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Microwave-Assisted Drying Of Sewage Sludge: Kinetic Optimization, Energy Efficiency, And C:N:P Preservation For Biomass Valorization

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ABSTRACT

Drying municipal sewage sludge represents a major energy bottleneck in biomass valorization, and conventional thermal methods often strip away its valuable nutrients. This research explores microwave-assisted drying as a strategy to enhance energy efficiency while preserving the carbon-to-nitrogen-to-phosphorus (C:N:P) stoichiometry critical for agricultural applications. Experimental trials evaluated sludge cakes across a broad spectrum of microwave powers (160–800 W) and various geometric configurations. The results revealed a consistent three-stage drying process, characterized by a distinct kinetic shift once moisture dropped below a 50% threshold. Below this point, internal steam generation created a strong pressure gradient—often referred to as the "beggar's chicken effect"—that drove thicker samples to dry more rapidly than thinner ones. A power setting of 480 W paired with a 2.5 cm cake diameter emerged as the optimal configuration, achieving a true thermal efficiency of 49% and a specific energy consumption of just 1.92 MJ/kg. This performance outpaced conventional hot-air and infrared drying methods, achieving a 34% lower specific energy consumption than hot-air drying. Crucially, the rapid, volumetric heating provided by microwaves mitigated the nitrogen loss typically triggered by prolonged thermal exposure. Consequently, the microwave-dried sludge maintained a C:N ratio of 11, closely mirroring the raw feedstock and ensuring high agronomic value. Ultimately, these findings provide a practical, energy-efficient pathway for transforming biosolids into premium bio-fertilizers and bioenergy feedstocks within circular economy models.

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INTRODUCTION

Municipal wastewater treatment generates substantial quantities of sewage sludge, a byproduct increasingly viewed as a valuable resource rather than mere waste. Global dry solids production currently reaches up to 45 million tons annually and continues to climb, particularly in developing regions (Fytili & Zabaniotou, 2008). Historically, managing this material meant landfilling or direct incineration. Today, however, strict environmental regulations and rising operational costs are pushing the industry toward sustainable alternatives like anaerobic digestion, pyrolysis, and land application as bio-fertilizers (Kelessidis & Stasinakis, 2012). Transforming sludge into energy and valuable resources has become a sustainable strategy for both resource recovery and environmental protection (Hamda et al., 2025; Liu et al., 2024). The primary challenge is that dewatered sludge is typically 75% to 85% water. Removing this moisture is a massive energy drain, creating a significant bottleneck for any downstream thermochemical or biochemical conversion process (Gao et al., 2020).

Conventional drying methods, such as hot air convection or infrared heating, rely on transferring heat from the surface inward. This approach is often slow and uneven, tending to bake a hard crust on the outside of the sludge. This crust traps moisture inside and severely slows down the overall drying process (Léonard et al., 2004). Microwave drying offers a fundamentally different mechanism. By using high-frequency electromagnetic waves (typically 2450 MHz), it triggers rapid dipole rotation and ionic conduction directly within the material (Rattanadecho & Makul, 2016; Stuerga, 2006). Because water absorbs microwave energy much more readily than dry organic solids, this creates volumetric, inside-out heating (Bennamoun et al., 2016; Chen et al., 2014; Li et al., 2015). This not only prevents surface crusting but also generates internal vapor pressure that actively pumps moisture to the surface—a phenomenon often referred to as the "beggar's chicken effect" or pumping effect (Fu et al., 2017; Ni et al., 1999). Recent studies have extensively modeled and experimentally validated these dielectric properties and moisture transport mechanisms during the microwave drying of wastewater sludge, confirming its superior heat and mass transfer capabilities (Bennamoun et al., 2016; Li et al., 2015).

Despite these clear mechanical advantages, scaling up microwave sludge drying remains challenging. Most existing research focuses on fixed power levels or simple experimental setups, leaving a gap in understanding how variable power and sample geometry interact to affect overall drying performance (Gao et al., 2020; Wang et al., 2024). While some studies have explored pilot-scale microwave technologies for sludge sanitization (Kocbek et al., 2020; Mawioo et al., 2017) and evaluated the effects of sludge physical-chemical properties on drying performance (Kocbek et al., 2022), the specific interplay between sample thickness, diameter, and microwave power requires further optimization. Recent advancements and high-impact studies have attempted to address this through hybrid systems (Eom et al., 2019), the use of microwave susceptors like SiC for thick-layer sludge drying (Xie et al., 2026), and systematic reviews on microwave pretreatment for biomass valorization (Venegas-Vásconez et al., 2025; Yousra et al., 2025). However, comprehensive mapping of the three-stage drying kinetics across a wide range of geometric configurations and power levels remains limited.

Furthermore, the end-use of dried sludge dictates its required quality. When sludge is destined for agricultural use, its macronutrient balance—specifically the carbon, nitrogen, and phosphorus (C:N:P) stoichiometry—is critical for soil health and crop productivity, as highlighted by recent agronomic Almási et al. (Almási et al., 2025). Prolonged exposure to high temperatures in conventional dryers often triggers Maillard reactions and ammonia volatilization, stripping away valuable nitrogen and degrading the fertilizer's quality. While microwave pyrolysis and pretreatment have been shown to alter organic components and affect biochar properties (Antunes et al., 2018; Liu et al., 2024), the specific impact of microwave drying on preserving the delicate C:N:P stoichiometry has received surprisingly little attention. Most pilot-scale evaluations prioritize pathogen reduction, ecotoxicity, and general energy demand over precise macronutrient retention (Kocbek et al., 2020; Mawioo et al., 2017). Whether microwave drying can effectively bypass the thermal degradation pathways associated with conventional heating to preserve the sludge's agronomic value remains a critical knowledge gap.

