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Performance Evaluation of Hybrid Sludge Fuel Made from Sewage Sludge and Spent Coffee Grounds

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Abstract

Purpose: This study aims to evaluate the performance of a hybrid biofuel composed of sewage sludge (SS) and spent coffee grounds (SCG), focusing on energy efficiency, drying kinetics, fuel quality, and odor reduction. **Research Design & Data:** A pilot-scale, low-temperature heat pump drying system equipped with a variable-speed compressor was used to process a 90:10 SS-SCG mixture. Key metrics assessed included final moisture content, specific energy consumption (SEC), lower heating value (LHV), volatile solids content, and odor dilution-to-threshold ratio. **Results:** The optimal performance was achieved at 160 Hz compressor frequency, resulting in a final moisture content of 5.1% and the lowest SEC (0.582 kWh/kg-H₂O). The hybrid fuel exhibited an LHV of 3,394 kcal/kg and volatile solids content of 66.8%, surpassing standard thresholds for solid recovered fuels. Odor emissions were significantly reduced by 98.8%, from 24,548 to 300 D/T units, due to SCG's adsorptive properties. **Conclusion:** The integration of SCG into SS improves drying performance, enhances fuel quality, and drastically reduces odor, offering a promising pathway for renewable energy production and sustainable waste management. These findings contribute to the circular economy by valorizing underutilized organic residues into high-performance biofuels.

Keywords : Hybrid sludge fuel, Spent coffee grounds (SCG), Sewage sludge valorization, Low-temperature drying, Renewable solid fuel

JEL Classification Code : O13, L95, Q42, Q53, Q55

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1. Introduction

The global imperative to transition towards sustainable waste management and renewable energy systems has intensified interest in the valorization of organic waste streams through thermochemical conversion into solid fuels. Among these waste types, sewage sludge (SS), as a semi-solid residue generated from municipal and industrial wastewater treatment, presents considerable environmental and operational challenges. Sludge incineration and landfilling are facing increasing public resistance and legal restrictions, driving interest in alternative valorization pathways (Fytili & Zabaniotou, 2008).

Its high moisture content (often exceeding 70%), strong odor emissions, and pathogenic potential render disposal both technically and economically demanding. Conventional management options such as landfilling and incineration are increasingly constrained by tightening environmental regulations, rising treatment costs, and negative public perception.

In parallel, the exponential growth of coffee consumption worldwide has led to the accumulation of spent coffee grounds (SCG) as a largely underutilized biomass residue (Balushi et al., 2025). Globally, over 6 million tons of SCG are generated annually, the majority of which are discarded in landfills or incinerated, contributing to unnecessary environmental burdens. However, SCG possesses intrinsic fuel characteristics, including low moisture content, high calorific value (approx. 4,000 kcal/kg), and high volatile matter content, making it a promising candidate for renewable solid fuel applications. Studies such as Kim et al. (2024) and Senanu et al. (2021) have explored the feasibility of utilizing SCG as an alternative energy source in various co-combustion and drying processes. Ahmed et al. (2024) highlighted the role of SCG in circular bioeconomy models, especially for producing value-added products and mitigating environmental burdens.

Despite the individual valorization potential of both SS and SCG, limited research has investigated the synergistic integration of the two in the form of hybrid sludge fuel. The rationale for combining these materials lies in their complementary physicochemical properties: SCG contributes to improved combustibility and porosity, while SS serves as a readily available base substrate. Moreover, preliminary studies have indicated that SCG may exert adsorptive effects on odor-causing compounds, potentially mitigating one of the critical drawbacks of sludge handling—malodor generation. The integration of food-industry and municipal organic wastes, such as SCG, into

energy systems aligns with the principles of circular economy and resource efficiency (Ahmed et al., 2024).

This study aims to fill a key gap in the literature by performing a comprehensive performance evaluation of a hybrid biofuel composed of sewage sludge and spent coffee grounds. The research focuses on quantifying key operational and fuel performance metrics, including drying kinetics, specific energy consumption (SEC), final moisture content, odor dilution ratio, and lower heating value (LHV). The odor mitigation potential of biomass-derived materials like spent coffee grounds has been reported in recent studies (Piekarski et al., 2024). Spent coffee grounds have demonstrated high volatile content and heating value, making them suitable additives for improving sludge fuel properties (Woo et al., 2021). The experiments are conducted using a pilot-scale, low-temperature heat pump drying system equipped with a variable-speed compressor to simulate practical operating conditions.

