



Efficient Microwave-Assisted Drying of Dairy Manure towards Biofuel Potential

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Abstract: The sustainability of thermochemical conversion processes is required to be enhanced by energy efficiency of drying of high-moisture biomass. This paper examines the microwave-assisted drying of dairy manure at different microwave power levels (400–800 W), temperatures (110–150 °C) and feedstock loads (10–50 g). Microwave power increased heating rate dramatically in the preheating phase, increasing the heating time of 503 s at 400 W to 162 s at 800 W (67.8% decreases) with no significant rise in total energy use. The sample temperature leveled at 95–100 °C during the drying process, which was the constant-rate evaporation stage. The rise in feedstock load, conversely, decelerated the heating and drying process because of lowered energy input per unit mass and a rise in internal transport resistance. The ratio of the power to mass was important in shaping the drying behavior. Apparently, volumetric microwave heating produces a high degree of internal vapor pressure that causes rapid mass loss at 700 W and 30 g and promotes the migration of moisture. But at high power (800 W) the surface became hard, and the transfer of mass was slowed down in the subsequent drying phase. A power of 700 W and a weight of 30 g gave the optimal drying performance.

Keywords: biomass; energy; microwave drying; cow manure

1. Introduction

With the increasing intensive dairy farming across the globe, sustainable livestock manure management has posed a serious environmental and energy issue. The moisture content of dairy manure is generally more than 70–80 wt% which restricts the direct application of dairy manure in thermochemical conversion processes which include pyrolysis, gasification and combustion. The moisture content of biomass feedstocks is very high, which significantly lowers the heating value and raises the amount of energy burned up in the thermal processing process thus efficient drying is a necessary step in preprocessing. In addition, poor handling of manure can result in the emission of greenhouse gases, soil erosion and contamination of soil and water resources, which underscore the necessity of better treatment technologies [1,2].

The process of drying biomass and organic wastes is normally done through conduction or convection heat transfer thus leading to a lengthy drying period, excessive use of energy, and uneven distribution of temperatures. Internal mass transfer resistance may greatly retard the drying process in the case of high-moisture and porous materials, as in the case of manure. Thus, other methods of drying that can enhance the use of energy and faster moisture extraction have gained the growing interest of research [3,4].

Microwave-assisted drying has proved to be a promising technology in the processing of biomass because of its distinct volumetric heating mechanism [5]. Direct interaction of the microwave energy with polar molecules like water in the material results in the generation of heat inside the material through the rotation of dipole and ionic conduction. This volumetric heating causes temperature to increase quickly, internal vapor pressure to be boosted and moisture movement to be accelerated hence, much less time is used to dry and more energy is saved. Microwave technology has been investigated in a range of biomass-related processes, such as pretreatment, hydrothermal conversion, extraction and drying [2,6].



Microwave irradiation has been found to be effective in treating and drying dairy manure. It has been proven to accelerate the process of drying manure and potentially reduce biological pollutants such as genes that lead to the development of antibiotic resistance. These findings indicate that using microwave-assisted processing can improve drying efficiency and promote safer manure handling. Nevertheless, it is still unknown how feedstock loading, microwave operating parameters, and manure drying behavior are related [7,8]. Nevertheless, regardless of these encouraging outcomes, the underlying correlations between microwave operating parameters and the feedstock loading, and the behavior of manure drying are not clearly understood.

Several important process variables, including microwave power, mass of the feedstock, and temperature, influence the heating properties, movement of moisture, and efficiency of energy greatly. The ratio of power to mass is very important to microwave drying system to ascertain the level of interior heating and the formation of vapor pressure inside porous biomass matrices [9,10]. Excessive microwave energy might cause uneven drying or surface hardness in the last stages of drying, which could impede the moisture diffusion process. Conversely, low energy supply can slow down the heating process and increase the time of drying. In the case of dairy manure, these parameters should be systematically investigated in order to maximize the performance of microwave drying as illustrated in Figure 1.

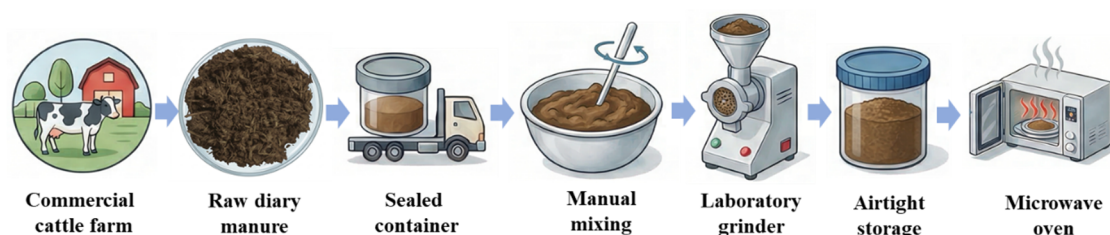


Figure 1. Conversion of animal manure into a treated solid via microwave drying.