To address these gaps, this study systematically investigates the microwave drying kinetics of municipal sewage sludge across a broad spectrum of power levels (160–800 W) and geometric configurations. The primary aim is to uncover the underlying thermodynamic and kinetic mechanics of the process, specifically by mapping the three-stage drying behavior to identify the moisture thresholds that govern thickness-dependent rate changes. Building on this kinetic framework, the research evaluates specific energy consumption and thermal efficiency to determine the most energy-effective operating conditions. Furthermore, the study assesses the impact of microwave drying on the sludge’s C:N:P stoichiometry compared to conventional thermal methods. Ultimately, this work seeks to demonstrate that microwave drying offers a highly efficient pathway for transforming biosolids into valuable bio-fertilizers and energy feedstocks without compromising their agronomic quality

MATERIALS AND METHODS

Experimental Materials and Sample Preparation

Fresh dewatered sewage sludge was collected from the belt-filter press dewatering unit of the South Tehran Wastewater Treatment Plant (Tehran, Iran). The sludge samples exhibited an average initial moisture content of 82.3 ± 0.8% (wet basis) and were homogenized prior to experimentation. Proximate analysis on a dry basis yielded volatile solids of 67.8%, fixed carbon of 19.2%, and ash of 13.0%. The initial elemental composition (dry basis) was determined as 35.2% total carbon (TC), 3.22% total nitrogen (TN), and 4.50% total phosphorus (TP), which aligns with typical nutrient stoichiometry and elemental profiles reported for municipal biosolids (Almási et al., 2025; Mao et al., 2019). Samples were stored at 4°C and used within 48 hours, to prevent biological degradation and preserve baseline physicochemical properties prior to testing (Association, 1926). For the drying experiments, the sludge was manually formed into cylindrical cakes. To investigate the thickness effect, cakes were prepared with a fixed diameter of 3 cm and variable thicknesses of 1, 2, and 3 cm. For the diameter effect, cakes were prepared with a fixed thickness of 3 cm and variable diameters of 2, 2.5, and 3 cm, allowing for the systematic evaluation of how sample geometry and thick-layer configurations impact microwave drying kinetics (Fu et al., 2017; Xie et al., 2026). The prepared samples were placed in pre-weighed, high-temperature-resistant ceramic crucibles.

To ensure uniformity in cake density and porosity across replicates, the homogenized sludge was manually pressed into cylindrical molds of fixed dimensions and standardized by mass (50 ± 0.1 g), yielding a consistent initial bulk density of approximately 1.150 kg/m³. Controlling these physical parameters is critical, as sludge density, porosity, and structural uniformity significantly influence microwave penetration depth and overall drying performance (Kocbek et al., 2022; Ni et al., 1999).

Microwave Drying Setup and Experimental Procedure

Drying experiments were performed using a modified household microwave oven (Model G80F20CSL-B8(R0), Galanz Co., Ltd., China) operating at a frequency of 2450 MHz. The microwave cavity dimensions were 300 × 300 × 250 mm, equipped with a rotating turntable to ensure uniform heating. The power output was adjustable across five discrete levels: 160, 320, 480, 640, and 800 W, reflecting standard operational ranges used to evaluate specific energy consumption (Guo et al., 2021; Wang et al., 2024). During the experiments, approximately 50 ± 0.1 g of the sludge cake was dried under the controlled power settings. Sample mass was monitored in real-time using a precision electronic balance (precision ±0.1 g) positioned adjacent to the cavity, a common method for capturing precise drying kinetics (Bennamoun et al., 2016; Kocbek et al., 2022). Mass readings were recorded at 30-second intervals for high-power conditions (640–800 W) and 60-second intervals for low-power conditions (160–480 W). The drying process was continued until the moisture content reached ≤ 2.0% (wet basis), aligning with standard stabilization targets (Association, 1926). The overall process of microwave sludge drying is illustrated in Figure 1. To benchmark the microwave drying performance, parallel experiments were conducted using standard conventional hot-air convection drying (105 ± 2°C) and infrared drying (700 W). These parameters were selected based on standard operational protocols widely reported in literature for baseline comparisons, rather than their absolute theoretical optima, to provide a realistic benchmark against current industry practices (Association, 1926; Léonard et al., 2004).

The sample geometry and endpoint moisture criteria were maintained consistently across all comparative methods, with the cake thickness specifically chosen to evaluate thick-layer drying dynamics (Fu et al., 2017; Xie et al., 2026). Although the cakes were manually molded rather than mechanically compacted to a specific pressure, the high initial moisture content (82.3%) ensures the sludge behaves as a saturated porous medium (Kocbek et al., 2022; Ni et al., 1999). Under these conditions, dielectric heating is overwhelmingly governed by water absorption, rendering the drying kinetics highly insensitive to minor, localized density fluctuations introduced during manual preparation (Antunes et al., 2018; Stuerga, 2006).

Figure 1. The process of microwave sludge drying: a) dewatered sludge, b) microwave process for drying, c) dried sludge by microwave

Energy Consumption and Efficiency Calculations

The moisture content (M, % wet basis) and the drying rate (R, kg water/(kg dry sludge·h)) were calculated to evaluate the drying kinetics, as defined in Eqs. (1) and (2) (Bennamoun et al., 2016; Guo et al., 2021):

$$M = \frac{W_t - W_d}{W_t} \times 100 \quad (1)$$

$$R = -\frac{dM}{dt} \times \frac{1}{(100 - M)} \quad (2)$$

Where W_t= sample mass at time t (g), W_d = dry mass after oven-drying at 105°C for 24 h (g), and t= drying time (h). The derivative $\frac{dM}{dt}$ was approximated using finite differences between consecutive measurement points.