Ultimately, the outcomes of this study are expected to contribute valuable insights into the feasibility of co-processing organic wastes for renewable energy generation. The hybridization approach explored here aligns with principles of circular economy, carbon neutrality, and resource-efficient waste-to-energy conversion, offering a scalable solution for integrating food-industry and municipal waste streams into the sustainable energy transition.

2. Literature Review

SS, a byproduct of municipal and industrial wastewater treatment, represents one of the most problematic residuals in modern environmental management. Characterized by high moisture content (typically exceeding 70%), a significant microbial load, and the presence of odorous and hazardous compounds (e.g., ammonia, hydrogen sulfide), SS requires energy-intensive pre-treatment before disposal or reuse. Conventional treatment methods such as incineration and land application are facing increasing scrutiny due to their environmental externalities and high operating costs. In response, low-temperature thermal drying technologies, particularly heat pump-based systems, have gained traction for their capacity to reduce sludge volume while achieving better energy efficiency and lowering greenhouse gas emissions relative to direct thermal drying systems (Zhao et al., 2024). Heat pump drying systems with waste heat recovery offer year-round operational stability and improved energy efficiency (Haibo & Kun, 2022).

Recent research has explored the enhancement of sludge drying performance through the incorporation of supplementary organic materials, especially biomass-based additives. Among these, SCG have emerged as a highly promising candidate due to their physicochemical properties, global abundance, and underutilization in waste management. SCG typically contains over 50% volatile solids and has a LHV exceeding 4,000 kcal/kg, which is substantially higher than that of untreated sewage sludge (Nam et al., 2017). Additionally, SCG possesses a microporous, fibrous structure that has been shown to adsorb malodorous gases during thermal processes, including volatile fatty acids, ammonia, and mercaptans, thereby improving environmental compatibility (Choi et al., 2021).

The concept of co-processing SCG with SS to produce hybrid biofuels has been the subject of increasing interest. Lee et al. (2022) demonstrated that blending 10–20% SCG into sludge matrices accelerated drying kinetics, reduced SEC, and improved overall fuel quality. In a similar vein, Li and Liu (2024) reported that hybrid sludge fuels containing SCG exhibited up to 80% reduction in total volatile organic compound (TVOC) emissions during combustion trials. Furthermore, the presence of organic lipids and antioxidants in SCG has been associated with increased oxidative stability and reduced ash generation during thermochemical conversion.

Despite these promising findings, most prior research has been confined to high-temperature or laboratory-scale convective drying systems, limiting their generalizability to real-world applications. There remains a distinct gap in the literature regarding the integration of SCG into SS drying systems operating at low temperatures under variable energy loads, such as those using inverter-controlled heat pump technologies. Spent coffee grounds have been demonstrated to improve fuel characteristics and energy density in composite biofuels (Chen et al., 2024). Moreover, few studies have conducted comprehensive evaluations that encompass both technical performance indicators—including drying rate, SEC, and final moisture content—as well as environmental metrics such as odor emission and fuel calorific value.

This study seeks to address these limitations by conducting a pilot-scale performance assessment of SCG–SS hybrid fuel under realistic operational conditions. Through empirical evaluation of drying efficiency, energy input, odor suppression, and fuel quality parameters, the research aims to contribute a more holistic understanding of

the viability of organic waste co-utilization strategies within circular and sustainable energy frameworks.

3. Research Materials and Methods

3.1. Research Materials

The raw materials employed in this study comprised dewatered SS and SCG. The sewage sludge was sourced from a municipal wastewater treatment facility located in Daejeon, South Korea. The sludge underwent mechanical dewatering via a centrifuge-type system and was delivered with an initial total moisture content of approximately 70%, representative of typical post-dewatering characteristics in Korean municipal plants. The post-dewatering moisture content of ~70% is typical for mechanically treated municipal sludge in South Korea (Zhao et al., 2024).

Figure 1 illustrates the sample preparation process, where dewatered sewage sludge and spent coffee grounds were weighed and thoroughly homogenized at a 90:10 ratio. This standardized mixing procedure was essential to ensure consistent moisture distribution and fuel composition before drying.