In this context, ‘efficient drying’ is defined as the process state, (GEC) is minimized while the dehydration rate is maximized through the synergistic coupling of microwave power and feedstock load. This study examined microwave-assisted drying of dairy manure under different microwave powers, temperatures, and feedstock loads to better understand the heating behavior and dehydration kinetics [11,12]. A study was conducted to determine optimal drying conditions based on temperature evolution, mass loss characteristics, and drying efficiency. These results provide insight into the mechanisms governing microwave-assisted dehydration of manure and contribute to the development of energy-efficient pretreatment strategies for biomass conversion systems. The results can provide the corresponding basis and guidance for the future expansion of the use of microwave drying technology to treat manure-based solid waste.

2. Materials and Methods

2.1. Materials

The dairy manure used in this study was obtained from Heilongjiang Zhongrun Environmental New Energy Technology Co., Ltd. (Heilongjiang, China), and originated from a commercial-scale cattle farm. After collection, the samples were sealed and transported to the laboratory for further treatment. Figure 1 shows the process of the microwave-assisted drying of dairy manure. The raw manure contained a considerable amount of straw fragments and partially digested plant fibers of different sizes, forming a porous agglomerated structure with uneven moisture distribution.

To reduce the influence of material heterogeneity and improve experimental repeatability, all samples were subjected to a uniform pretreatment before the drying experiments. The manure was first manually mixed to ensure overall consistency. Portions of 200 g were then processed in a laboratory grinder at room temperature for 10 min to break down long fibrous components and improve structural uniformity. After grinding, the material was mixed again and stored in airtight containers prior to use. The physical properties of the pretreated samples were then characterized. The true density of the manure was measured as 1.21 g/cm³ using the liquid displacement method. Due to the high moisture content, the thermal conductivity and specific heat capacity of the feedstock were estimated to be in the ranges of 0.45–0.55 W/(m·K) and 3.2–3.8 kJ/(kg·K), respectively, based on established values for organic waste with similar moisture level [13,14].

ASTM E871 was used to determine the initial moisture content. A crucible that had been previously dried and weighed was filled with about 5–10 g of the prepared sample. The samples were dried in a forced-air oven at 105 ± 2 °C until a constant mass was reached. During drying, the crucibles were periodically removed, cooled in

a desiccator, and weighed. Constant mass was considered achieved when the difference between two successive measurements was less than 0.1%. The wet-basis moisture content was calculated from the mass loss before and after drying. The average initial moisture content of the manure was $71.2 \pm 1\%$, based on three parallel measurements.

2.2. Experimental Setup

The microwave drying experiments were conducted using a laboratory-scale microwave heating system operating at a frequency of 2.45 GHz. The microwave power could be adjusted within the predefined experimental range. An external electricity meter was connected to the system to monitor the input electrical power and cumulative energy consumption during each run [15,16].

Temperature evolution inside the sample was measured using a thermocouple-based temperature recorder. The probe was inserted into the geometric center of the manure bed to minimize boundary effects. The temperature data were measured at the intervals of 1 s and at the beginning of the whole heating process to record transient thermal behavior [17].

The change in sample mass of the dried sample was measured on a tension-type load cell attached to a data acquisition system. Mass signal was also captured at time intervals of 1s, and this enabled the real time analysis of the kinetics of moisture removal. The temperature and mass data could be obtained synchronously, thus allowing the drying curves and DTG profiles to be constructed later.

The reported electricity usage was used to determine the electrical energy consumption. The energy in kJ was calculated from the cumulative electrical usage (kWh) using the following equation:

$$E_{\text{kJ}} = \text{Energy}_{\text{kWh}} \times 3600 \quad (1)$$

where E represents the total electrical energy input during the experiment.

A quantitative analysis of the drying behaviour was conducted by calculating the moisture ratio (MR), drying rate (DR), power-to-mass ratio (PMR), total energy consumption (TEC). And The Gram Energy Consumption (GEC , kJ/g) was used to evaluate the energy required to remove a unit mass of moisture, as calculated using Equations (2)–(6). As a result of these parameters, microwave operating conditions can be linked with moisture transport dynamics and energy efficiency [18].

$$PMR = \frac{P}{m} \quad (2)$$

$$TEC = \frac{P \times t}{1000} \quad (3)$$

$$GEC = \frac{TEC}{m_w} \quad (4)$$

$$DR = \frac{-dM}{dt} \quad (5)$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (6)$$

M is the mass of evaporated water (kg), M_0 is the initial moisture content, M_t moisture content at time t , M_e is the equilibrium moisture content where P is the microwave power (W) and m is the sample mass (g).

