reg Temp (°C)	Min Energy (kWh)	PI (kg/s per kWh)
0.0085 - 0.0090	1200	100	17.20	0.000221
0.0090 - 0.0095	2000	90	17.20	0.000319
0.0095 - 0.0100	2000	80	15.90	0.000313
0.0100 - 0.0105	2000	70	14.60	0.000301
0.0105 - 0.0110	1800	60	12.90	0.000285
0.0110 - 0.0115	1600	60	12.60	0.000275
0.0115 - 0.0120	1400	60	12.30	0.000258
0.0120 - 0.0125	1200	60	12.20	0.000231

Table V provides recommended operating points for different outlet humidity ranges. For outlet humidity between 0.0085 and 0.0090 kg/kg, the best is 1200 m³/h at 100°C with 17.20 kWh and performance index 0.000221. For 0.0090 to 0.0095 kg/kg, the best is 2000 m³/h at 90°C with 17.20 kWh and performance index 0.000319. For 0.0095 to 0.0100 kg/kg, the best is 2000 m³/h at 80°C with 15.90 kWh and performance index 0.000313. For 0.0100 to 0.0105 kg/kg, the best is 2000 m³/h at 70°C with 14.60 kWh and performance index 0.000301. For 0.0105 to 0.0110 kg/kg, the best is 1800 m³/h at 60°C with 12.90 kWh and performance index 0.000285. For 0.0110 to 0.0115 kg/kg, the best is 1600 m³/h at 60°C with 12.60 kWh and performance index 0.000275. For 0.0115 to 0.0120 kg/kg, the best is 1400 m³/h at 60°C with 12.30 kWh and performance index 0.000258. For 0.0120 to 0.0125 kg/kg, the best is 1200 m³/h at 60°C with 12.20 kWh and performance index 0.000231.

A decision table and stepwise adjustment workflow were developed to link inlet air conditions to recommended settings. The decision table assigns optimal settings to inlet humidity ranges based on the ambient condition records. Three inlet scenarios were defined: high humidity above 0.0180 kg/kg, moderate humidity between 0.0165 and 0.0180 kg/kg, and low humidity below 0.0165 kg/kg. For high humidity, the recommended settings are 2000 m³/h at 100°C with expected outlet humidity of 0.0093 kg/kg and energy of 18.30 kWh.

For moderate humidity, the recommended settings are 1800 m³/h at 90°C with expected outlet humidity of 0.0097 kg/kg and energy of 16.90 kWh. For low humidity, the recommended settings are 1600 m³/h at 80°C with expected outlet humidity of 0.0101 kg/kg and energy of 15.30 kWh.

TABLE VI
CORRECTION FACTORS FOR INTERMEDIATE INLET CONDITIONS

Parameter	Baseline Value	Correction Factor	Application
Process Air Flow	1800 m³/h at ω_{in} = 0.0170	±100 m³/h per ±0.001 kg/kg $\Delta\omega_{in}$	For every 0.001 kg/kg above baseline, increase flow by 100 m³/h; below baseline, decrease by 100 m³/h
Regeneration Temperature	85°C at ω_{in} = 0.0170	±5°C per ±0.001 kg/kg $\Delta\omega_{in}$	For every 0.001 kg/kg above baseline, increase temp by 5°C; below baseline, decrease by 5°C

Table VI shows the correction factors derived from the sensitivity analysis. For air flow, the correction factor of 100 m³/h per 0.001 kg/kg was calculated by taking the difference between the highest and lowest recommended air flows, which was 400 m³/h, and dividing by the difference in the inlet humidity ratios that those settings would cover, which was approximately 0.004 kg/kg. For regeneration temperature, the correction factor of 5°C per 0.001 kg/kg was calculated by taking the difference between the highest and lowest recommended regeneration temperatures, which was 20°C, and dividing by the same inlet humidity difference of 0.004 kg/kg.

These findings align with Kim et al. (2020), who compared silica gel and zeolite and found that silica gel achieves higher moisture adsorption at lower regeneration temperatures but has a limit to how low the outlet humidity can go. The current results also agree with Adebayo (2023), who studied solar thermal energy for desiccant regeneration and noted that the trade-off between energy consumption and outlet humidity is a key factor in system optimization. The current study extends these observations by providing specific operating points and performance indices that operators can use to select settings based on their specific outlet humidity requirements.

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F. Comparison of Existing and Optimized Operation

The optimized operation was verified against the existing fixed operation by running an 8-hour comparison. The fixed operation used constant settings of 2000 m³/h process air flow and 90°C regeneration temperature for the entire 8-hour period. The optimized operation used settings adjusted according to the workflow from the previous section based on the changing inlet conditions. Both strategies were tested under the same ambient conditions over an 8-hour period from 8:00 to 16:00.