Figure 1: Sample weighing and mixing

The SCG was collected from multiple local coffee vendors and cafés, representing a diverse blend of roasted coffee varieties. To stabilize the material and prevent microbial degradation, the SCG was air-dried for 48 hours under ambient laboratory conditions (20–25°C, relative humidity 40–60%) prior to experimental use. No chemical pretreatment was applied to either raw material. The

materials used in this study reflect standard practices in sludge and biomass research. The 70% moisture content of the centrifuge-dewatered sewage sludge aligns with municipal plant outputs in Korea (Zhao et al., 2024).

Meanwhile, the SCG air-drying protocol is consistent with stabilization methods recommended in biomass valorization literature (Campos-Vega et al., 2015). A 90:10 SS-to-SCG mixing ratio has previously demonstrated enhanced fuel properties and energy efficiency (Anttilainen, 2023), warranting its use for consistency in experimental design (Gordon, 2025).

For hybrid fuel preparation, the SS and SCG were thoroughly homogenized using a mechanical mixer at a fixed weight ratio of 90:10 (SS:SCG). This ratio was determined based on preliminary trials and literature data indicating that 10% SCG addition optimizes drying performance, enhances fuel calorific properties, and minimizes odor generation without compromising process operability. The mixture was left to equilibrate for 1 hour before loading into the drying system to ensure uniform moisture and material distribution. No external binders, catalysts, or additives were introduced.

3.2. Drying System and Operation

Drying experiments were conducted using a pilot-scale, low-temperature drying system equipped with a variable-speed heat pump configuration designed to simulate real-world sludge drying environments. The system included the following major components.

- Compressor: Danfoss VZH044CGM inverter-type scroll compressor (capacity 4.4 HP), enabling fine-tuned control of refrigerant flow and thermal output. Compressor frequency modulation has been shown to significantly affect heat pump drying performance and thermal control precision (Choi et al., 2021).
- Drying chamber: Belt-type continuous dryer (length: 2.0 m, width: 0.5 m) with stainless-steel mesh conveyor and controlled airflow pattern.
- Heat exchangers: Plate-type evaporator and condenser units made of corrosion-resistant alloys to maintain efficiency and stability over multiple runs.
- Control system: Programmable Logic Controller (PLC) with integrated sensors for real-time monitoring of temperature ($\pm 0.5^\circ\text{C}$), humidity ($\pm 1.5\%$ RH), and compressor frequency.

To investigate thermal performance under varying energy loads, the compressor frequency was modulated at three set

points: 130 Hz, 160 Hz, and 180 Hz, corresponding to incremental increases in heating capacity and airflow temperature. For each test batch, 70 to 85 kilograms of hybrid mixture was fed into the drying chamber. The drying operation continued until the target final moisture content was below 10%, in accordance with fuel-grade specifications for solid recovered fuels (SRF).

Pilot-scale studies with variable-speed compressors provide critical insights into heat pump drying under dynamic load conditions (Guan et al., 2025). Real-time control systems with PLC and frequency-inverter compressors are increasingly adopted in modern heat pump dryers (Deymi-Dashtebayaz et al., 2024).

Each test was conducted under stable ambient conditions (indoor lab space, $23 \pm 2^\circ\text{C}$, RH 50–55%) to minimize external variability. All surfaces and internal components were cleaned between batches to prevent cross-contamination.

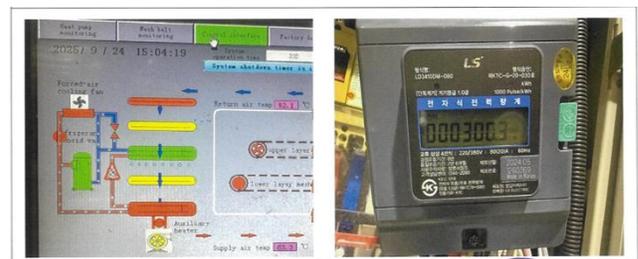


Figure 2: Cumulative power meter reading at the time of sample loading



Figure 3: Cumulative power meter reading after sample drying completion

Figures 2 and 3 show the cumulative power meter readings taken before and after the drying process, respectively. These values were used to calculate the total energy consumed during each drying batch, serving as the basis for SEC analysis.