The drying performance was measured by a power-to-mass ratio (PMR), total energy consumption (TEC), gram energy consumption (GEC), drying rate (DR), and a moisture ratio (MR). The PMR values varied widely between 14.0 and 80.0 W/g with respect to power input of microwaves and feedstock loading. According to the measured heating times, the preheating-stage energy demand decreased from 227.2 kJ at 400 W to 129.6 kJ at 800 W, indicating that process intensification reduced cumulative energy consumption despite higher nominal power levels. In the drying process, the maximum rate of drying between 400 W and 800 W corresponded to the maximum rate, and the lowest gram energy consumption was measured at 700 W and a mass of 30 g with an approximate value of 40 kJ/kg. Overall, these findings show that the effective power-to-mass ratio can be identified as the main factor of microwave drying performance because it defines both the rate of moisture removal and the efficiency of energy use [19]. To ensure experimental repeatability and minimize material heterogeneity, all trials were performed in triplicate.

2.3. Experimental Procedures

Drying experiments were conducted in a microwave oven ($300 \times 360 \times 300 \text{ mm}^3$) operating at 2450 MHz with a 100–1000 W power range. To facilitate rapid moisture escape, two quartz reactors (30 mm diameter; 200 and 400 mm height) were employed. A thermocouple was inserted into the sample's geometric center for temperature monitoring. The system included a rotating turntable to ensure uniform power distribution and minimize hot spots. The probe was entered vertically through a sealed opening at the top of the microwave oven, ensuring that the sensing tip was positioned at the exact center of the bed material, thereby minimizing boundary effects. The packing density of the manure bed was regulated to $0.4 \pm 0.1 \text{ g/cm}^3$ during the loading, so that the structure of the bed and the similarity of the internal heat and mass transfer conditions during the various experimental runs could be maintained. Figure 2 shows the schematic setup of the experimental apparatus.

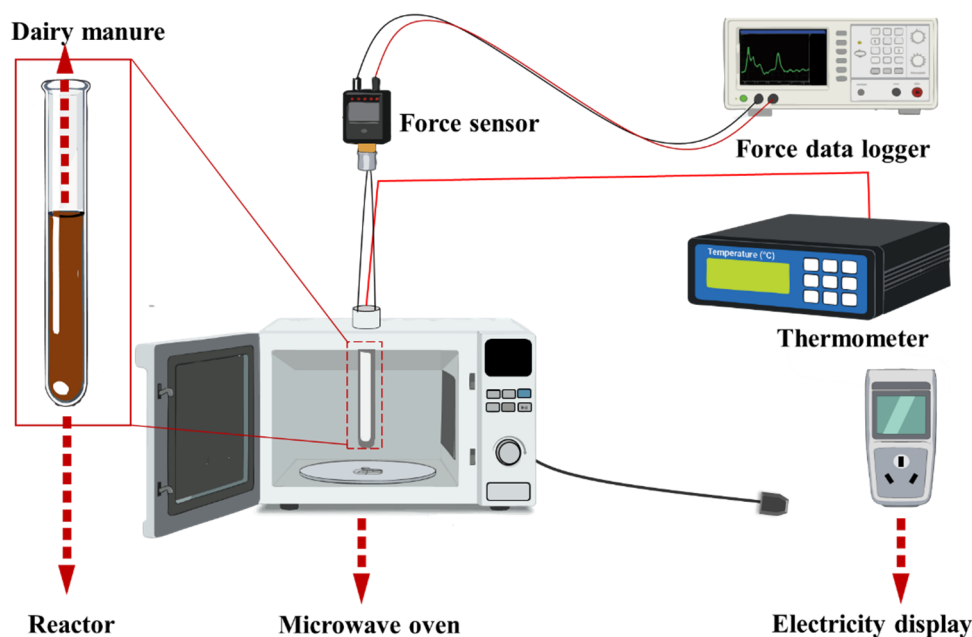


Figure 2. Schematic of experimental setup drying of dairy manure.

2.4. Data Analysis

This paper critically analyzed the variables that affect the behavior of microwave drying and energy usage. Three important variables were chosen, which are the power of the microwave, maximum temperature of the target, and the mass of the sample. These parameters indicate intensity of energy input, driving force of thermodynamics and structural characteristics of the bed respectively. They all control microwave coupling, moisture migration and energy efficiency.

The microwave power was experimented at five levels of 400, 500, 600, 700 and 800 W. The purpose of this setup was to determine the relationship between energy input rates and heating profiles and Specific Energy Consumption (SEC). The maximum temperatures were adjusted to 110, 120, 130, 140, and 150 °C. These points were used to examine the effect of thermal endpoints on dehydration and drying processes. Lastly, mass of samples was altered to 10, 20, 30, 40 and 50 g. We prepared various bed heights by varying the mass to study their heat and mass transfer resistance.

