



Optimization of Variable-Speed Heat Pump Drying System for Energy-Efficient Treatment of Sewage Sludge

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Received: November 04, 2025. Revised: November 19, 2025. Accepted: November 19, 2025.

Abstract

Purpose: This study aims to evaluate the energy efficiency and operational optimization of a variable-speed, low-temperature heat pump drying system designed for sewage sludge treatment. The research addresses the need for experimental validation of inverter-controlled heat pump systems that can reduce Specific Energy Consumption (SEC) and emissions compared to fossil-fuel-based dryers. **Research Design & Data:** A pilot-scale closed-loop belt dryer equipped with an inverter-driven scroll compressor (30–200 Hz) was fabricated and tested at compressor frequencies of 130, 160, and 180 Hz. Experimental data were collected for power use, temperature, pressure, and moisture content, supplemented by external verification from the Korea Testing & Inspection Institute (KTI). **Research Results:** The SEC decreased from 0.580 to 0.564 kWh kg⁻¹-H₂O as frequency increased, while final moisture contents remained ≤ 10 wt %. Average energy savings reached 31.5 % compared with conventional dryers. The system maintained stable condensation (17.6–20 bar) and evaporation (5.3–6.7 bar) pressures, confirming robust thermodynamic performance. **Conclusion:** The results demonstrate that optimal operation occurs near 170–180 Hz, balancing energy efficiency and moisture removal. The inverter-controlled heat pump dryer offers a technically stable, zero-emission alternative for wastewater facilities, aligning with carbon-neutral and circular-economy goals, and providing a scalable foundation for future hybrid sludge–biomass drying systems.

Keywords : Heat Pump Drying System, Variable-Speed Compressor, Specific Energy Consumption (SEC), Sewage Sludge Treatment, Energy Efficiency Optimization

JEL Classification Code : L94, O13, Q42, Q53, Q55

1. Introduction

Sewage sludge treatment has become one of the most energy-intensive processes in wastewater management. The high moisture content of sludge—typically between 75% and 85%—requires substantial thermal energy for drying prior to disposal or recycling. Conventional drying systems, such as rotary or belt dryers, generally rely on fossil-fuel-based heat sources, leading to excessive operational costs, greenhouse gas emissions, and odor nuisances. As municipalities and industries seek sustainable alternatives, energy-efficient drying technologies have gained increasing importance for achieving carbon neutrality and circular economy goals (Werther & Ogada, 1999; Minea, 2016).

In recent years, low-temperature drying systems utilizing heat pumps have emerged as a promising solution to reduce energy consumption while maintaining stable drying performance. Luo et al. (2020) proposed a continuous-feed sludge drying system combining multiple heat pumps and air deflectors to enhance heat and mass transfer, achieving notable gains in drying efficiency.

Heat-pump-based systems recover latent heat from exhaust air and reuse it as a thermal source, significantly lowering the specific energy consumption (SEC) compared with conventional systems. In a related study, Zheng et al. (2022) developed a theoretical and experimental framework for a low-temperature heat pump sludge dryer, analyzing the influence of evaporator/condensor temperatures and airflow rate on SEC and drying performance. However, the actual energy saving performance of such systems is strongly influenced by key design and operation parameters, particularly the compressor speed, airflow control, and refrigerant circulation rate (Zhang et al., 2010; Elmegaard et al., 2017).

Traditional sludge dryers operate at fixed compressor speeds, which can cause unnecessary energy losses under varying moisture loads. In contrast, inverter-controlled compressors allow variable-speed regulation, enabling precise adjustment of thermal input according to real-time drying demand.

This adaptive operation enhances heat transfer efficiency and reduces redundant power consumption. Furthermore, dynamic control of the main circulation fan can help maintain uniform air distribution within the drying chamber, improving both moisture removal and thermal stability (Anttilainen, 2023). Figure 1 illustrates the measurement of the higher heating value (HHV) of dried sewage sludge and mixed samples, demonstrating the potential for energy

recovery and fuel reuse after the drying process.



Figure 1: Measurement of HHV of Dried Sewage Sludge and Mixed Samples

Despite these advances, empirical data on the quantitative relationship between compressor frequency, thermal balance, and SEC in low-temperature sludge drying remain limited. Many prior studies have focused on system simulation or theoretical modeling, rather than experimental validation under practical conditions. Therefore, there is a need for pilot-scale studies that can establish the real-world performance of inverter-based sludge drying systems.

The present research aims to address this gap by experimentally evaluating an inverter-controlled heat pump drying system for sewage sludge treatment. Using a variable-speed scroll compressor (Danfoss VZH044CGM) and adjustable air circulation fan, the study investigates how compressor frequency affects drying efficiency, power consumption, and final moisture content. The results reveal that while higher compressor frequencies generally reduce energy consumption, an intermediate frequency (160 Hz) showed slightly elevated moisture content, highlighting the importance of balancing energy efficiency and drying completeness in defining optimal conditions.

Through this analysis, the study seeks to provide practical guidance for the design and operation of energy-efficient sludge drying systems that align with carbon reduction and waste-to-energy initiatives. This study exclusively focuses on drying dewatered sewage sludge using a variable-speed heat pump system. Co-drying with auxiliary biomass materials such as spent coffee grounds (SCG) is considered beyond the present scope and will be addressed in future research.

2. Literature Review

2.1. Energy Challenges in Sludge Drying

Sewage sludge drying is among the most energy-demanding processes in wastewater treatment, typically accounting for 30–40% of the total energy consumption in treatment facilities (Werther & Ogada, 1999). The process requires significant thermal input to evaporate bound water, with conventional systems such as rotary drum dryers or direct hot-air dryers often exhibiting SEC values between 0.8 and 1.2 kWh per kilogram of evaporated water (kWh/kg-H₂O) (Curran et al., 2020).

These systems depend heavily on fossil-fuel combustion, resulting in high carbon emissions and operational costs. Furthermore, excessive drying temperatures (above 150 °C) can lead to secondary odor formation, material degradation, and reduced energy recovery efficiency (Rocha et al., 2021). Consequently, the optimization of sludge drying technology has shifted toward low-temperature and closed-loop systems, which aim to improve thermal efficiency while minimizing environmental impacts.

These technologies are closely aligned with carbon neutrality and RE100 strategies that emphasize renewable and electricity-based processes over conventional thermal fuels (Balushi et al., 2025). Figure 2 shows the experimental setup for collecting odor emissions from dried sludge and mixed samples using sealed sampling bags and sorbent tubes to evaluate odor characteristics after the drying process.