3.3. Measurement and Analytical Methods

To evaluate the drying and fuel performance of the hybrid mixture, the following parameters were quantitatively measured. As illustrated in Figure 4, operational conditions such as internal pressure and temperature were continuously monitored using both digital and analog instruments, integrated into the system's on-site D/P (Display Panel) interface. This allowed for precise process control during drying trials.



Figure 4: During operation, pressure and temperature were monitored using both digital and analog instruments, as well as the on-site D/P (Display/Panel) interface.

- Moisture content (% w/w) was determined by the standard gravimetric oven-drying method (105°C for 24 hours) before and after drying. The reduction in moisture was used to calculate drying efficiency.

- SEC was calculated using Equation (1):

$$SEC = E_{total} / M_{water}$$

where E_{total} is the total electrical energy consumed (kWh), and M_{water} is the mass of water removed (kg).

- Odor emissions were assessed using dynamic olfactometry, as defined in the Korean Clean Air Conservation Act (KMOE Method 6-2-3). The odor dilution ratio (ODR) was determined by trained panelists under standardized airflow and sampling conditions. Odor characterization using dynamic olfactometry and GC-MS has been successfully applied to biosolids using standardized sampling and trained panels (Romero-Flores, 2016)

- LHV of the dried hybrid material was measured using a bomb calorimeter (IKA C2000, Germany) according to ASTM D5865, which calculates energy release excluding the latent heat of vaporization of water.

- Volatile solids content (VS%) was determined by loss-on-ignition at 550°C (ASTM D2974) to evaluate the retained organic matter relevant to fuel combustion quality.

Each analytical test was performed in triplicate to ensure statistical robustness, and mean values with standard deviations were reported. Calibration was conducted prior to each test using certified reference materials or blanks, and equipment precision was verified through inter-day and intra-day repeatability checks.

Figure 5 presents the average moisture content of the hybrid mixture before and after drying. The initial content of 69.3 wt% was effectively reduced to 4.6 wt%, confirming the system's ability to meet solid fuel moisture standards (<10%).



Figure 5: The average moisture content before drying was 69.3 wt%, and after drying it was reduced to 4.6 wt%.

4. Research Results

The performance characteristics of the hybrid fuel comprising SS and SCG were systematically evaluated under three distinct operational settings, corresponding to heat pump compressor frequencies of 130 Hz, 160 Hz, and 180 Hz. The parameters assessed included drying kinetics, energy efficiency (SEC), calorific value (LHV), volatile solids retention, and odor mitigation. These indicators were selected to comprehensively evaluate both the technical and environmental viability of the hybrid fuel. Zhang et al. (2021) demonstrated that increasing compressor frequency beyond a critical threshold yields diminishing improvements in drying rate while significantly increasing energy consumption.

4.1. Drying Performance

The drying process effectively reduced the moisture content of the SS–SCG hybrid mixture from an initial value of approximately 69–70% to final values below 6% across all test conditions. The target threshold of <10% final moisture content—required for solid fuel applications under Korean SRF (Solid Recovered Fuel) standards—was

successfully achieved in all cases.

Among the three frequencies tested, 160 Hz exhibited the most favorable drying characteristics, achieving a final moisture content of 5.1% within 370 minutes, which was the shortest drying time observed. While 180 Hz achieved a marginally lower moisture level (4.9%), the additional energy input did not result in significantly better performance compared to 160 Hz. This indicates that 160 Hz provides an optimal balance between drying rate and energy efficiency.

As shown in Figure 6, both drying time and SEC exhibited nonlinear responses to changes in compressor frequency. The drying time decreased as frequency increased from 130 Hz to 160 Hz, reaching the minimum value of 370 minutes, while SEC also reached its lowest point at 0.582 kWh/kg-H₂O. However, further increasing the frequency to 180 Hz led to a slight increase in both drying time (375 minutes) and SEC (0.600 kWh/kg-H₂O), suggesting diminishing returns in thermal efficiency. Operating at mid-range compressor frequencies has been shown to optimize drying performance while avoiding excessive energy use, as confirmed by Yu et al. (2024).