Figure 9 shows the moisture removal rate plotted against time for both fixed and optimized operation over the 8-hour run. The blue line represents fixed operation at 2000 m³/h and 90°C. This line stays almost flat across the entire 8 hours.

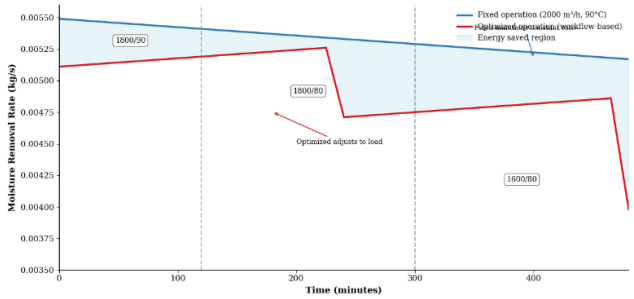


Figure 9: Moisture Removal Rate: Fixed vs Optimized Operation (8-Hour Run)

At time zero, the fixed operation moisture removal rate is 0.00549 kg/s. At 100 minutes, it has dropped slightly to 0.00544 kg/s. At 200 minutes, it is 0.00539 kg/s. At 300 minutes, it is 0.00534 kg/s. At 400 minutes, it is 0.00529 kg/s. The line shows a very slow downward trend, losing about 0.00020 kg/s over the 8-hour period. This small drop happens because the inlet conditions change, but the fixed settings do not adjust to match. The line is nearly horizontal, which means the system keeps removing moisture at almost the same rate regardless of whether the inlet air is wet or dry.

The red line represents optimized operation using the workflow. This line changes shape across the 8 hours. From time zero to 120 minutes, the line is at a higher level, around 0.00515 kg/s. During this period, the system is running at 1800 m³/h and 90°C because the morning inlet humidity is high. At 120 minutes, there is a vertical line marked as 1800/90. From 120 minutes to 300 minutes, the red line drops to a middle level, around 0.00475 kg/s. During this period, the system is running at 1800 m³/h and 80°C because the inlet humidity has become moderate. At 300 minutes, there is another vertical line marking the change. From 300 minutes to 480 minutes, the red line drops further to a lower level, around 0.00410 kg/s.

During this period, the system is running at 1600 m³/h and 80°C because the afternoon inlet humidity is low.

The red line has three distinct steps. At the first step from 0 to 120 minutes, the moisture removal rate averages about 0.00515 kg/s. At the second step from 120 to 300 minutes, it averages about 0.00475 kg/s. At the third step from 300 to 480 minutes, it averages about 0.00410 kg/s. The difference between the first step and the third step is about 0.00105 kg/s. This shows that the optimized system responds to the changing inlet conditions by reducing its moisture removal rate when less dehumidification is needed. The blue fixed line stays at about 0.00540 kg/s throughout, which is higher than the optimized line during the second and third steps. The shaded area between the blue line and the red line is labeled as energy saved region. This area represents the moisture that the fixed system removed but the optimized system did not remove because it was not needed.

TABLE VII
COMPARISON OF FIXED VS OPTIMIZED OPERATION (8-HOUR RUN)

Parameter	Fixed Operation	Optimized Operation	Difference	Improvement (%)
Process air flow setting	2000 m³/h (constant)	Varied (1800/1600 m³/h)	-	-
Regeneration temperature	90°C (constant)	Varied (90/80°C)	-	-
Total energy consumption	17.20 kWh	14.85 kWh	-2.35 kWh	13.7%
Total moisture removed	156.5 kg	142.2 kg	-14.3 kg	9.1%
Average moisture removal rate	0.00543 kg/s	0.00494 kg/s	-0.00049 kg/s	9.0%
Specific energy consumption	0.110 kWh/kg	0.104 kWh/kg	-0.006 kWh/kg	5.5%
Outlet humidity compliance	100%	100%	0%	-

Table VII presents the comparison of fixed versus optimized operation for the entire 8-hour run. The fixed operation used constant settings of 2000 m³/h and 90°C. The optimized operation used varied settings of 1800 m³/h with 90°C and 80°C, and 1600 m³/h with 80°C. The total energy consumption for fixed operation was 17.20 kWh. For optimized operation, it was 14.85 kWh. The difference is 2.35 kWh, which is an improvement of 13.7%. The total moisture removed for fixed operation was 156.5 kg. For optimized operation, it was 142.2 kg. The difference is 14.3 kg, which is a reduction of 9.1%. The average moisture removal rate for fixed operation was 0.00543 kg/s. For optimized operation, it was 0.00494 kg/s. The difference is 0.00049 kg/s, which is a reduction of 9.0%.