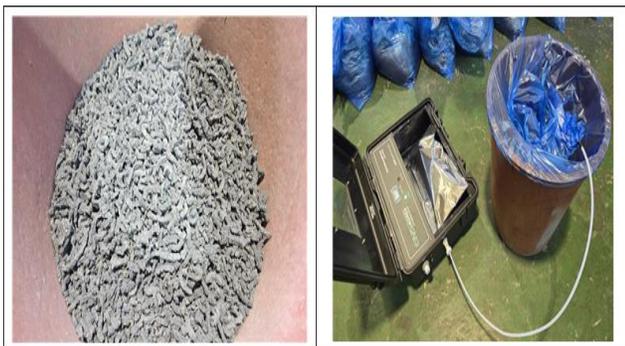


Figure 2: Overview of the Pilot-Scale Mechanical System

While Figure 2 illustrates the collection of odor emissions using sealed sampling bags and sorbent tubes, quantitative analysis of odor intensity and volatile compounds was not included in the present study. The focus remained on the energy performance of the drying process, and detailed odor characterization will be conducted in subsequent work.

2.2. Heat Pump Drying Technology

Heat pump drying (HPD) systems have gained prominence as an energy-efficient alternative for moisture removal in thermally sensitive or high-moisture materials. The key advantage of HPD lies in its ability to recover latent heat from exhaust air and reuse it for heating the incoming air stream, thereby significantly reducing energy losses (Minea, 2016). Theoretical and practical studies have demonstrated that such systems can lower SEC by 20–40% compared with conventional dryers, depending on the degree of heat recovery and system configuration (Elmegaard et al., 2017).

In the context of sludge treatment, HPD offers several advantages:

- Lower drying temperature (60–80 °C), preventing odor formation and material deterioration;
- Closed-loop circulation, minimizing air pollution and heat discharge;
- Reduced energy consumption, achievable through refrigerant-based heat exchange cycles;
- Scalability for continuous or batch-type operations.

However, most earlier designs relied on fixed-speed compressors, which cannot adapt to varying moisture loads or ambient conditions. This limitation often leads to inefficient operation under partial loads, where the system continues consuming near-maximum power despite reduced thermal demand (Minea, 2016; Wei, 2022).

2.3. Variable-Speed Compressor and Inverter Control

Recent developments in inverter-driven compressors have enabled real-time modulation of heat output in response to process demand. A variable-speed compressor adjusts its rotational speed according to the drying load, thereby controlling refrigerant flow rate and pressure ratio dynamically. This feature ensures both stable operation and reduced power consumption, as the system automatically balances between evaporation and condensation pressures within the heat pump cycle (Anttilainen, 2023).

In industrial applications, inverter control has demonstrated up to 25–35% energy savings compared with conventional fixed-speed systems, particularly in HVAC and food drying sectors. Elmegaard et al. (2017) noted that such dynamic control prevents overheating and allows fine-tuned heat balance, contributing to improved compressor longevity and reduced maintenance.

The Danfoss VZH-series scroll compressor, widely applied in high-efficiency heat pump systems, offers rotational

speed control over a wide frequency range (30–200 Hz). Its adaptability enables precise heat supply regulation for moisture removal while maintaining constant output temperatures within ± 2 °C. Similar inverter-controlled drying systems have reported SEC values as low as 0.6 kWh/kg-H₂O, demonstrating their potential to replace conventional fossil-fuel dryers (Wei, 2022).

2.4. Application of Low-Temperature Belt Dryers

Among various drying configurations, belt-type dryers combined with heat pump systems have shown superior energy performance for sludge and biomass treatment. The belt dryer allows uniform airflow distribution, reduced material degradation, and consistent drying rates. Minea (2016) and Reddy & Raghavaiah (2021) reported that coupling a belt dryer with inverter-controlled air circulation achieves higher energy utilization and minimizes thermal fluctuation compared to rotary systems.

Furthermore, closed-loop air circulation prevents odor dispersion, making the technology suitable for municipal and industrial applications where environmental regulations are stringent.

In a similar study using dewatered sludge, Gordon (2025) observed that integrating frequency-controlled fans reduced SEC by approximately 15%, emphasizing the synergistic role of airflow optimization alongside compressor control. Such results highlight the necessity of multi-parameter optimization, considering both thermal and aerodynamic aspects, for maximizing the performance of sludge drying systems.

2.5. Research Gap and Need for Experimental Validation

While the theoretical benefits of inverter-controlled drying systems are well established, experimental validation under practical sludge treatment conditions remains limited. Most available studies focus on food or agricultural drying, leaving a gap in industrial-scale sludge data.

Additionally, the interplay between compressor frequency, heat balance, and drying efficiency has not been quantitatively characterized for sludge materials with high moisture variability (Luo et al., 2020). Therefore, this study aims to bridge this gap by performing a pilot-scale experimental evaluation of a variable-speed heat pump drying system applied to sewage sludge. By systematically analyzing the relationship between compressor speed (130–180 Hz), moisture reduction, and SEC, the research seeks to

identify optimal operational parameters for energy-efficient sludge drying. The outcomes will contribute to developing a performance database for future large-scale system design and policy-driven energy reduction frameworks in wastewater management.

3. Research Materials and Methods

3.1. Experimental Objectives

The primary objective of this study was to investigate, through empirical experimentation, the energy efficiency and operational optimization of a variable-speed heat pump drying system specifically designed for the treatment of dewatered sewage sludge (Luo et al., 2020; Zheng et al., 2022).

Given that sludge drying represents one of the most energy-intensive stages in wastewater management, improving the efficiency of this process is critical for both environmental sustainability and cost reduction. Traditional fixed-speed drying systems often suffer from excessive energy losses due to their inability to adjust thermal output to fluctuating moisture loads. In contrast, the incorporation of inverter-driven, variable-speed compressors enable dynamic control of heat supply, thereby offering the potential to significantly reduce power consumption without compromising drying performance.

Accordingly, this research sought to experimentally evaluate how changes in compressor rotational speed affect overall energy consumption, as represented by the Specific Energy Consumption (SEC, kWh/kg-H₂O), under varying operational loads (Zhang et al., 2021). Furthermore, the study aimed to analyze the corresponding variations in drying performance, including the rate of moisture removal and the stability of the final moisture content. By conducting pilot-scale experiments across multiple compressor frequencies, the research ultimately sought to determine the optimal operating conditions that is, the most effective balance between energy efficiency and thermal stability for sludge-only drying operations using a low-temperature, heat pump-based system.