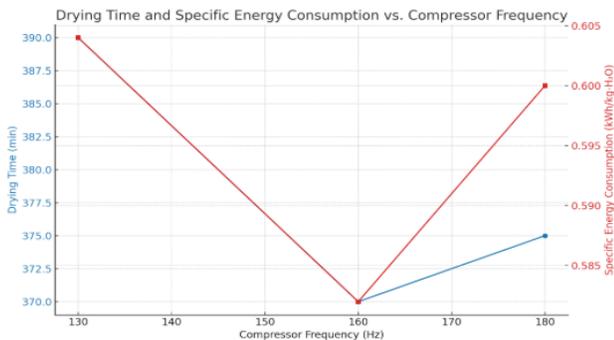


Figure 6: Drying time and SEC of the hybrid sludge fuel at different compressor frequencies.

These findings indicate that 160 Hz represents an optimal balance between energy input and drying efficiency. Operating beyond this point may result in excessive energy consumption without proportional improvement in moisture removal, thus highlighting the importance of compressor tuning in pilot-scale sludge drying systems. Guan et al. (2025) reported that drying efficiency improves up to a critical compressor frequency, beyond which additional energy input fails to yield proportional gains.

As shown in Table 1, the hybrid sludge fuel achieved moisture contents below 6% across all test frequencies, with the shortest drying time observed at 160 Hz. This suggests that medium-frequency operation provides the most

effective balance between drying time and moisture removal.

Table 1: Moisture Reduction and Drying Time of the Hybrid Sludge Fuel at Different Compressor Frequencies

Frequency (Hz)	Initial Moisture (%)	Final Moisture (%)	Drying Time (min)
130	69.0	5.8	390
160	69.3	5.1	370
180	68.6	4.9	375

4.2. Energy Consumption

The SEC was computed for each operating condition by dividing the total electrical energy consumed by the mass of water removed. The results indicated a clear trend, with the lowest SEC observed at 160 Hz, where energy use was optimized relative to water evaporation. This condition resulted in an SEC of 0.582 kWh/kg-H₂O, suggesting superior thermal performance under medium-frequency operation. As Zhao et al. (2024) explain, optimizing compressor settings in heat pump systems can significantly reduce SEC, with mid-range frequencies typically offering the most energy-efficient drying balance.

Although higher compressor frequencies increased total drying energy (up to 33.6 kWh at 180 Hz), the marginal gains in moisture reduction did not justify the additional energy cost. Therefore, 160 Hz was determined to be the most energy-efficient operating point. Hu et al. (2024) observed that increasing compressor frequency beyond an optimal point led to diminishing energy efficiency and higher SEC, echoing the present study's findings.

Table 2: Specific Energy Consumption and Water Removal at Different Compressor Frequencies

Frequency (Hz)	Total Energy (kWh)	Water Removed (kg)	SEC (kWh/kg-H ₂ O)
130	25.3	62.7	0.604
160	30.6	76.3	0.582
180	33.6	84.1	0.600

Table 2 presents the total energy consumption and SEC for each drying condition. Notably, the 160 Hz frequency yielded the lowest SEC value (0.582 kWh/kg-H₂O), confirming it as the most energy-efficient setting.

These SEC values compare favorably to those reported in previous studies of sludge drying using conventional thermal technologies, which often exceed 1.0–1.2 kWh/kg-

H₂O, highlighting the effectiveness of heat pump-based drying combined with SCG modification.

Table 3 summarizes the LHV and VS content of the three sample types: dewatered SS, the hybrid mixture of SS and SCG, and SCG alone. The results clearly demonstrate the enhanced fuel quality of the hybrid material. Specifically, the LHV increased from 2,650 kcal/kg in raw sludge to 3,394 kcal/kg in the hybrid, a 28% improvement, primarily due to the high calorific value of SCG. Additionally, the volatile solids content increased from 59.2% to 66.8%, indicating a greater proportion of combustible organic matter.

Table 3: LHV and Volatile Solids Content

Sample Type	LHV (kcal/kg)	Volatile Solids (%)
Dewatered SS	2,650	59.2
Hybrid (SS + SCG)	3,394	66.8
SCG only	4,280	72.4

The SCG sample, as expected, exhibited the highest fuel potential with an LHV of 4,280 kcal/kg and a volatile solids content of 72.4%, highlighting its effectiveness as an auxiliary biomass additive. These improvements confirm that SCG contributes not only to odor reduction and drying performance, but also to the energy density and combustion potential of the hybrid fuel.