Manure was well mixed in each trial. An electronic balance with a resolution of 0.01 gm was used to weigh samples. The initial mass was registered. The manure was loaded into a quartz tube reactor. A small amount of pressure was used to flatten the surface and keep the packing density constant. This was to provide that the bed height is the only thing that varies but the compactness is the same. As such, we would be able to research various moisture movement routes and vapor escape resistances.

The real-time internal temperature was monitored. A thermocouple probe was put inside the geometric center of the sample. High-resolution heating curves were recorded at 1 s to record data. The heating system was then initiated after the power and target temperature were set. Synchronous recording of temperature and total time was done. Heating stopped once the core reached the target temperature. The total reaction time was documented. Samples were then cooled to room temperature in a desiccator. The final mass was recorded. We calculated the

moisture removal rate based on mass loss. SEC was determined using the cumulative electricity recorded by the energy meter. For analysis, electrical energy in kWh was converted to kilojoules (kJ).

All experiments were performed at least in triplicate to ensure reliability. The relative error for each group was kept below 5%. Final results are reported as the mean values of these parallel trials. Therefore, experiments as shown in Table 1 were carried out separately.

Table 1. Expected working conditions for microwave pyrolysis.

Factor	Working Condition
Microwave power (W)	400, 500, 600, 700, 800
Feedstock load (g)	10, 20, 30, 40, 50

3. Results and Discussion

3.1. Transient Temperature

A transient temperature profile during microwave-assisted drying can be seen in Figure 3a,b. Microwave power is the principal operating variable in Figure 3a. As microwave power increased, the heating rate accelerated significantly during the initial preheating stage. Increasing the microwave power from 400 W to 800 W resulted in a reduction in preheating time of 67.8% from 503 s to 162 s. Moreover, the reduction in processing time did not result in a proportionate increase in energy consumption. At higher power densities, the material quickly traverses the energy accumulation stage, during which absorbed microwave energy is primarily converted into sensible heat within the sample matrix.

Drying proceeds at a constant rate, where the sample temperature stabilizes at approximately 95–100 °C. The temperature plateau at 95–100 °C during the constant-rate drying period is a result of the dominant consumption of microwave energy as the latent heat of vaporization. This phase-change cooling effect offsets the energy input, maintaining a dynamic thermal equilibrium within the manure matrix. At this point, a dynamic energy balance is established, in which most of the microwave energy is consumed as latent heat of vaporization for the purpose of removing moisture from the air. Furthermore, surface condensation also provides evidence in favor of the typical volumetric heating process of microwave drying. Internal vapors are produced, and this leads to pressure gradients that promote rapid movement of moisture within the porous system of the manure matrix, thus ensuring that the drying rate remains constant.

After this phase, the drying process proceeds to the falling-rate phase, which is a nonlinear phase of drying rate. This process has led to the removal of most of the easily available free water and the rest of the moisture is mainly attached to the solid matrix. The effective dielectric loss factor also decreases significantly because of the high level of reduction in the liquid water content; therefore, the material and the microwave field lose their coupling. Based on these, the absorption of microwave energy in dry solid framework is passed to solid framework leading to a gradual rise in temperature as the drying process continues. Figure 3b illustrates how sample loading affects heating behavior. The time needed to attain the temperature plateau was greatly extended by increasing the sample's bulk from 10 g to 50 g. Nevertheless, under constant microwave power settings, the increase in heating time was not exactly proportionate to the increase in mass, larger sample loads decrease the specific energy input per unit mass, while also altering the internal heat and mass transfer characteristics within the material bed. It is likely that such effects are due to the alterations in the distribution of electromagnetic field, dielectric interactions, and moisture migration routes, that, in turn, influence the global dynamics of the heating process.

In this paper, the temperature change measured is in line with the behavior of microwave drying reported in the past. In the microwave drying of plant materials, such as coriander leaves, the same heating patterns were found, whereby, the temperature rises quickly after which it flattens around the boiling point of water because of the volumetric heating of the microwave and consumption of latent heat during evaporation [20]. The same tendency can be traced in sewage sludge drying, where the power intensity of a microwave has a strong impact on the heating rates and kinetics of drying [21]. These results suggest that the intensity of microwave power and the loading of the sample are important factors determining heating behavior, moisture movement, and drying efficiency of the microwave-assisted drying processes, according to these findings, and the past research on manure-derived materials [8,22].