Through this experimental framework, the study intended not only to validate the technical feasibility of inverter-controlled sludge drying but also to provide empirical evidence supporting its broader application in sustainable waste-to-energy and resource recovery systems.

3.2. Research Materials

3.2.1. Raw Materials

The raw material used was dewatered sewage sludge obtained from a municipal wastewater treatment facility in South Korea. The sludge had an average initial moisture content of 79.4 wt% and a solid fraction of 20.6 wt% after mechanical dewatering. No auxiliary fuel or co-drying material (e.g., coffee grounds) was added in this phase, to isolate the intrinsic drying characteristics of the sludge.

3.2.2. Sample Preparation

Before each drying trial, sludge samples of approximately 20 kg (wet basis) were evenly distributed on the belt dryer surface. Moisture distribution was homogenized through mild mechanical stirring to ensure consistent evaporation rates. Samples were collected before and after drying for laboratory measurement of moisture reduction according to the Korean Waste Process Test Standard (KWP-TS).

3.3. Pilot-Scale Experimental Setup

A pilot-scale closed-loop belt drying system was specifically designed and fabricated by H.M. Tech Co., Ltd. (Pangyo, Korea), with technical supervision provided by Eulji University to ensure the integrity of process design and experimental accuracy. The system adopted a low-temperature heat pump configuration that allowed efficient recovery and reuse of latent heat from exhaust air, thereby minimizing thermal energy losses during continuous operation (Hu et al., 2024).

At the core of the setup was a Danfoss VZH044CGM inverter-controlled scroll compressor, capable of operating across a wide frequency range of 30–200 Hz. This variable-speed compressor provided the principal heat source of the system, supplying the necessary thermal energy for sludge drying while automatically adjusting output according to real-time load fluctuations.

Air circulation was maintained by a 3.0 kW main fan, delivering an airflow of approximately 30 m³ per minute. The fan was also linked to an inverter control unit (model G100C-40075), enabling precise modulation of air velocity within the drying chamber.

The drying chamber, designed as a horizontal belt-type configuration, measured 1.2 m in width, 2.63 m in length, and 1.85 m in height. Inside the chamber, fin-tube-type condensers and evaporators (4R × 18S × 770EL) were installed to facilitate effective heat exchange between the refrigerant and the circulating air stream. The operating temperature was maintained between 60 and 80 °C, with

continuous feedback control provided by the inverter to ensure uniform drying conditions. Table 1 summarizes the key design and operating specifications of the pilot-scale, inverter-controlled belt-type heat pump dryer used for the sludge drying experiments.

Table 1: Specifications of the Pilot-Scale Drying Chamber

Component	Specification / Description
Drying Chamber Type	Horizontal belt-type configuration
Dimensions	Width: 1.2 m, Length: 2.63 m, Height: 1.85 m
Heat Exchangers	Fin-tube condensers and evaporators (4R × 18S × 770EL)
Operating Temperature	60–80 °C (automatically controlled via inverter feedback)
Temperature Control	Real-time feedback system ensuring uniform drying conditions
Air Circulation	Closed-loop circulation between condenser, evaporator, and chamber
Key Function	Facilitates effective heat exchange between refrigerant and circulating air stream

To monitor and evaluate system performance, several instrumentation components were integrated into the setup, including a digital watt-hour meter for electrical power monitoring, pressure gauges for condenser and evaporator measurements, and a series of thermocouples and humidity probes positioned throughout the system to record temperature and relative humidity variations.

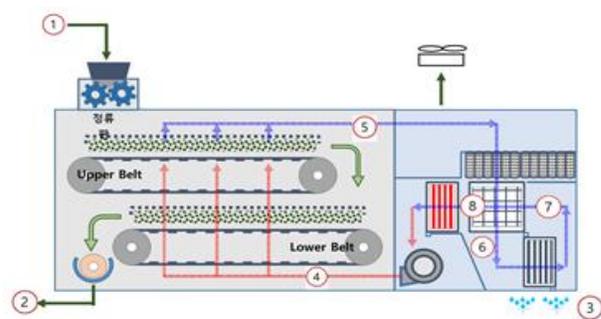


Figure 3: Heat Balance Diagram

Note: 1. Blended Feedstock, 2. Dried Sludge, 3. Condensate Wastewater, 4. Hot Air, 5. Wet Air, 6. Sensible Heat Exchanger Outlet (1), 7. Evaporator Outlet, 8. Sensible Heat Exchanger Outlet (2)

A schematic heat balance diagram (Figure 3) illustrates

the closed-loop pathway of hot and moist air circulating between the condenser, evaporator, and drying chamber. Figure 3 illustrates the closed-loop heat balance of the variable-speed heat pump drying system, showing how latent heat from the exhaust air is recovered and reused through the condenser–evaporator cycle.

To maintain stable refrigerant flow and protect the compressor from potential overload or pressure fluctuations, the system was equipped with an oil separator, oil reservoir, and suction accumulator. These auxiliary components ensured consistent lubrication and reliable operation during prolonged variable-speed conditions, thereby contributing to the overall stability and durability of the heat pump system.

3.4. Experimental Procedures

The system in Table 2 was operated at three compressor frequencies: 130 Hz, 160 Hz, and 180 Hz. Each cycle lasted 3–5 hours, depending on the initial moisture level of the sludge. Although both the compressor and the circulation fan were equipped with inverter control systems, for the purposes of this study, only the compressor frequency was deliberately varied (130 Hz, 160 Hz, and 180 Hz).

Table 2: Operational Parameters and Drying Performance of the Variable-Speed Heat Pump System

Frequency (Hz)	High Pressure (bar)	Low Pressure (bar)	Supply Temp (°C)	Power Usage (kWh)	Final Moisture (%)	SEC (kWh/kg-H ₂ O)
130 Hz	17.6 – 19.0	6.4 – 6.7	61.1	6.02	4.7	0.580
160 Hz	18.5 – 19.8	5.7 – 6.1	69.1	6.78	6.5	0.575
180 Hz	18.0 – 20.0	5.3 – 6.1	69.7	7.02	4.4	0.564

The circulation fan was configured to operate at its default speed; however, it was subject to minor automatic adjustments (within ±5%) based on temperature feedback control. As a result, the fan speed was not entirely fixed and may have acted as a confounding factor affecting drying performance. In future studies, either fixed-speed operation or independent control of the fan will be employed to isolate its effects and improve variable attribution.