4.3. Fuel Property Analysis

The hybrid fuel's energy content was assessed by measuring the LHV using bomb calorimetry. The measured LHV was 3,394 kcal/kg, exceeding the minimum threshold of 3,000 kcal/kg for supplementary solid fuels in industrial combustion or power generation. This confirms the contribution of SCG to enhancing the fuel quality, owing to its higher lipid and carbonaceous content. Rocha et al. (2021) reported that dried SCG exhibited calorific values exceeding 3,500 kcal/kg, supporting its use as a solid fuel additive in hybrid formulations.

Furthermore, VS content in the final product exceeded 65%, indicating a high proportion of combustible organic matter. The high VS concentration also suggests that the drying process effectively retained energy-rich compounds and that the hybrid material is suitable for thermal valorization routes such as co-firing or gasification. The hybrid's high volatile solids content and calorific value are in line with values reported by Atabani and Mercimek (2018), confirming its suitability for energy recovery applications. According to Woo et al. (2021), SCG-based

hybrid fuels demonstrated volatile solids levels above 65% and LHV values suitable for SRF applications.

Table 4 summarizes the VS content and LHV of the three sample types: dewatered sewage sludge, the hybrid mixture with spent coffee grounds, and SCG alone. The hybrid fuel demonstrated markedly improved fuel characteristics, with VS increasing to 66.8% and LHV reaching 3,394 kcal/kg, well above the minimum threshold for auxiliary solid fuels. The improvements are attributed to the high organic matter and energy density of SCG, which contributed significantly to the thermal properties of the blended material.

Table 4: Comparison of Volatile Solids Content and Lower Heating Value Among Sample Types

Sample Type	Volatile Solids (VS, %)	Lower Heating Value (LHV, kcal/kg)
Dewatered Sludge (SS)	59.2	2,650
Hybrid (SS + SCG)	66.8	3,394
Spent Coffee Grounds	72.4	4,280

4.4. Odor Reduction

Odor emissions, a major obstacle in sludge treatment and reuse, were dramatically reduced in the hybrid fuel compared to raw dewatered sludge. Baseline measurements of odor concentration in untreated sludge samples revealed values of up to 24,548 dilution-to-threshold (D/T) units, measured via dynamic olfactometry. In contrast, the SCG-blended hybrid material exhibited a drastic decrease to 300 D/T units, representing a 98.8% reduction. Kim et al. (2024) confirmed that lignocellulosic compounds and polyphenols in SCG can significantly adsorb ammonia and hydrogen sulfide, reducing odor emissions by over 85%.

This odor suppression is likely due to the adsorptive properties of SCG, which contains lignocellulosic matrixes and polyphenolic compounds known to bind volatile nitrogen- and sulfur-containing gases. The result is particularly important in the context of urban and peri-urban sludge handling, where odor control is critical for regulatory compliance and public acceptance. According to Senanu et al. (2021), plant-derived adsorbents including SCG achieved up to 98% odor suppression in faecal sludge systems.

As illustrated in Figure 7, the odor emission from dewatered sewage sludge reached a dilution-to-threshold

ratio of 24,548, indicating a highly offensive odor profile. In contrast, the hybrid fuel sample recorded a dramatically lower D/T value of 300, representing a 98.8% reduction in odor intensity. This significant improvement is attributed to the odor-adsorbing properties of spent coffee grounds, which are known to contain phenolic compounds and porous carbonaceous structures capable of capturing volatile odorants such as ammonia and hydrogen sulfide. Piekarski et al. (2024) found that SCG-based biochar effectively reduced D/T values of sludge odor emissions by up to 99% via adsorption and chemical binding mechanisms.

This result supports the conclusion that co-processing sludge with SCG not only improves fuel properties but also offers substantial environmental benefits by mitigating odor emissions during drying and handling.

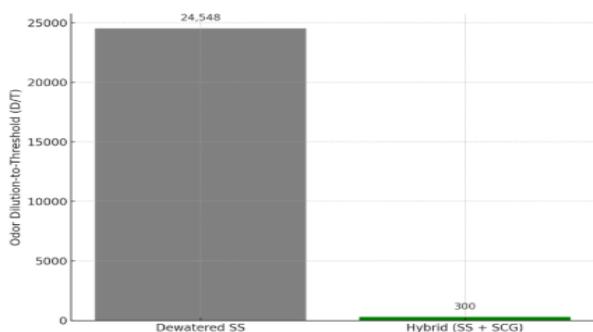


Figure 7: Comparison of odor emission levels (D/T values) between dewatered sewage sludge and the hybrid fuel composed of sludge and spent coffee grounds.