Mathematical Modeling and Statistical Analysis of Drying Kinetics

To mathematically describe the moisture transport mechanisms and strengthen the scientific rigor of the kinetic analysis, the experimental drying data were fitted to four widely used thin-layer drying models: Newton, Page, Henderson and Pabis, and Midilli (Henderson & Pabis, 1961; Midilli et al., 2002; Page, 1949). The application of these empirical and semi-theoretical models has been extensively validated for the microwave drying of sewage sludge in recent literature (Bennamoun et al., 2016; Guo et al., 2021). The moisture ratio (M_R) was defined as:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (3)$$

Given that the equilibrium moisture content (M_e) is negligible compared to the initial and final moisture contents under microwave drying, MR was simplified to $\frac{M_t}{M_0}$. The models are defined as follows:

Newton: $MR = \exp(-kt)$

Page (Page, 1949): $MR = \exp(-kt^n)$

Henderson and Pabis (Henderson & Pabis, 1961): $MR = a\exp(-kt)$

Midilli et al. (Midilli et al., 2002): $MR = aexp(-kt^n) + bt$

The goodness of fit was evaluated using the coefficient of determination R^2, root mean square error (RMSE), and reduced chi-square (χ^2) (Kocbek et al., 2022; Wang et al., 2024). All non-linear regressions and statistical analyses were performed using SigmaPlot software (version 15). Furthermore, all drying experiments and analytical measurements were performed in triplicate, with data presented as mean ± standard deviation. A one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) post-hoc test, was conducted to evaluate the statistical significance of differences in drying rates, specific energy consumption, and elemental composition across various microwave powers and geometric configurations. Statistical significance was defined at $p < 0.05$.

Energy Performance Evaluation

Specific Energy Consumption (SEC, MJ/kg water removed) and thermal efficiency (η) were calculated to evaluate the final energy performance (Guo et al., 2021; Kocbek et al., 2020; Wang et al., 2024). To address the physical limitations of the initial calculation, the thermal efficiency was revised to account for the sensible heat required to raise the temperature of the dry solids and the remaining moisture to the evaporation temperature. Furthermore, since reflected power and cavity wall losses were not directly measured, an overall cavity absorption efficiency factor ($\eta_{abs} \approx 0.85$) was applied to the input power to estimate the actual energy absorbed by the sludge, based on standard microwave cavity performance metrics (Rattanadecho & Makul, 2016; Xie et al., 2026). The revised equations are:

$$SEC = \frac{P \times t}{W_0 - W_f} \quad (4)$$

$$\eta = \eta_{abs} \times \frac{m_w\lambda + m_s C_{ps}(T_{evap} - T_{amb}) + m_{w,rem} C_{pw}(T_{evap} - T_{amb})}{P \times t} \times 100 \quad (5)$$

where P is microwave power (kW), t is total drying time (h), W_0 and W_f are initial and final water mass (kg), m_w is the mass of water removed ($W_0 - W_f, kg$), λ is the latent heat of vaporization (2.26 MJ/kg at 100°C), η_{abs} is the cavity absorption efficiency factor (0.85), m_s is the mass of dry solid (kg), C_{ps} is the specific heat of dry sludge (1.5 kJ/kg·K),$m_{w,rem}$ is the mass of remaining water in the final product (kg), C_{pw} is the specific heat of water (4.18 kJ/kg·K), and T_{evap} and T_{amb} are the evaporation and ambient temperatures (k), respectively.

Analytical Methods and Stoichiometry Evaluation

To evaluate the fertilizing potential and nutrient retention of the dried sludge, the C:N:P stoichiometry was analyzed (Almási et al., 2025; Yousra et al., 2025). Total carbon (TC) and total nitrogen (TN) were determined using an elemental analyzer (Vario MACRO cube, Elementar, Germany). Total phosphorus (TP) was measured using inductively coupled plasma optical emission spectrometry (ICP-OES, Agilent 5110, USA) following microwave-assisted acid digestion (HNO_3/HCl/HF) in accordance with standard methods (Association, 1926). The mass ratios of C:N, C:P, and N:P were subsequently calculated to assess the preservation of nutrients, a critical factor since thermal drying processes can significantly alter nitrogen mass balances and drive mineralization (Kokurewicz et al., 2018; Mao et al., 2019; Szypulska et al., 2021). All analytical data are presented as the mean ± standard deviation (n = 3).

Statistical Analysis

All drying experiments and analytical measurements were performed in triplicate. Data are presented as mean ± standard deviation. One-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post-hoc test was utilized to evaluate the statistical significance of differences in drying rates, specific energy consumption, and elemental composition across different microwave powers and geometric configurations. Statistical significance was defined at $p < 0.05$. All statistical analyses were performed using SigmaPlot, version 15.

RESULTS AND DISCUSSION

Drying Kinetics Under Variable Microwave Power

The drying rate curves for sewage sludge cakes (diameter = 3 cm) under microwave powers ranging from 160 to 800 W consistently exhibited a three-stage pattern. As illustrated in Figure 2, at a microwave power of 160 W, the process began with an acceleration phase (70% < moisture < 83.3%), followed by a constant-speed phase (50% < moisture < 70%), and concluding with a deceleration phase (moisture < 50%). This kinetic behavior aligns closely with the findings of Bennamoun et al. and Wang et al., who reported that microwave drying of sewage sludge proceeds through preheating, constant-rate, and decreasing-rate stages corresponding to the sequential removal of free and bound water fractions (Bennamoun et al., 2016; Wang et al., 2024). Furthermore, recent mathematical modeling of microwave drying behavior by Guo et al. corroborates these distinct kinetic phases, emphasizing the critical role of internal moisture diffusion in governing the falling-rate period (Guo et al., 2021).