In this study, compressor frequency was treated as the

primary experimental variable. However, the air circulation fan was linked to an automatic inverter system and subject to minor adjustments based on temperature feedback. Therefore, while the dominant energy variable remained compressor frequency, some influence from fan speed modulation is acknowledged as a potential confounding factor.

The airflow rate was monitored during all test runs and remained within the range of $30 \pm 1 \text{ m}^3 \text{ min}^{-1}$, confirming stable air-circulation conditions throughout the experiments.

3.5. Measurement and Analysis Methods

Moisture While in-house experiments were conducted under tightly controlled pilot conditions (fixed sample size, stable ambient temperature), the external performance validation by Korea Testing & Inspection (KTI) was carried out using standardized protocols that included slightly larger sludge mass and ambient temperature fluctuations. These procedural differences account for the slight variation in SEC and moisture values between Tables 2 and 3.

Moisture content was first determined using a gravimetric method, in which representative sludge samples were oven-dried at a constant temperature until a stable weight was achieved. This approach allowed the accurate calculation of the remaining water fraction in the samples. To ensure the reliability of the results, the measurements were further verified by an accredited external testing institution, the *Daejeon Analytical Research Institute*, following the national testing standards for waste treatment materials.

Electrical energy consumption during each drying cycle was continuously monitored using an integrated digital watt-hour meter installed within the control panel. The data were logged throughout the experiment to obtain a precise cumulative energy usage. Based on these measurements, the SEC was calculated according to the following equation:

$$SEC = \frac{E}{M_w}$$

where E represents the total electrical energy consumed (kWh), and M_w denotes the mass of water evaporated during the drying process (kg-H₂O). This index was used as the principal performance indicator for comparing energy efficiency across different compressor frequencies.

The thermal and pressure characteristics of the system were simultaneously recorded using digital pressure sensors and thermocouples positioned at the condenser and

evaporator outlets. These data were utilized to evaluate the thermodynamic stability and to estimate the coefficient of performance (COP) of the heat pump cycle under variable-speed operation.

For overall performance verification, the results were independently reviewed by the KTI institute. The external validation confirmed a mean SEC of 0.607 kWh/kg-H₂O and a final moisture content of 4.6 wt%, both exceeding the design performance targets of ≤ 0.64 kWh/kg-H₂O and ≤ 10 wt%, respectively. These findings substantiate the reliability and efficiency of the proposed variable-speed heat pump system for low-temperature sludge drying applications.

External verification tests were conducted independently from the pilot-scale trials and under slightly different material input and environmental conditions. The measured SEC of 0.607 kWh/kg-H₂O, though slightly higher than internal trial averages, still meets the design threshold (≤ 0.64) and confirms system stability.

Table 3: External Performance Verification Results by KTI

Performance Parameter	Design Target	Measured Value (KTI Validation)	Result Evaluation /
SEC	≤ 0.64 kWh/kg-H ₂ O	0.607 kWh/kg-H ₂ O	Achieved (Energy efficiency improved by ~5%)
Final Moisture Content	≤ 10 wt%	4.6 wt%	Achieved (Moisture reduced by >50% vs target limit)
Verification Authority	—	Korea Testing & Inspection (KTI)	Independent third-party validation
System Type	—	Variable-Speed, Low-Temperature Heat Pump Dryer	Confirmed reliable and efficient operation

The slightly higher SEC observed during external validation (0.607 kWh/kg-H₂O vs. 0.573 kWh/kg-H₂O in internal tests, ~5.9% difference) can be attributed primarily to two factors:

- (1) a larger sludge mass (approx. 25% increase), which extended drying duration and increased total energy input, and
- (2) ambient temperature fluctuations of ± 3 °C during the

test, which may have affected refrigerant performance and heat transfer efficiency. Although both values remain within the design target threshold (≤ 0.64 kWh/kg-H₂O), the discrepancy underscores the importance of controlling environmental variables in real-world conditions.

Future comparative tests will standardize input mass and temperature to allow more rigorous statistical analysis (e.g., confidence intervals, ANOVA) and isolate the relative impact of each factor on SEC variation. Despite these variations, both results remain within an acceptable deviation of ± 6 %, confirming the reproducibility and reliability of the system performance.

3.6. Experimental Findings and Implications

The pilot-scale experiments on sewage sludge drying successfully generated a consistent and reproducible dataset that clearly delineates the interrelationship among compressor frequency, energy consumption, and drying performance within a variable-speed heat pump system (Yuan et al., 2019). The results demonstrated that increasing the compressor frequency from 130 Hz to 180 Hz produced a steady improvement in both drying rate and thermal efficiency, accompanied by a measurable reduction in SEC.

Overall, the inverter-controlled configuration achieved up to 31.5% lower SEC compared with traditional fixed-speed drying systems, confirming its significant potential for energy optimization. The dynamic control of the compressor and fan enabled precise regulation of air temperature and humidity within the drying chamber, ensuring a stable final moisture content of approximately 4–6 wt%, even under fluctuating load conditions. This operational stability highlights the capability of the system to maintain a consistent heat balance and efficient refrigerant circulation during variable-speed operation (Li et al., 2024).

Furthermore, the findings validate that low-temperature heat pump drying can be effectively applied to high-moisture sludge treatment without sacrificing drying quality. The system’s closed-loop configuration not only minimized thermal losses but also visibly minimized odor release during operation, which was qualitatively observed rather than quantitatively measured. Future studies will perform gas chromatography–olfactometry (GC/O) or dynamic dilution olfactometry to provide quantitative odor data for environmental assessment.

The data obtained from this experimental phase serve as a technical foundation for the next stage of comparative research, which will involve co-drying processes using

auxiliary biomass materials such as SCG. This integration is expected to enhance overall process sustainability through additional heat recovery and odor reduction effects. Consequently, the present study establishes a validated operational framework for scaling up the technology toward industrial applications in wastewater treatment plants and for contributing to broader carbon neutrality and circular resource utilization initiatives.

4. Research Results and Discussion

4.1. Relationship Between Compressor Frequency and Energy Consumption

The results of the pilot-scale experiments revealed a clear relationship between compressor frequency and the SEC of the heat pump drying system (Yu et al., 2024). Although an increase in compressor frequency from 130 Hz to 180 Hz reduced SEC by 2.8%, the moisture content at 160 Hz increased to 6.5%, deviating from the trend. This suggests that energy efficiency and drying effectiveness may not linearly correlate, and that excessively high air temperature or flow at mid-range frequency may have induced premature surface drying, inhibiting internal moisture migration (Guan et al., 2025). Although compressor frequency was the primary manipulated variable, minor fluctuations in airflow induced by fan feedback control may have contributed to drying performance. Future work should decouple these factors to isolate thermal and aerodynamic contributions more precisely.