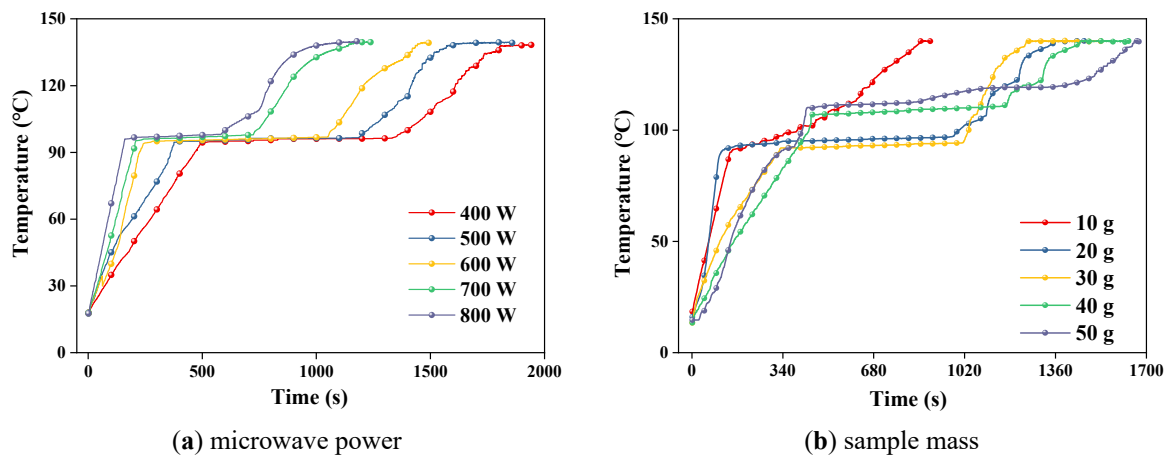


Figure 3. Temperature profiles during microwave drying.

3.2. Transient Weight

Figure 4 displays the change in mass of the sample with drying time under varying levels of microwave power and under varying loads of the feedstock. As indicated in Figure 4a, the dehydration process significantly increased with a rise in microwave power between 400 W to 800 W was indicated by the steeper slopes of the mass loss curves. The time taken by the sample to reach equilibrium moisture content reduced by about 39.3% at 800 W when compared to the minimum power condition because high power of the microwave produces a stronger electromagnetic field that increases rotational polarization of water molecules. This causes the proportion of the microwave energy that is transformed into thermal energy in the material to increase and this leads to sensible heating of the material as well as rapid evaporation of moisture.

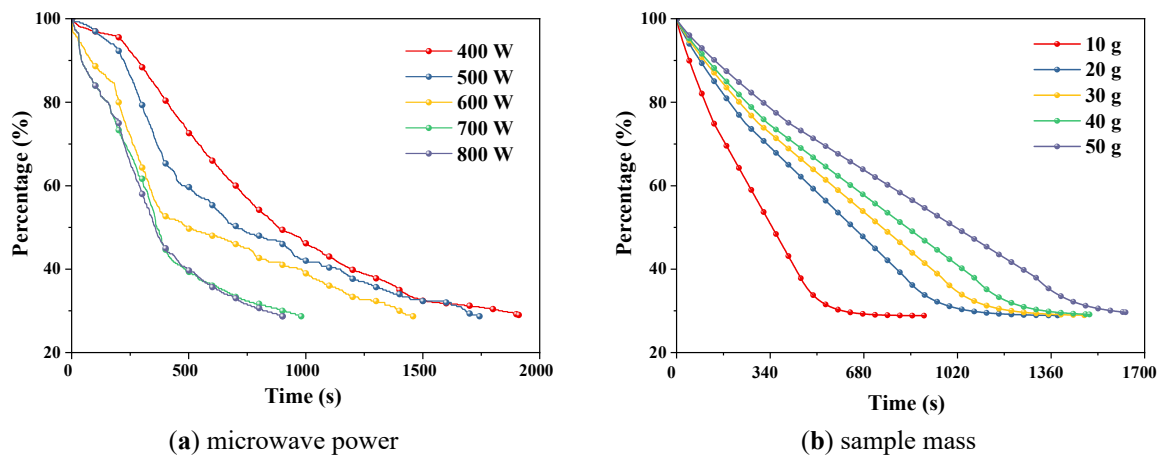


Figure 4. Weight during microwave drying.

On the contrary, Figure 4b demonstrates that the process of drying is dramatically retarded in case of high load of feedstock. Mass reduction of the 10 g sample was rapid, and the 50 g sample exhibited much slower mass loss kinetics with a distinct plateau to the mass loss curve. This is caused mainly by variations in a particular energy input per unit mass. Since microwave energy is held constant at 700 W, a smaller load of feedstock is given higher energy density, rapid internal heating and constant-rate drying starts sooner.