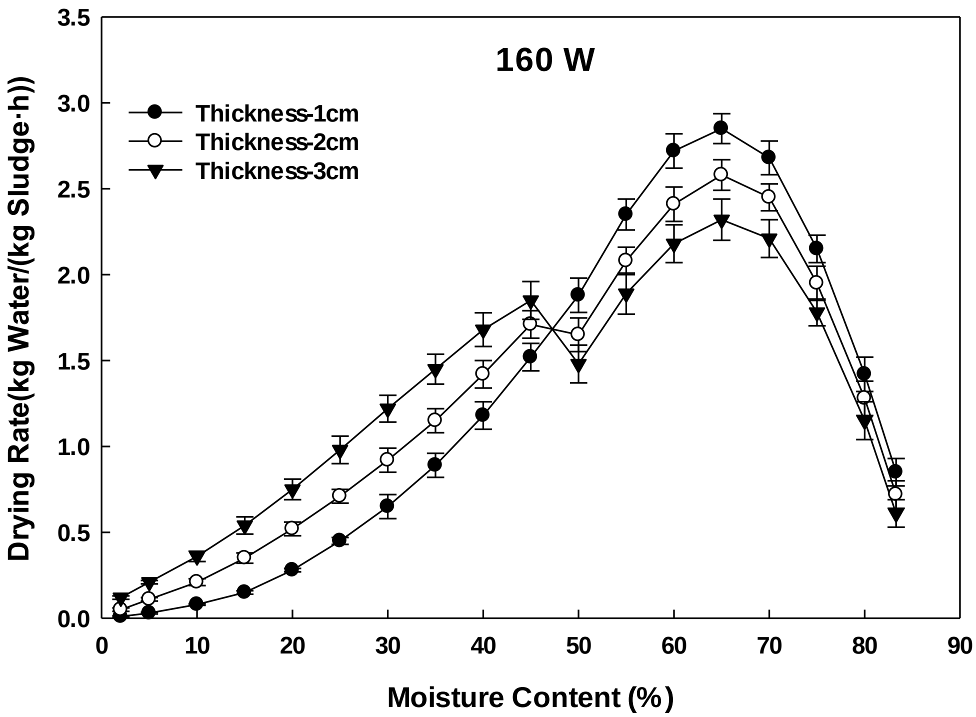

Figure 2. Drying rate curves of sewage sludge at different cake thicknesses (1, 2, and 3 cm) under a microwave power of 160 W (fixed cake diameter: 3 cm).

Increasing the power to 320 W and 480 W (Figs. 3 and 4) significantly accelerated the peak drying rates, reaching 4.12 and 6.82 kg water/(kg sludge·h), respectively, for a 1 cm thickness. At higher powers of 640 W and 800 W (Figs. 5 and 6), the peak drying rates scaled to 8.45 and 9.31 kg/(kg·h). These peak drying rates are substantially higher than those reported by Chen et al. for conventional convective drying, validating the superior volumetric heating capacity of microwave dielectric properties (Chen et al., 2014). A critical observation across Figurs. 2 to 6 was a thickness-dependent reversal in drying rate behavior at the 50% moisture content threshold. When moisture > 50%, the drying rate decreased with increasing sludge thickness (1 cm > 2 cm > 3 cm) due to longer internal diffusion paths. Conversely, when moisture < 50%, the drying rate increased with thickness (3 cm > 2 cm > 1 cm). For instance, Figure 4 shows that at 40% moisture and 480 W, the rates became 2.68, 3.42, and 4.25 kg/(kg·h) for 1, 2, and 3 cm thicknesses, respectively. This phenomenon is explained by the pressure-gradient mechanism (the “beggar's chicken effect”), wherein internal steam generation creates a vapor pressure differential that drives moisture outward more effectively in thicker samples (Fu et al., 2017; Ni et al., 1999). Higher microwave power significantly amplifies this pressure-gradient advantage, disproportionately enhancing the drying efficiency of thicker sludge cakes during the falling-rate period.

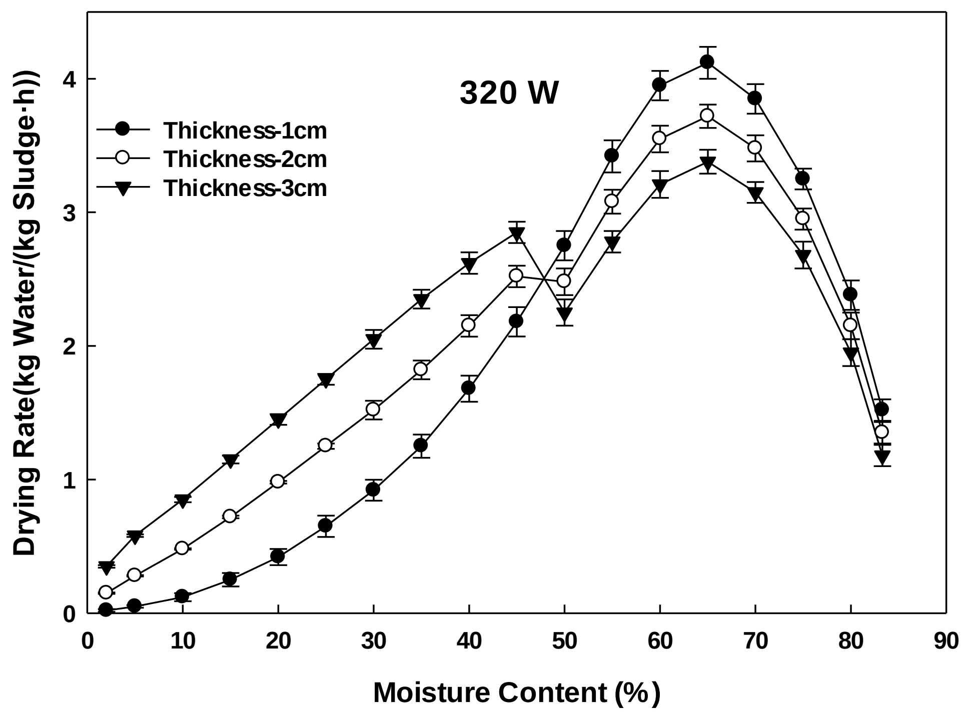

Figure 3. Drying rate curves of sewage sludge at different cake thicknesses (1, 2, and 3 cm) under a microwave power of 320 W (fixed cake diameter: 3.0 cm).