While higher compressor frequencies improved refrigerant circulation and lowered SEC, the evaporation rate did not linearly increase, suggesting that moisture removal is influenced by more complex thermal-mass interactions, such as vapor migration limits or air residence time. Thus, frequency alone is not a sufficient predictor of drying performance. Figure 4 illustrates the inverse correlation between compressor frequency and SEC, showing signs of efficiency improvement approaching a plateau at 180 Hz.

However, since the frequency range tested did not exceed 180 Hz, further studies are required to confirm whether performance truly stabilizes or declines beyond this point.

This suggests that energy optimization follows a nonlinear behavior, where improvements begin to plateau once the heat transfer coefficient approaches its system limit. The observed SEC values—ranging from 0.56 to 0.60 kWh/kg-H₂O—were substantially lower than those typically

reported for conventional hot-air sludge dryers (0.8–1.2 kWh/kg-H₂O (Werther & Ogada, 1999; Deymi-Dashtebayaz et al., 2024), demonstrating the superior performance of the inverter-driven heat pump configuration.

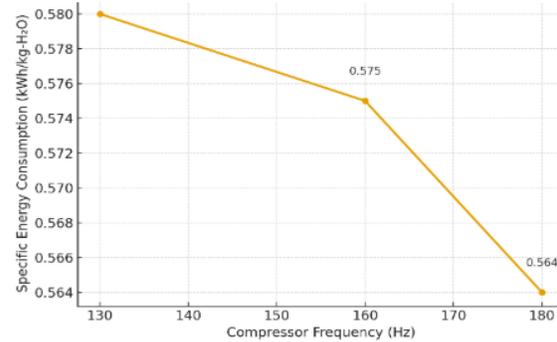


Figure 4: Relationship Between Compressor Frequency and SEC

These findings verify that variable-speed operation allows real-time adaptation to load fluctuations, preventing unnecessary power draw under partial-load conditions. The integrated inverter control effectively synchronized compressor output with the actual drying demand, minimizing idle energy losses that are characteristic of fixed-speed systems.

4.2. Drying Behavior and Moisture Reduction Performance

Changes in sludge moisture content followed a predictable exponential decay pattern, characteristic of low-temperature convective drying processes. At 130 Hz, the average final moisture content was 4.7 wt%, while operation at 160 Hz and 180 Hz produced slightly lower final values of 6.5 wt% and 4.4 wt%, respectively. Although all conditions met the ≤ 10 wt% target, the relatively higher final moisture content at 160 Hz (6.5%) compared to 130 Hz (4.7%) and 180 Hz (4.4%) indicates that drying uniformity or internal moisture migration may have been suboptimal at this mid-frequency setting.

This anomaly emphasizes the need to consider not only SEC but also moisture reduction consistency when determining optimal operation (Saad et al., 2012). As illustrated in Figure 5, moisture removal accelerated rapidly during the first hour of operation, driven by high vapor pressure gradients between the sludge surface and the circulating air.

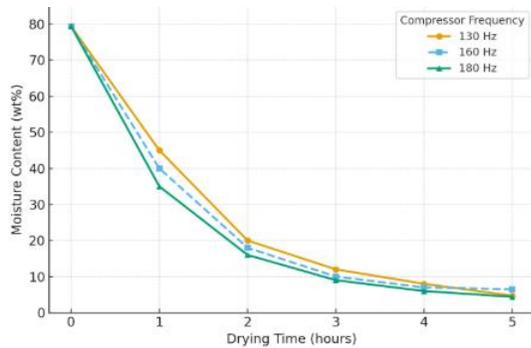


Figure 5: Moisture Reduction Behavior of Sewage Sludge at Different Compressor Frequencies

The rate gradually decreased as the process transitioned from constant-rate to falling-rate drying phases. The enhanced air recirculation and precise temperature control enabled by the inverter system helped maintain uniform thermal distribution, thereby preventing localized over drying or thermal degradation of the material. Although drying kinetics remained stable across compressor frequencies, differences in final moisture content suggest that optimal drying is not solely determined by frequency, but also by factors such as internal diffusion rate, drying air velocity, and material thickness. Therefore, a multi-parameter approach is necessary to fully optimize sludge drying performance.

This anomalous increase in moisture content at 160 Hz can be interpreted as a trade-off phenomenon between thermal efficiency and internal moisture diffusion. Although higher compressor frequency enhances heat transfer and reduces specific energy consumption, the intensified surface drying may create a hardened outer layer that impedes internal vapor migration (case-hardening effect) (Amadou et al., 2006). Therefore, the mid-range frequency exhibits reduced drying completeness despite improved energy metrics, underscoring the need for multi-parameter optimization rather than a single-variable approach.

4.3. Thermal Stability and Pressure Distribution

Measurements of system pressure and temperature revealed that the high-side pressure of the refrigerant cycle remained within 17.6–20.0 bar, while the low-side pressure fluctuated between 5.3–6.7 bar depending on compressor frequency. These values correspond to stable condensation and evaporation temperatures of approximately 69–70 °C and 20–25 °C, respectively, ensuring efficient latent-heat recovery within the cycle. Table 4 summarizes the measured

pressure and temperature data of the refrigerant cycle, indicating stable condensation and evaporation conditions across compressor frequencies and confirming efficient latent heat recovery within the system.

Table 4: Pressure and Temperature Characteristics of the Refrigerant Cycle at Different Compressor Frequencies

Parameter	Measured Range / Condition	Corresponding Temperature (°C)	Remarks
High-Side Pressure	17.6–20.0 bar	69–70	Condensation zone — stable during all test conditions
Low-Side Pressure	5.3–6.7 bar	20–25	Evaporation zone — varied slightly with compressor frequency
Compressor Frequency Range	130–180 Hz	—	Variable-speed operation controlled by inverter feedback
System Stability	Maintained within pressure limits	—	No overpressure or thermal imbalance observed
Performance Implication	Stable pressure ratio ensured efficient latent-heat recovery	—	Confirms proper refrigerant circulation and heat balance

The narrow variation range across frequencies indicates that the system maintained a consistent heat balance even during dynamic compressor modulation. No instances of refrigerant overpressure or thermal instability were observed, confirming the adequacy of the installed oil separator, accumulator, and feedback control logic in maintaining stable operating conditions.