Interaction effects between the power of microwaves and the feedstock loading show that the important factor in determining the drying kinetics is the effective input of energy. It is noteworthy that similar drying trajectories were observed under conditions of high microwave power (800 W) and low feedstock loading (10 g), suggesting that power-to-mass ratios are critical for controlling moisture migration during microwave-assisted drying.

A very high rate of mass loss at 700 W when fed with 30 g feedstock showed that the strong internal vapor pressure gradient had developed within the manure matrix. Since the heating process by microwaves is volumetric, vapor is produced directly in the porous structure of the substance. Due to this process, liquid water and vapour are forced to the surface thereby increasing mass transfer in the early drying process.

The drying curves also, however, show that the drying rate also slows down considerably in the later stages of the process especially when using 800 W. There is a sudden loss of mass when the reduction of moisture becomes 25.5%. This behavior can be caused by structural change in the material, e.g., surface hardening or collapse of some of the pores, which raises resistance to diffusion of water.

A better ratio between vapor generation and bed permeability seems to be 700 W and 30 g. Consequently, rate of internal vapor formation in the instance is like the capability of the porous matrix to transport moisture easily, and thus, the porous structure can remove moisture efficiently without using too much energy.

As it is shown in this paper, the power-to-mass ratio is one of the main parameters of controlling the transient loss of mass during the drying process of dairy manure with the use of microwave.

The tendencies found in this research are comparable to the tendencies that were already documented in the past concerning the microwave drying of food and agricultural products. Other power-dependent acceleration of mass loss has been observed using microwave drying of concentrated skim milk [23] and onion slices [24], in which increased power of the microwave accelerated internal heating and movement of moisture. These investigations also emphasized the role of material loading and energy density in defining the drying kinetics. The current results thus support the fact that microwave power-to-mass ratio needs to be controlled to ensure that the moisture elimination and energy conservation in microwave drying systems are maximized.

3.3. Drying Rate Evolution

Figure 5a,b indicates that the drying rate can be changed with time and the level of the microwave power. Microwave power intensity and sample loading are influential factors that affect drying behaviors, as shown by the curves.

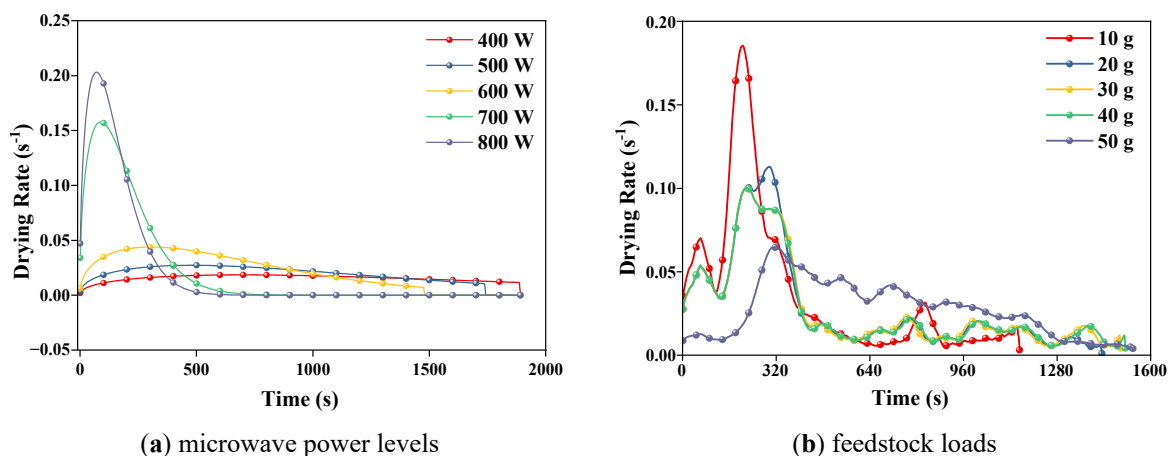


Figure 5. Variation of influencing factors on drying dairy manure.

Figure 5a shows that an increase in microwave power, 400 W to 800 W, had a great impact on the peak drying rate and faster initiation of the rapid drying stage. The highest drying rate was observed to go up with power, thereby reaching about 0.20 s⁻¹ at 800 W, as compared to below 0.02 s⁻¹ at 400 W. Due to increased electromagnetic field produced by the increased powers in the microwaves, the rate at which the dielectric heating is enhanced and the rate at which internal energy generation occurs in the manure matrix is enhanced. As such, quick transformation of the microwave energy into thermal energy facilitates quicker evaporation of moisture and speedy extraction of free water in the primary drying phase.