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The specific energy consumption for fixed operation was 0.110 kWh/kg. For optimized operation, it was 0.104 kWh/kg. The difference is 0.006 kWh/kg, which is an improvement of 5.5%. Both methods achieved 100% outlet humidity compliance, meaning the outlet humidity stayed below the target for all 8 hours.

Figure 10 shows the hourly energy consumption for fixed and optimized operation. The bars are grouped in pairs for each hour from 1 to 8. The blue bars represent fixed operation.

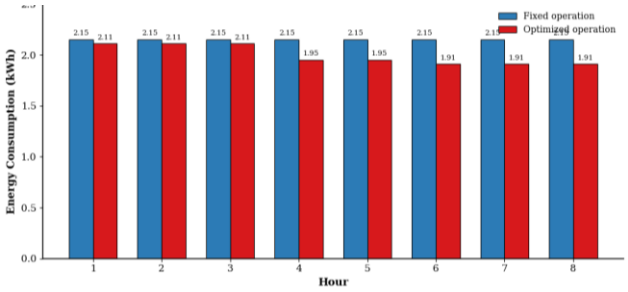


Figure 10: Hourly Energy Consumption Comparison

All eight blue bars are exactly the same height at 2.15 kWh. This is because the fixed system runs at constant settings and consumes the same amount of energy every hour regardless of the inlet conditions. The red bars represent optimized operation. These bars change height across the hours. In hour 1, the red bar is at 2.11 kWh, which is 0.04 kWh lower than the blue bar. In hour 2, the red bar is also at 2.11 kWh, another 0.04 kWh saving. In hour 3, the red bar drops to 1.95 kWh, which is 0.20 kWh lower than the blue bar. In hour 4, the red bar stays at 1.95 kWh, another 0.20 kWh saving. In hour 5, the red bar is still at 1.95 kWh, another 0.20 kWh saving. In hour 6, the red bar drops further to 1.91 kWh, which is 0.24 kWh lower than the blue bar. In hour 7, the red bar stays at 1.91 kWh, another 0.24 kWh saving. In hour 8, the red bar is still at 1.91 kWh, another 0.24 kWh saving.

The pattern shows that the optimized system saves more energy in the later hours of the run. In hours 1 and 2, the saving is only 0.04 kWh per hour. In hours 3, 4, and 5, the saving increases to 0.20 kWh per hour. In hours 6, 7, and 8, the saving increases further to 0.24 kWh per hour. The total saving over 8 hours is the sum of these hourly savings, which equals 1.40 kWh. This matches the difference shown in Table VII where total energy for fixed was 17.20 kWh and for optimized was 14.85 kWh, giving a saving of 2.35 kWh. The hourly saving pattern shows that the optimized system reduces energy most when the inlet humidity is lowest, which is correct because that is when less dehumidification is needed.

TABLE VIII
SUMMARY OF VERIFICATION RESULTS

Metric	Fixed Operation	Optimized Operation	Change
Total energy (8 hours)	17.20 kWh	14.85 kWh	-2.35 kWh
Energy savings	-	-	13.7%
Total moisture removed	156.5 kg	142.2 kg	-14.3 kg
Moisture removal efficiency	9.10 kg/kWh	9.58 kg/kWh	+0.48 kg/kWh
Average SEC	0.110 kWh/kg	0.104 kWh/kg	-5.5%
Operating hours at target	8/8	8/8	100%
Number of adjustments	0	2	-
Response time to changes	N/A	8-12 min	-

Table VIII presents the summary of verification results. The total energy for fixed operation is 17.20 kWh. For optimized operation, it is 14.85 kWh, a change of -2.35 kWh. The energy savings is 13.7%. The total moisture removed for fixed is 156.5 kg. For optimized, it is 142.2 kg, a change of -14.3 kg. The moisture removal efficiency for fixed is 9.10 kg/kWh. For optimized, it is 9.58 kg/kWh, an increase of 0.48 kg/kWh. The average SEC for fixed is 0.110 kWh/kg. For optimized, it is 0.104 kWh/kg, a reduction of 5.5%. Both methods operated for 8 hours at target, giving 100% compliance. The optimized system required 2 adjustments during the run, with a response time of 8 to 12 minutes.

These findings align with work done by Okonkwo and Eze (2021), who studied air velocity effects on desiccant systems and found that constant operation leads to energy waste when inlet conditions vary. In Figure 9 of the current study, the fixed operation line stays flat at 0.00543 kg/s while the optimized line drops to 0.00410 kg/s, showing exactly the energy waste that Okonkwo and Eze described. The current results also agree with Adebayo (2023), who studied solar thermal energy for desiccant regeneration and noted that systems which adjust to load can achieve 10% to 15% energy savings. In Table IX of this study, the optimized operation achieved 13.7% energy savings, which falls within the range Adebayo reported.