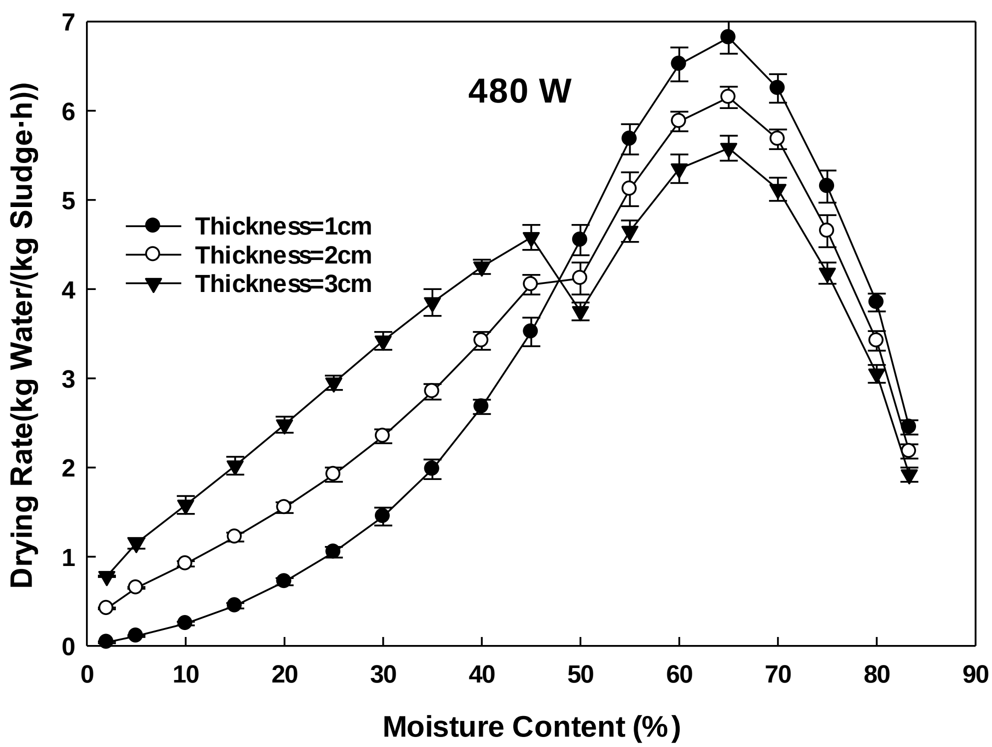

Figure 4. Drying rate curves of sewage sludge at different cake thicknesses (1, 2, and 3 cm) under a microwave power of 480 W (fixed cake diameter: 3 cm).

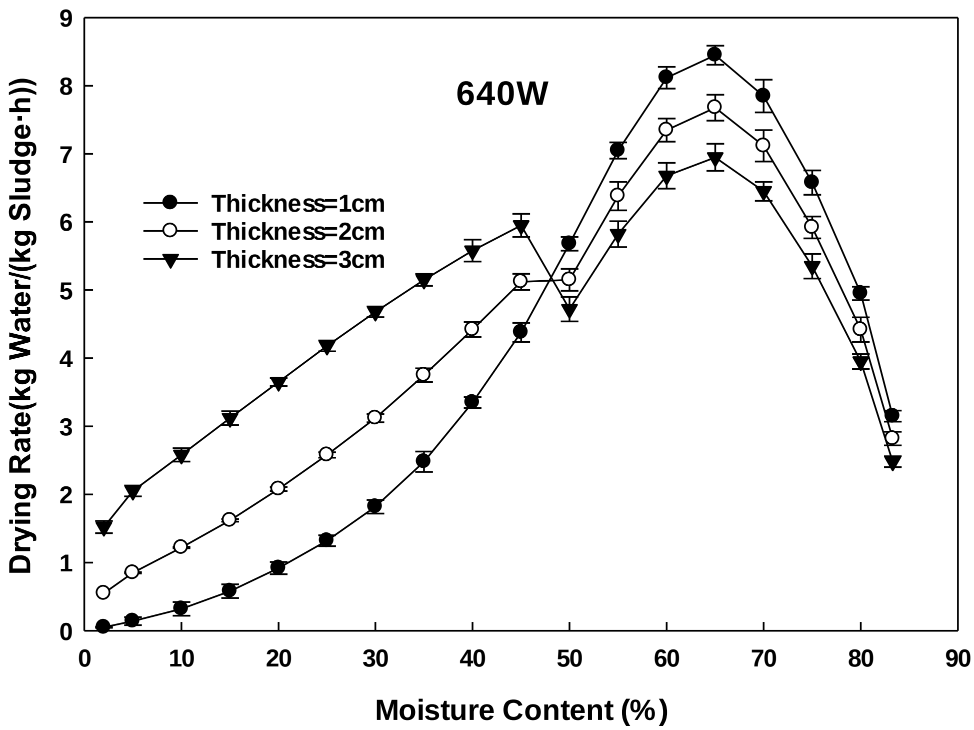

Figure 5. Drying rate curves of sewage sludge at different cake thicknesses (1, 2, and 3 cm) under a microwave power of 640 W (fixed cake diameter: 3 cm).