During the initial stage of drying, the rate of drying has a sharp peak, and it is followed by a steep decrease. This implies that the drying process occurs at first in an accelerating stage and then in a falling-rate stage, instead of a long constant-rate stage that is seen in conventional convection drying. Due to pressure-induced flow within the porous structure of manure, the rapid increase in drying rate can be attributed to the combined effects of volumetric microwave heating and internal vapor pressure generation.

After reaching its peak value, the drying rate continues to decline over time. This behavior corresponds to the gradual depletion of free water and the transition into the removal of bound moisture. When the moisture content of the material decreases, the dielectric loss factor of the material decreases, which weakens the coupling between the microwave field and the sample. As a result, less microwave energy is absorbed by the material and moisture transport becomes increasingly limited by internal diffusion resistance.

Figure 5b illustrates how feedstock loading influences drying rate. Lower sample masses produced significantly higher peak drying rates as well as earlier drying-rate maxima. The 10 g sample displayed the highest peak drying rate, exceeding 0.17 s^{-1} , while the 50 g sample displayed a much lower and broader drying rate profile. Figure 5a,b indicates that the drying rate can be changed with time and the level of the microwave power. Microwave power intensity and sample loading are influential factors that affect drying behaviors, as shown by the curves.

Previously reported microwave drying behavior for biomass and sludge materials is consistent with these findings. Similar rapid drying-rate peaks followed by a falling-rate period have been reported for microwave drying of sewage sludge and plant material, where volumetric heating and internal vapor pressure gradients significantly improve early-stage moisture removal, while diffusion limitations dominate at lower moisture contents [18,25]. A similar pattern of behavior indicates that microwave power density and sample loading are key factors determining the drying efficiency of microwave-assisted biomass drying systems.

3.4. TG analysis

A thermogravimetric (TG) profile of dairy manure under different microwave power levels and feedstock loads is presented in Figure 6a,b. As a result of the TG curves, one can determine how the mass fraction changes with temperature as well as what behavior the material exhibits during thermal dehydration.

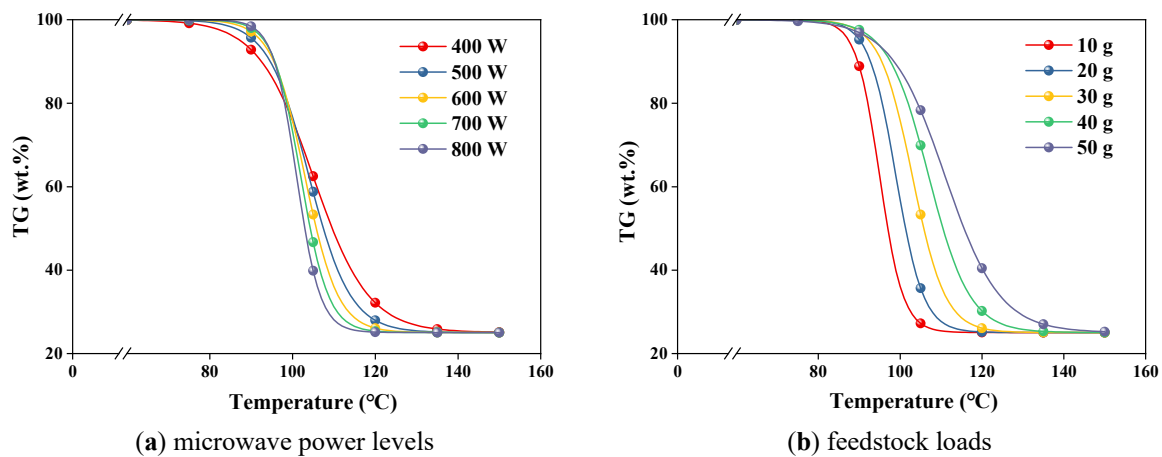


Figure 6. TG analysis of dairy manure.

This can be seen in Figure 6a, all samples exhibit a similar thermogravimetric trend. The three major stages are an initial stable region, a rapid mass loss region, and a final stabilization stage. In the initial stage (below approximately 90–95 °C), only minor mass variations are observed, indicating limited moisture evaporation as the temperature increases. As the temperature approaches the boiling point of water, the TG curves exhibit a sharp decline, corresponding to the primary moisture removal stage. In this region, free and capillary water within the porous structure of the manure evaporates rapidly.

Microwave power has a significant influence on the position and steepness of this area of mass loss. As microwave power is increased from 400 W to 800 W, the rapid mass loss stage is induced earlier, and the TG slope becomes steeper, indicating faster moisture removal. In microwave dielectric heating, the rate of dehydration increases, increasing the internal heat generation rate and accelerating the formation of vapor pressure gradients. Furthermore, these gradients enhance the efficiency of water removal in addition to promoting moisture outward transport.