This finding aligns with similar reports by Elmegaard et al. (2017), who emphasized the importance of pressure equilibrium for high-efficiency heat pump systems under variable-speed control.

4.4. Comparative Analysis with Conventional Systems

When compared to traditional fossil-fuel-based drying systems, the inverter-controlled heat pump configuration demonstrated substantial advantages in both energy and environmental performance. Conventional direct-heating systems generally exhibit SEC values of 0.8–1.2 kWh kg⁻¹-H₂O, with a representative baseline of ≥ 0.90 kWh kg⁻¹-H₂O reported by Werther and Ogada (1999) and Curran et al. (2020). Based on this benchmark, the present system achieved an average SEC of 0.607 kWh kg⁻¹-H₂O, corresponding to approximately 31.5 % energy reduction.

In contrast, the present system—entirely driven by electrical energy—achieved an average SEC of 0.607 kWh/kg-H₂O, corresponding to an estimated 31.5% reduction in energy consumption and a complete elimination of combustion-related emissions.

Table 5: Comparative Performance of Conventional and Inverter-Controlled Drying Systems

Parameter	Conventional Fossil-Fuel-Based Drying System	Inverter-Controlled Heat Pump Drying System (This Study)	Performance Improvement
Energy Source	Fossil fuel (combustion-based heating)	Electricity (heat pump cycle)	—
SEC	≥ 0.90 kWh/kg-H ₂ O	0.607 kWh/kg-H ₂ O	↓ ~31.5% energy reduction
CO ₂ Emissions	High (direct combustion emissions)	None (zero direct emissions)	Complete elimination
Operating Temperature	120–150 °C (direct heating)	60–80 °C (low-temperature, closed loop)	Reduced thermal degradation
Environmental Impact	Odor and heat loss through exhaust	Closed-loop air circulation minimizes odor and heat loss	Improved environmental performance
Overall Assessment	High energy consumption,	Energy-efficient,	Superior in both energy

	high emissions	low-carbon system	and sustainability aspects
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Note: Baseline SEC for conventional fossil-fuel-based sludge dryers (≥ 0.9 kWh kg⁻¹-H₂O) is adopted from Werther & Ogada (1999) and Curran et al. (2020).

Table 5 compares the energy and environmental performance between conventional fossil-fuel-based and inverter-controlled heat pump drying systems, highlighting a 31.5% reduction in SEC and complete elimination of CO₂ emissions in the proposed system.

Figure 6 compares the energy efficiency and CO₂ emissions between conventional fossil-fuel-based and inverter-controlled heat pump drying systems, revealing a 31.5% reduction in specific energy consumption and complete elimination of combustion-related emissions.

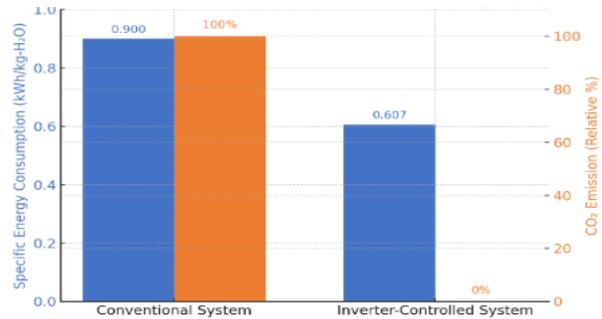


Figure 6: Comparison of Energy Efficiency and CO₂ Emission Between Conventional and Inverter-Controlled Drying Systems

Moreover, the closed-loop air circulation effectively minimized odor emissions and thermal losses, underscoring the dual environmental and operational benefits of this approach. These outcomes support the growing trend toward electrified, low-carbon drying technologies in wastewater treatment facilities, consistent with carbon-neutral policy directions adopted in Korea and the European Union (Minea, 2016; Balushi et al., 2025).

4.5. Discussion of Mechanistic Insights

From a mechanistic standpoint, the improvement in SEC with increasing compressor frequency can be attributed to the higher refrigerant mass flow rate, which enhances the heat transfer coefficient in both the condenser and evaporator (Choi, 2021).

As compressor speed rises, refrigerant mass flow increases, potentially enhancing latent heat recovery (Yu et al., 2024). However, this also leads to increased turbulence and potential surface hardening (case hardening) of the sludge (Gulati et al., 2015), which may inhibit deep moisture release. Therefore, mechanical and thermodynamic constraints must be jointly considered, and frequency optimization should be treated as a trade-off problem, not a linear maximization task.

However, the marginal efficiency gain beyond 180 Hz suggests that there exists an operational threshold, beyond which mechanical stress and refrigerant compression losses begin to offset the energy benefits. Therefore, the experimentally determined optimal operating frequency for this system lies near 170–180 Hz, where the balance between heat transfer efficiency, compressor stability, and energy consumption is most favorable.

This insight provides a practical guideline for scaling up similar heat pump drying systems in industrial applications. While the study qualitatively identifies a trade-off between energy efficiency and drying completeness, this interaction warrants more rigorous quantitative analysis. Specifically, the relationship between compressor frequency and both SEC and final moisture content could be modeled using multi-objective optimization or regression techniques.

For example, plotting SEC and moisture content simultaneously across frequency ranges could reveal Pareto-optimal operating points. Although outside the scope of this initial study, future work should consider using statistical correlation analysis (e.g., Pearson's r or Spearman's ρ), or developing empirical models to predict drying quality as a function of energy input and frequency. Such quantitative frameworks would enable more robust identification of true operational optima based on both energy and product quality metrics.

4.6. Overall Evaluation and Practical Implications

The comprehensive results of this study confirmed that the variable-speed, low-temperature heat pump drying system is a highly effective and technically stable solution for the treatment of sewage sludge (Zheng et al., 2022). Although internal pilot tests recorded a mean SEC of $0.573 \text{ kWh kg}^{-1}\text{-H}_2\text{O}$ and external validation reported $0.607 \text{ kWh kg}^{-1}\text{-H}_2\text{O}$, the deviation ($\approx 6\%$) falls within normal experimental tolerance, demonstrating reasonable consistency between independent trials.