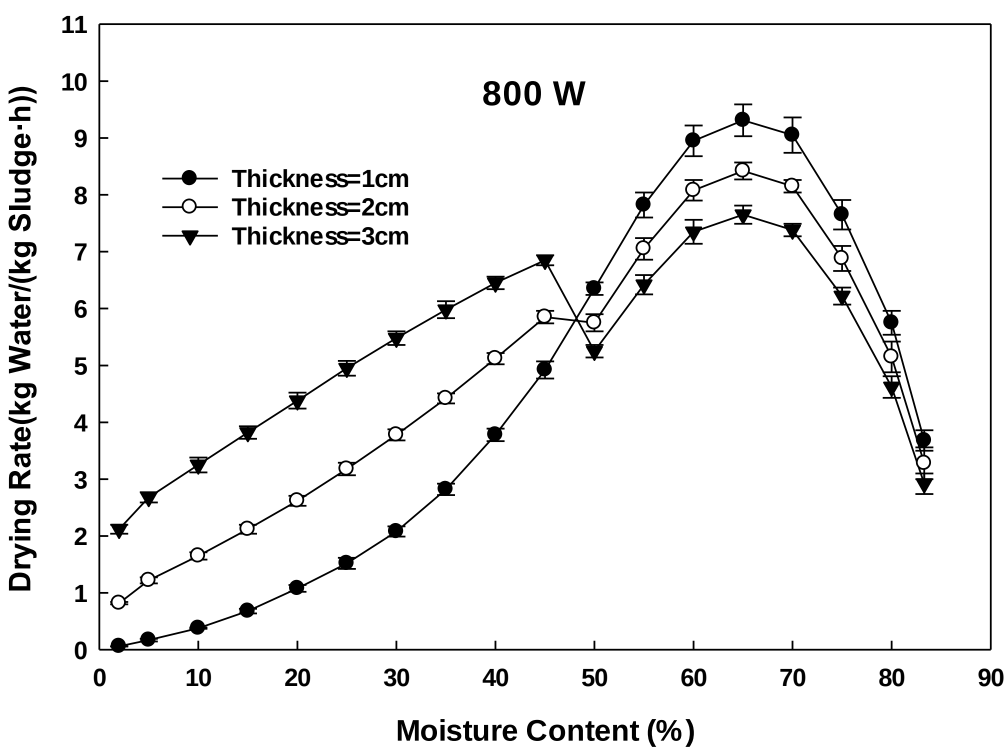

Figure 6. Drying rate curves of sewage sludge at different cake thicknesses (1, 2, and 3 cm) under a microwave power of 800 W (fixed cake diameter: 3 cm).

Mathematical Modeling of Drying Kinetics

The experimental moisture ratio data were fitted to the four thin-layer drying models to mathematically validate the moisture transport mechanisms. As shown in Table 1, the Page model consistently provided the best fit for the microwave drying of sewage sludge across all power levels, yielding R^2 values > 0.985 and the lowest $RMSE$ and χ^2 values.

Table 1. Statistical parameters of the thin-layer drying models fitted to microwave drying data at 480 W (3 cm thickness).

Model	Equation	R^2	$RMSE$	χ^2
Newton	$MR = \exp(-kt)$	0.894	0.054	0.0031
Page	$MR = \exp(-kt^n)$	0.992	0.011	0.0001
Henderson & Pabis	$MR = a\exp(-kt)$	0.910	0.048	0.0025
Midilli	$MR = aexp(-kt^n) + bt$	0.988	0.015	0.0002

The high accuracy of the Page model, which incorporates an exponential exponent (n), mathematically corroborates that the drying process—particularly in the falling-rate period—is governed by complex internal moisture diffusion and the pressure-gradient mechanisms (the "beggar's chicken effect"), rather than simple surface evaporation described by the Newton model. This modeling approach aligns with recent findings by Guo et al. and Bennamoun et al. for microwave sludge drying, providing robust mathematical evidence for the internal pumping phenomenon observed in this study (Bennamoun et al., 2016; Guo et al., 2021).

Influence of Sludge Geometry at Optimal Power

The effect of lateral dimensions on drying kinetics at the optimal 480 W power setting is depicted in Figure 7. Throughout the majority of the drying process (down to 40% moisture), the drying rate strictly followed the order: 3 cm > 2.5 cm > 2 cm. At the peak drying point (65% moisture), Figure 7 shows the rates were 4.72, 5.18, and 5.58 kg water/(kg sludge·h) for 2, 2.5, and 3 cm diameters, respectively. The 3 cm diameter yielded an 18% higher peak rate than the 2 cm diameter. This diameter effect indicates that larger sample diameters reduce edge effects and improve exposure to the standing wave pattern, enhancing microwave coupling efficiency, a mechanism well-documented by Rattanadecho and Makul (Rattanadecho & Makul, 2016). However, a secondary geometric reversal was observed in the final stages of drying (below 20% moisture) in Figure 7. In this late falling-rate period, the 2.5 cm diameter outperformed both the 3 cm and 2 cm diameters. At the final 2% moisture, the 2.5 cm diameter (1.22 kg/(kg·h)) led the 2 cm (0.95 kg/(kg·h)) and 3.0 cm (0.78 kg/(kg·h)) samples. While the 3 cm diameter is excellent for volumetric heating, it suffers from a lower surface-area-to-volume ratio in the final stages. The 2.5 cm diameter emerges as the optimal geometry for final moisture removal, providing an ideal physical compromise between microwave absorption volume and surface area for bound moisture evaporation.