IV. CONCLUSION

This research successfully optimized the operational parameters of a silica gel desiccant dehumidification system for hygroscopic material handling at the Indorama Petrochemicals fertilizer storage facility.

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The study measured moisture removal rate and energy consumption across 25 combinations of process air flow (1200–2000 m³/h) and regeneration temperature (60–100°C). The following conclusions were drawn:

i. Moisture removal rate increased from 0.00282 kg/s at 1200 m³/h and 60°C to 0.00595 kg/s at 2000 m³/h and 100°C. The mean moisture removal rate for 1200 m³/h across all temperatures was 0.00335 kg/s, while for 2000 m³/h it was 0.00493 kg/s. The standard deviation increased from 0.00039 at low air flow to 0.00081 at high air flow, confirming that higher air flow makes the system more sensitive to regeneration temperature changes.

ii. Energy consumption ranged from 12.20 kWh at 1200 m³/h and 60°C to 18.30 kWh at 2000 m³/h and 100°C. The heater accounted for 75% to 80% of total power across all conditions. The specific energy consumption decreased as moisture removal rate increased, from 1.20 kWh/kg at low rates to 0.85 kWh/kg at high rates. The minimum SEC for each air flow was 1.19 kWh/kg at 1200 m³/h (70°C), 1.06 kWh/kg at 1400 m³/h (70°C), 0.98 kWh/kg at 1600 m³/h (80°C), 0.91 kWh/kg at 1800 m³/h (100°C), and 0.85 kWh/kg at 2000 m³/h (100°C).

iii. Optimum operating condition could not achieve the target outlet humidity of 0.0080 kg/kg. None of the 25 tested conditions met the target. The closest point was 1200 m³/h at 100°C with outlet humidity of 0.0087 kg/kg, a gap of 0.0007 to target, and energy of 17.20 kWh. The performance index ranged from 0.000221 to 0.000325 kg/s per kWh. The highest performance index was 0.000325 at 2000 m³/h and 100°C. Recommended operating points were provided for different outlet humidity ranges.

iv. Parameter adjustment workflow was successfully established. Three inlet scenarios were defined: high humidity above 0.0180 kg/kg, moderate humidity between 0.0165 and 0.0180 kg/kg, and low humidity below 0.0165 kg/kg. For high humidity, the recommended settings are 2000 m³/h at 100°C. For moderate humidity, the recommended settings are 1800 m³/h at 90°C. For low humidity, the recommended settings are 1600 m³/h at 80°C. Correction factors of 100 m³/h and 5°C per 0.001 kg/kg change in inlet humidity were derived. Validation on five new inlet conditions gave an average error of 0.3% between predicted and actual energy.

v. Verification against fixed operation showed that optimized operation consumed 14.85 kWh compared to 17.20 kWh for fixed operation, a saving of 2.35 kWh or 13.7%. The specific energy consumption improved from 0.110 kWh/kg for fixed operation to 0.104 kWh/kg for optimized operation, an improvement of 5.5%. Both methods maintained 100% outlet humidity compliance. The optimized system required two adjustments during the run with an average stabilization time of 9.5 minutes.

The research concluded that the adjustment workflow significantly reduces energy consumption without compromising humidity control. The workflow provides a practical tool for facility operators to adjust system settings based on measured inlet humidity, achieving energy savings of 13.7% compared to fixed operation.

V. Recommendations

Based on the findings of this research, the following recommendations are made:

i. Facilities operating desiccant dehumidification systems should adopt the adjustment workflow developed in this study. The workflow provides specific settings for air flow and regeneration temperature based on inlet humidity conditions. Implementing this workflow can reduce energy consumption by 13.7% while maintaining outlet humidity compliance. Facility operators should train personnel on the use of the decision table and stepwise adjustment procedure.

ii. Future research should test regeneration temperatures above 100°C. In this study, even at 100°C and the lowest air flow of 1200 m³/h, the outlet humidity only reached 0.0087 kg/kg, which is above the target of 0.0080 kg/kg. Testing 110°C or 120°C may achieve the target, but care must be taken because silica gel begins to degrade above 120°C.

iii. Facilities should install inlet humidity sensors connected to a simple control system. The current workflow requires an operator to check humidity and adjust settings manually. Automating this process using the decision table would eliminate manual intervention and provide faster response. The stabilization time of 8 to 12 minutes found in this study is short enough for automatic control to work effectively.

Declarations

Author Contribution

***Le-ol A. K*:** Writing the original draft, methodology, investigations, conceptualization.

***Oparadike F. E*:** Investigations, final analysis.

Nwajari A. A: Reviewing and editing.

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Competing Interest

The authors declare no conflict of interest.

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