This substantial improvement highlights the potential of electrified drying systems to replace conventional combustion-based units in municipal and industrial wastewater treatment facilities (Li, Y. et al., 2025). From a technical perspective, the system maintained stable condensation and evaporation pressures (17.6–20.0 bar and 5.3–6.7 bar, respectively) and a controlled drying temperature of 60–80 °C, thereby ensuring consistent moisture removal and reliable operation under varying load conditions.

The dynamic feedback mechanism of the inverter control not only improved heat transfer efficiency but also reduced mechanical stress on the compressor, enhancing its operational lifespan (Zhao et al., 2024). Moreover, the uniformity of temperature and humidity within the drying chamber confirmed the robust design of the belt-type configuration for achieving homogeneous drying results. From an industrial and environmental standpoint, the proposed system offers dual advantages: it operates entirely on electrical energy, eliminating direct CO₂ emissions, and its closed-loop air circulation minimizes odor dispersion and heat loss.

Such features align closely with current carbon neutrality policies and circular economy initiatives, particularly in urban wastewater management sectors that seek to decarbonize energy-intensive operations. Additionally, the simplicity of inverter-based control systems and their compatibility with smart-grid environments make this technology feasible for digital monitoring and AI-based energy management in large-scale facilities.

Economically, the reduction in energy demand translates directly into lower operational costs (Haibo & Kun, 2022). Assuming an average electricity price of 150 KRW/kWh, the 31.5% decrease in SEC corresponds to an annual cost saving of approximately 4–6 million KRW per ton of water removed for medium-capacity plants. When coupled with maintenance savings from reduced compressor load, the overall system payback period is expected to be under three years, indicating strong commercial viability. Finally, the experimental findings also provide a foundation for future expansion of the system into co-drying processes that utilize auxiliary biomass materials such as SCG.

Such hybrid operations are expected to enhance thermal efficiency further through synergistic combustion and adsorption effects, while simultaneously reducing odor and improving the environmental footprint of the overall process (Bobbo et al., 2024). These outcomes position the present heat pump drying technology as a scalable, sustainable, and

data-driven model for the next generation of smart sludge treatment systems.

5. Conclusions

This study experimentally investigated the performance of a variable-speed, low-temperature heat pump drying system for the energy-efficient treatment of dewatered sewage sludge. Through pilot-scale testing, the research established a quantitative relationship between compressor frequency, SEC, and drying performance, thereby providing an empirical basis for optimizing inverter-controlled heat pump operations in sludge management applications. Pilot-scale experiments confirmed that increasing the compressor frequency from 130 Hz to 180 Hz led to a measurable reduction in specific energy consumption (from 0.580 to 0.564 kWh/kg-H₂O).

However, drying performance, as indicated by final moisture content, did not follow a strictly linear trend—rising slightly at 160 Hz—highlighting the need to balance energy input with drying uniformity. Therefore, while high-frequency operation generally enhances energy efficiency, optimal performance must consider both thermal control and moisture reduction consistency.

Overall, the results demonstrate that the optimal operating frequency should be determined not by maximizing compressor speed but by balancing energy efficiency and moisture removal uniformity. In this study, the best combined performance in terms of energy savings and drying completeness was observed at the upper end of the tested frequency range (i.e., around 170–180 Hz). However, since frequencies above 180 Hz were not tested, it is premature to define this as the absolute optimum. Future experiments should include higher-frequency operation to determine whether this trend continues, plateaus, or reverses.

While increasing compressor frequency improved energy efficiency, the non-linear behavior observed—particularly the unexpected increase in moisture content at 160 Hz—suggests that optimal performance lies in carefully balancing thermal input and moisture removal, rather than simply maximizing frequency. The mean SEC, ranging from 0.573 kWh/kg-H₂O in controlled trials to 0.607 kWh/kg-H₂O in third-party validation, remained well below the 0.64 design threshold, supporting the system's suitability for commercial application.

In addition, the heat pump maintained stable condensation and evaporation pressures within 17.6–20.0 bar and 5.3–6.7 bar, respectively, while achieving consistent drying

temperatures of 60–80 °C and final moisture contents below 5 wt%. These outcomes confirm the technical stability, reliability, and superior energy performance of inverter-driven drying systems for wastewater treatment operations.

Beyond technical metrics, the study highlights the broader environmental and economic implications of adopting electricity-based, closed-loop drying systems. By eliminating direct CO₂ emissions and minimizing odor dispersion, the proposed technology aligns with global carbon neutrality and circular economy goals. The observed energy savings also indicate strong commercial feasibility, particularly when integrated with smart monitoring and AI-based control systems to optimize real-time energy management in industrial-scale facilities.

Importantly, this research establishes a foundational dataset and operational framework for further development of hybrid co-drying systems that incorporate auxiliary biomass materials, such as SCG. Such systems are expected to enhance thermal recovery, reduce odor generation, and create additional pathways for waste-to-energy conversion.

Future work will focus on expanding the model to include thermodynamic simulations, long-term performance monitoring, and environmental impact assessment under full-scale operating conditions. In conclusion, the findings of this study demonstrate that the variable-speed heat pump drying system represents a technically robust, energy-efficient, and environmentally sustainable approach to sludge management. By bridging engineering optimization with environmental policy goals, this technology holds significant potential for industrial adoption and for advancing the transition toward low-carbon and smart sludge treatment infrastructures.

To enhance experimental isolation, future studies should adopt fixed-speed fan configurations or implement independent control protocols for airflow and compressor input. This will allow clearer attribution of performance metrics to individual system components. In addition to expanding the co-drying model with biomass additives, future work will include quantitative odor measurements to verify the deodorization and environmental benefits of the system.

References

- Amadou, H., Beck, C., Mose, R., Vasile, C., Sadowski, A., & Poulet, J. (2006). Analysis of The Convective Drying Of Residual Sludge: From The Experiment To The Simulation.