Comparative Energy Efficiency Analysis

Table 2 demonstrates that microwave drying at 480 W achieves the optimal balance between drying rate and energy efficiency. At 480 W, the process required 16.5 minutes, yielding a specific energy consumption (SEC) of 1.92 MJ/kg water removed and a true thermal efficiency (η) of 49%. While 800 W achieved the fastest drying time (9.8 min), its higher SEC (2.45 MJ/kg) and reduced true thermal efficiency (39%) indicate diminishing returns due to dielectric saturation and increased thermal losses.

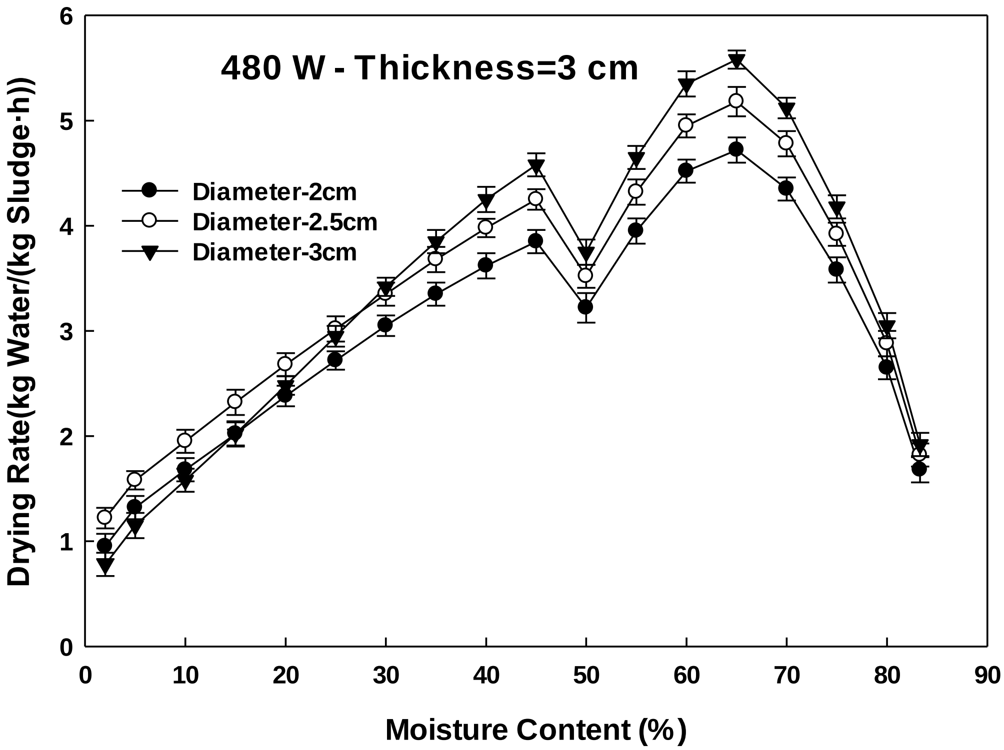

Figure 7. Drying rate curves of sewage sludge at different cake diameters (2, 2.5, and 3 cm) under a microwave power of 480 W (fixed cake thickness: 3 cm).

Table 2. Comparison of drying methods for sewage sludge (initial moisture 82.3%).

Method	Power/Temp	Drying time (min)	SEC (MJ/kg)	Apparent thermal efficiency (%)	True Thermal Efficiency (%)
Microwave	480 W	16.5	1.92	65	49
Microwave	800 W	9.8	2.45	52	39
Hot air	105 ^{0}C	28	2.91	39	29
Infrared	700 W	21	2.38	47	35

The SEC of 1.92 MJ/kg achieved in this study is notably lower than the 2.4–2.8 MJ/kg reported by Kocbek et al. (2020) for pilot-scale microwave drying, which can be attributed to the optimized geometric configuration (2.5 cm diameter) minimizing edge effects and maximizing microwave coupling efficiency. Furthermore, the comparative performance of infrared drying (SEC = 2.38 MJ/kg, true η= 35%) and hot-air convection (SEC = 2.91 MJ/kg, true η= 29%) corroborates the energy advantage of volumetric microwave heating over conventional methods. These findings align with the energy savings reported by Mawioo et al. and Léonard et al. (Léonard et al., 2004; Mawioo et al., 2017), and the direct comparative analyses of hot air versus microwave drying for dewatered sludge by Wulyapash et al. (Wulyapash et al., 2022), confirming that microwave technology significantly reduces the thermal energy bottleneck in sludge management.

Preservation of C:N:P Stoichiometry and Fertilizing Value

Beyond energy efficiency, the end-use of dried sludge as a bio-fertilizer is critically dependent on its macro-nutrient stoichiometry. Table 3 presents the elemental composition and C:N:P stoichiometry. It is important to note that while the absolute mass percentages of TC and TN increased on a dry-weight basis, a mass-balance analysis indicates this is not solely due to water removal. Rather, it is attributed to the concentration effect combined with the minor thermal loss of highly volatile organic fractions during the drying process, which effectively concentrates the remaining elemental mass. Therefore, the true agronomic preservation is evaluated through the stable stoichiometric ratios. The C:N ratio remained virtually unchanged (10.9 to 11) under microwave drying, indicating that the relative mass balance of carbon and nitrogen was preserved, effectively preventing the severe nitrogen volatilization typical of prolonged conventional heating (Kokurewicz et al., 2018; Szypulska et al., 2021).