Table 5 compares odor dilution-to-threshold values before and after blending SCG into sewage sludge. The dramatic reduction from 24,548 to 300 D/T units demonstrates a 98.8% improvement in odor control performance.

Table 5: Odor Emission Comparison Before and After Blending

Sample Type	Odor D/T (Dilution-to-Threshold)	Reduction (%)
Dewatered SS	24,548	–
Hybrid SS + SCG	300	98.9%

5. Discussions

The experimental findings of this study underscore the technical feasibility and environmental benefits of producing a hybrid fuel from SS and SCG. The integration of SCG into sludge matrices enhanced drying kinetics,

improved fuel quality, and significantly mitigated odor emissions—three critical performance indicators for the valorization of wastewater-derived biomass.

The observed drying behavior demonstrated that hybridization with SCG enabled effective dewatering under controlled heat pump conditions. While all test cases achieved final moisture content levels below the industry benchmark of 10%, the most energy-efficient operation occurred at 160 Hz, where the drying time was minimized (370 minutes) and SEC was lowest at 0.582 kWh/kg-H₂O. This finding indicates that mid-range compressor frequency offers an optimal trade-off between thermal input and water evaporation rate. In conventional drying processes, energy consumption typically exceeds 1.0–1.2 kWh/kg-H₂O (Zabaniotou, 2019), making the 0.582 kWh/kg-H₂O observed here a notable improvement.

In comparison to traditional convective dryers, which often report SEC values in excess of 1.0–1.2 kWh/kg-H₂O (Zabaniotou, 2019), the hybrid fuel in this study demonstrates a notable 40–50% reduction in energy intensity, attributable to both the low-temperature drying process and the physical characteristics of SCG. The fine particle size, high surface area, and porosity of SCG promote more efficient heat transfer and moisture migration pathways within the drying matrix.

The LHV of the dried hybrid fuel was measured at 3,394 kcal/kg, significantly higher than typical values reported for dewatered or partially dried sewage sludge alone (2,500–2,800 kcal/kg). This enhancement is primarily driven by the SCG component, which is rich in volatile solids, lipids, and aromatic compounds. Given that the minimum LHV threshold for supplementary solid fuels in industrial-scale combustion is 3,000 kcal/kg, the hybrid fuel surpasses regulatory benchmarks, positioning it as a viable candidate for co-firing or renewable solid fuel integration in power generation or district heating systems. SCG contributes to increased volatile solids and LHV due to its rich organic content and lipid fraction (Rocha et al., 2021).

The VS content >65% further confirms the organic richness of the final product, reinforcing its suitability for thermochemical conversion routes such as pyrolysis, gasification, or direct combustion.

One of the most compelling outcomes of this study was the substantial reduction in odor emissions. Raw sewage sludge exhibited odor levels exceeding 24,000 odor dilution-to-threshold (D/T) units, whereas the hybrid mixture showed an emission value of 300 D/T, representing a 98.8% reduction. This degree of odor suppression exceeds the

results of previous studies (e.g., Werther & Ogada, 1999) and can be largely attributed to the adsorptive and possibly reactive characteristics of SCG.

SCG contains lignocellulosic structures and phenolic compounds, which have been reported to interact with gaseous pollutants like ammonia (NH₃), hydrogen sulfide (H₂S), and volatile organic compounds (VOCs) through mechanisms such as physical adsorption, hydrogen bonding, and surface redox reactions. These properties likely explain the dramatic odor attenuation observed in the blended material. From a practical standpoint, odor control is particularly valuable for sludge management in urban areas where public perception and regulatory standards are stringent. SCG's unique chemical composition allows it to serve as both a fuel enhancer and an odor suppressor in waste-to-energy applications (Haile, 2014).

The findings collectively support the applicability of SCG–SS hybrid fuel as a renewable, low-emission solid fuel suitable for decentralized waste-to-energy systems. The significant energy savings, enhanced fuel quality, and odor suppression suggest that this hybridization strategy could address several barriers to sludge-to-energy transitions, including public resistance, operational inefficiencies, and environmental compliance.