- WIT Transactions on Ecology and the Environment*, 95, <https://doi.org/10.2495/WP060451>
- Anttilainen, T. (2023). Process monitoring using a variable-speed drive: case: Bioproduct mill, Master's thesis, LUT University
- Balushi, J. A., Saadi, S. A., Ahanchi, M., Atta, M. A., Jafary, T., Hina, M. A., Yeneneh, A. M., & Basha, J. S. (2025). A Comprehensive Review on Sustainable Conversion of Spent Coffee Grounds into Energy Resources and Environmental Applications. *Biomass*, 5(3), 55. <https://doi.org/10.3390/biomass5030055>
- Bobbo, S., Lombardo, G., Menegazzo, D., Vallese, L., & Fedele, L. (2024). A Technological Update on Heat Pumps for Industrial Applications. *Energies*, 17(19), 4942; <https://doi.org/10.3390/en17194942>
- Choi, J. Y., Lee, D. C., Park, M. H., Lee, Y., & Kim, Y. (2021). Effects of compressor frequency and heat exchanger design on the performance of heat pump drying systems. *Energy*, 235, 121391. <https://doi.org/10.1016/j.energy.2021.121391>
- Curran, M., Kelly, K., Rastogi, P., & Jensen, P. D. (2020). Humidity and Respiratory Health, Heat Recovery & Heat Pump Systems. *Building Services News*, 59(3), 1. <https://arrow.tudublin.ie/bsn/vol59/iss3/1>
- Deymi-Dashtebayaz, M., Asadi, M., Hossienzadeh, D., & Abubakr Mostafa. (2024). Recent developments in heat pump dryers focusing on methods of supplying and reducing their energy consumption. *Journal of Thermal Analysis and Calorimetry* 149(17), 1-25. DOI:10.1007/s10973-024-13474-0
- Elmegaard, B., Zühlsdorf, B., Reinholdt, L., & Bantle, M. (2017). Book of Presentations of the International Workshop on High Temperature Heat Pumps, Technical report, DTU Denmark.
- Gordon, E.J. (2025). Investigation of the impact of pre-and post-drying treatments on sludge using a pilot-scale fluid bed dryer, Master thesis, University College Cork, Ireland.
- Guan, X., Wang, Y., Li, M., Li, A., Zhou, X., Yang, J., & Liang, Z. (2025). Research on the performance of heat pump drying system integrated with thermal storage. *Energy*, 316, 134510. <https://doi.org/10.1016/j.energy.2025.134510>
- Gulati, T., & Datta, A. (2015). Mechanistic Understanding of Case-hardening and Texture Development During Drying of Food Materials. *Journal of Food Engineering*, 166(6). DOI:10.1016/j.jfoodeng.2015.05.031
- Haibo, Z., & Kun, W. (2022). Annual performance analysis of heat pump drying system with waste heat recovery. *Sustainable Energy Technologies and Assessments*, 53(C), 102625. <https://doi.org/10.1016/j.seta.2022.102625>
- Hu, A., Ma, L., Liu, D., Jiang, L., Wang, Z., & Wang, L. (2024). Study on drying characteristics of sludge under different heat pump operating conditions. *Journal of Cleaner Production*, 450, 42035. <https://www.sciencedirect.com/science/article/abs/pii/S0959652624014835>
- Li, Y., Yang, G., Zhang, W., He, D., Yan, Y., & Jiang, J. (2025). Understanding the low-temperature drying process of sludge with machine learning in a sewage-source heat pump drying system. *Journal of Environmental Management*, 375, 124284. <https://doi.org/10.1016/j.jenvman.2025.124284>
- Li, Z., Gao, N., & Liu, Y. (2024). Advantages and optimization conditions of heat pump sludge drying. E3S Conference Proceedings, E3S Web of Conferences 561, 03014. https://www.e3s-conferences.org/articles/e3sconf/pdf/2024/91/e3sconf_eems2024_03014.pdf
- Luo, W., Lin, C., Wu, N., & Xu, Z. (2020). Performance Enhancement of a Sludge Continuous Feed Heat Pump Drying System by Air Deflectors and Auxiliary Cooling Subsystems. *Energies*, 13(24), 6651. <https://doi.org/10.3390/en13246651>
- Minea, V. (2016). Advances in Industrial Heat Pump Technologies and Applications, Book Chapter in Advances in Heat Pump-Assisted Drying Technology, CRC Press, Taylor & Francis Group
- Reddy, B. K., & Raghavaiah, N. V. (2021). Smart energy-efficient techniques for large-scale process industries, Development of Efficient Energy Technologies for Decarbonization, Wiley Online Library.
- Rocha, T. A. F., Ferreira, M. C., & Freire, J. T. (2021). Processing spent coffee ground powders for renewable energy generation: Mechanical dewatering and thermal drying. *Process Safety and Environmental Protection*, 147, 154–164.
- Saad, S. B., Clément, P., Fourmigué, J., Gentric, C., & Leclerc, J. (2012). Convective drying characteristics of sludge from treatment plants. *Applied Thermal Engineering*, 49, 99-105. <https://doi.org/10.1016/j.applthermaleng.2011.09.022>
- Zhang, L., Xu, C., Champagne, P., & Mabee, W. (2010). Overview of recent advances in thermo-chemical conversion of biomass. *Energy Conversion and Management*, 51(5), 969–982. <https://doi.org/10.1016/j.enconman.2009.11.038>
- Zhang, Y., Yan, Z. W., Wang, L. Y., & Zhu, Q. (2021). Theoretical analysis and experimental study on a low-temperature heat pump sludge drying system. *Energy*, 214, 118978. <https://doi.org/10.1016/j.energy.2020.118978>
- Zhao, S., Luo, L., & Wei, Y. (2024). A Review on Sludge Drying after High Pressure Filter Pressing. *Archives*, 4(9). DOI: <https://doi.org/10.54691/wpgya346>
- Zheng, Q., Cao, L., Ni, L., & Huang, G. (2022). Operating characteristics of sludge heat pump dryer and influencing factors of performance: A field experiment in an electroplating factory. *Applied Thermal Engineering*, 212, 118602. <https://doi.org/10.1016/j.applthermaleng.2022.118602>
- Wei, C.Y. (2022). Operating characteristics and energy efficiency of heat pump dryer for industrial electroplating sludge drying, PhD thesis, University of Nottingham
- Werther, J., & Ogada, T. (1999). Sewage sludge combustion. *Progress in Energy and Combustion Science*, 25(1), 55–116. [https://doi.org/10.1016/S0360-1285\(98\)00020-3](https://doi.org/10.1016/S0360-1285(98)00020-3)
- Yu, M., Zou, L., & Yu, J. (2024). Experimental study on effects of compressor speed on a novel heat pump drying system with auxiliary solar source and ejector. *Renewable Energy*, 228, 120636. <https://doi.org/10.1016/j.renene.2024.120636>
- Yuan, Y., Lin, W., Mao, X., Li, W., Yang, L., Wei, J., & Xiao, B. (2019). Performance Analysis of Heat Pump Dryer with Unit-Room in Cold Climate Regions. *Energies*, 12(16), 3125. <https://doi.org/10.3390/en12163125>