The initial dewatered sludge exhibited a C:N ratio of 10.9. However, conventional hot-air drying at 105 °C significantly increased the C:N ratio to 14.1. This increase is attributed to prolonged thermal exposure, which promotes organic nitrogen mineralization (Kokurewicz et al., 2018) and ammonia volatilization, leading to substantial nitrogen loss and altering the overall nitrogen mass balance of the treatment process (Szypulska et al., 2021). In contrast, microwave drying at the optimal 480 W preserved the C:N ratio at 11, closely matching the raw sludge. The rapid, volumetric heating mechanism of microwaves minimizes the thermal degradation time, effectively preventing nitrogen volatilization.

Table 3. Elemental composition and C:N:P stoichiometry of sewage sludge under different drying conditions.

Method	TC (%)	TN (%)	TP (%)	C:N	C:P	N:P
Raw sludge	35.2 ± 0.8	3.22 ± 0.1	4.5 ± 0.2	10.9	7.8	0.7
Microwave (480 W)	42.1 ± 0.5	3.81 ± 0.1	5.25 ± 0.1	11.0	8.0	0.7
Hot air (105 °C)	44.5 ± 0.6	3.15 ± 0.1	5.18 ± 0.2	14.1	8.6	0.6
Infrared (700 W)	43.2 ± 0.4	3.42 ± 0.1	5.20 ± 0.1	12.6	8.3	0.7

Note: TC = Total Carbon, TN = Total Nitrogen, TP = Total Phosphorus. Data expressed on a dry weight basis.

The preservation of this optimal C:N stoichiometry is crucial, as it directly correlates with microbial community dynamics and prevents nitrogen immobilization in the soil (Mao et al., 2019). Furthermore, maintaining the correct C:N:P ratios is essential for long-term soil health; recent long-term experiments have demonstrated that optimized sewage sludge compost C:N:P ratios significantly enhance soil enzyme activities and nutrient availability (Almási et al., 2025). Additionally, optimizing nutrient stoichiometry in agricultural soils is a key strategy for enhancing carbon sequestration (Yousra et al., 2025). Therefore, the microwave-dried sludge, with its preserved optimal C:N, C:P, and N:P mass ratios, not only avoids the nitrogen penalties of conventional drying but also maximizes its potential as a high-quality bio-fertilizer that supports soil microbial assimilation and carbon sequestration.

Mechanistic Interpretation and Engineering Implications

The drying behavior observed can be mechanistically interpreted through the dielectric properties of water. Water's high relative permittivity makes it the primary absorber of microwave energy, resulting in volumetric heating (Stuerga, 2006). This mechanism explains both the accelerated drying rates and the pressure-gradient effects that enhance moisture removal at low moisture contents. The integration of microwave drying into sludge-to-energy pathways offers additional benefits. The preserved organic fraction and enhanced porosity of microwave-dried sludge improve pyrolysis bio-oil yields and gasification efficiency (Liu et al., 2024; Venegas-Vásconez et al., 2025). Future research should explore adaptive control strategies that modulate power input based on real-time moisture content to leverage the complementary advantages of different drying regimes, further optimizing the dual benefits of bioenergy production and sustainable agriculture.

A limitation of the current experimental setup is the absence of real-time internal temperature and pressure profiling, which precludes direct measurement of localized hot spots or internal vapor flux. However, the observed kinetic reversal at 50% moisture strongly corroborates the 'beggar's chicken' mechanism. As moisture decreases, the dielectric loss factor of the sludge drops, but the internal vapor pressure—governed by the Clausius-Clapeyron relation—increases exponentially due to continued microwave absorption by the remaining bound water. This creates a strong internal pressure gradient that actively pumps moisture to the surface, a phenomenon well-described by multiphase porous media models (Fu et al., 2017; Ni et al., 1999). Future studies will incorporate fiber-optic temperature mapping to directly quantify these thermal gradients.

Despite the promising batch-scale results, scaling up microwave drying presents distinct engineering challenges. The limited penetration depth of microwaves (typically 1–3 cm in high-moisture sludge) restricts the effective cake thickness. For industrial implementation, batch microwave ovens must be replaced by continuous belt microwave dryers equipped with multi-magnetron arrays to ensure uniform field distribution. Furthermore, the high capital expenditure of microwave generators necessitates a rigorous techno-economic analysis to justify the operational energy savings and the premium value of the preserved bio-fertilizer.

CONCLUSIONS

This study provides a comprehensive optimization of microwave-assisted drying for municipal sewage sludge, delivering critical insights into drying kinetics, geometric configurations, energy efficiency, and nutrient preservation. The drying kinetics consistently followed a three-stage pattern, characterized by a critical transition at a 50% moisture threshold that governs thickness-dependent behavior through the internal pressure-gradient mechanism, or the “beggar's chicken effect”. Furthermore, geometric analysis revealed that a 2.5 cm cake diameter provides the optimal physical compromise for maximizing moisture removal during the final falling-rate stages. Energy evaluations established 480 W as the ideal operating condition, achieving a superior balance between processing speed and energy conservation, yielding a specific energy consumption of just 1.92 MJ/kg and a true thermal efficiency (η) of 49%. Crucially, the rapid volumetric heating of microwave technology significantly outperformed conventional hot-air and infrared methods in preserving the sludge's delicate C:N:P stoichiometry. By minimizing the duration of thermal exposure, the process effectively prevented ammonia volatilization, maintaining an optimal C:N ratio of 11.0 that closely mirrors the raw sludge. Ultimately, these findings offer a robust, scalable framework for advanced sludge management. By overcoming the traditional energy bottlenecks of thermal drying while safeguarding macronutrient balance, microwave drying emerges as an energy-efficient pathway for transforming biosolids into premium bio-fertilizers and bioenergy feedstocks within circular economy models.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

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

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