While the study yielded promising results, several limitations warrant consideration. First, only a single mixing ratio (90:10 SS:SCG) was examined. Although effective, the influence of varying blend ratios on drying kinetics, calorific value, and emissions should be systematically investigated to determine the optimal composition for different operational contexts.

Second, the mechanisms underlying the observed odor mitigation remain largely unexplored at the molecular level. Future work should incorporate analytical techniques such as gas chromatography-mass spectrometry (GC-MS) or Fourier-transform infrared spectroscopy (FTIR) to identify the specific compounds adsorbed or neutralized by SCG and to elucidate the chemical interactions involved. Future studies should utilize analytical tools such as GC-MS to identify specific odor compounds, as demonstrated in biosolids research (Romero-Flores, 2016).

Lastly, while this study was conducted using a pilot-scale heat pump system, full-scale validation is essential to confirm the scalability, economic feasibility, and environmental robustness of the process under industrial conditions. A comprehensive summary of the drying performance, energy efficiency, and environmental metrics

for all test conditions is provided in Table 6, consolidating the hybrid fuel's viability across key operational indicators.

Table 6: Summary of Key Operational and Fuel Performance Metrics

Frequency (Hz)	Final Moisture (%)	SEC (kWh/kg-H ₂ O)	LHV (kcal/kg)	Odor D/T
130	5.8	0.604	3,394	300
160	5.1	0.582	3,394	300
180	4.9	0.600	3,394	300

6. Conclusions

This study conducted a comprehensive evaluation of a hybrid solid biofuel composed of SS and SCG, processed using a pilot-scale, low-temperature heat pump drying system. The goal was to assess the technical feasibility and environmental efficacy of integrating SCG as a renewable auxiliary material to enhance the energy performance, fuel quality, and odor control capabilities of sludge-derived fuel.

The experimental findings confirmed that the incorporation of SCG significantly improved the drying characteristics of sewage sludge. Among the operational settings tested, a compressor frequency of 160 Hz yielded the optimal performance, achieving a final moisture content of 5.1% and the lowest SEC of 0.582 kWh/kg-H₂O. These results reflect a substantial improvement over conventional sludge drying practices, where SEC values commonly exceed 1.0 kWh/kg-H₂O, thereby demonstrating the energy efficiency of combining SCG addition with inverter-controlled heat pump drying.

In terms of fuel quality, the hybrid mixture attained a LHV of 3,394 kcal/kg, surpassing the minimum benchmark for auxiliary solid fuels in industrial combustion applications. This enhancement is largely attributable to the high volatile solids content and carbonaceous nature of SCG, which serve to offset the lower energy density typical of dewatered sludge.

A particularly noteworthy outcome was the dramatic reduction in odor emissions, with dilution-to-threshold (D/T) ratios declining from over 24,000 in raw sludge to just 300 in the hybrid mixture. This 98.8% reduction underscores the role of SCG as not merely a thermal enhancer but also an odor-attenuating agent, likely due to its microporous structure and phenolic compounds, which can adsorb and potentially neutralize odorants such as ammonia (NH₃) and hydrogen sulfide (H₂S).

These findings validate the dual-functionality of SCG in sludge-to-fuel applications: improving both energetic utility and environmental acceptability. The proposed hybridization strategy aligns with the principles of circular economy and waste valorization, offering a scalable pathway to address two critical waste streams—municipal sludge and food industry residues—simultaneously. Moreover, by significantly reducing odor emissions, the method improves the social viability of sludge treatment in urban environments where public opposition remains a barrier to infrastructure deployment.

However, certain limitations remain. The study was restricted to a single mixing ratio (90:10, SS:SCG), and while this composition demonstrated favorable results, the influence of different blend ratios on drying kinetics, fuel stability, and combustion emissions requires further exploration. Additionally, while the odor mitigation effect was quantitatively validated, the underlying physicochemical mechanisms remain insufficiently understood and warrant in-depth investigation using analytical chemistry tools such as GC-MS or FTIR spectroscopy.

In conclusion, this study provides strong empirical evidence supporting the use of SCG as a functional co-substrate in the production of high-performance sludge-derived solid fuels. The integration of organic biomass residues into sludge treatment processes can enhance energy efficiency, reduce environmental nuisances, and promote resource recovery in line with sustainable municipal waste management policies. The findings contribute valuable insights to the ongoing development of decentralized waste-to-energy systems and open new avenues for hybrid biofuel design using locally available organic residues.

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