As shown in Figure 6a, all TG curves eventually converged to a similar residual mass (25–27 wt.%), suggesting that while microwave parameters significantly dictate the drying rate, they do not alter the final solid composition. This confirms that no substantial thermochemical decomposition occurred at the operating temperatures (<150 °C). In solid matrices, residual moisture is removed more slowly due to stronger binding forces and diffusion limitations.

In Figure 6b, the effect of feedstock loading on thermogravimetric behavior is illustrated. Lower sample masses have a wider and delayed dehydration profile than higher feedstock loads. In this regard, the 10 g sample becomes heated to the rapid mass loss phase at a lower temperature than the 50 g sample, and as a result, smaller loads are heated and lose moisture more quickly.

In this instance, the variations in the input of microwave energy per unit mass can be used to explain the observed behavior. Smaller samples are subjected to a higher energy density under constant microwave power,

leading to a higher temperature increase and faster water movement. Heavy masses of samples reduce the amount of effective energy available per unit mass and amplify the internal heat and mass transfer resistance which retards the occurrence of rapid dehydration.

It is necessary to add that despite such differences, the fraction of mass that is left over is rather similar to all operating conditions. This suggests that the microwave power and feedstock loading have a greater impact on drying kinetics than the final solid composition of the dried manure.

As a result of the TG results, microwave power accelerates moisture removal by intensifying dielectric heating, while feedstock loading determines uniformity of heating and internal resistance to transport within the material bed.

Microwave drying of biomass and sludge materials has been observed in previous studies. A similar TG profile characterized by rapid moisture loss near water boiling point has been observed for sewage sludge and agricultural residues, where volumetric microwave heating facilitates efficient dehydration while maintaining a relatively constant residual solid fraction. Energy density and sample loading play an important role in controlling the thermogravimetric drying characteristics of microwave-treated biomass [14,26].

3.5. Energy Analysis

A comparison of the energy performance of microwave drying under different operating conditions is shown in Figure 7a,b, total energy consumption (TEC) and gram energy consumption (GEC). This combination of metrics captures the combined effects of microwave power and feedstock loading on the absolute energy demand and the amount of energy required per unit weight of water removed.

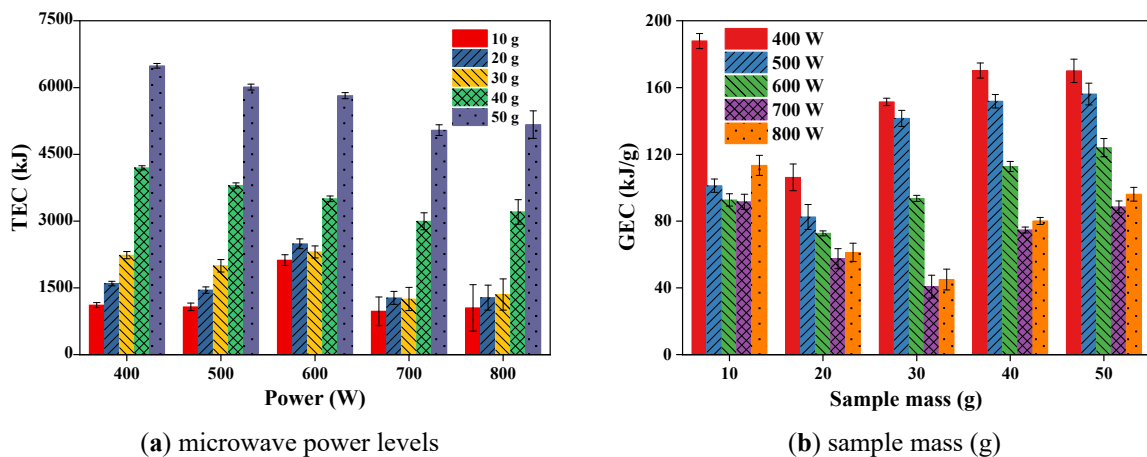


Figure 7. Energy performance of microwave drying dairy manure.

As shown in Figure 7a, TEC increased significantly as sample mass increased at all microwave power levels. For a given power input, 50 g samples consistently showed the highest total energy consumption, whereas 10 g samples showed the lowest consumption. The trend is expected because larger feedstock loads require a greater amount of energy to heat the material bed and evaporate a greater amount of moisture. Although microwave power had a monotonic effect on TEC, the effect was not linear. By increasing the power from 400 W to 800 W, most sample masses showed a reduction in total energy consumption, indicating that the reduction of drying time at high power more than compensated for the increase in instantaneous power. Based on this behavior, it is evident that process duration, rather than microwave power alone, determines the total energy consumption of a process.

At intermediate and high feedstock loads, the reduction in TEC becomes particularly apparent. Therefore, in such circumstances, the increased power of microwaves enhances the total energy condition by increasing the speed of the preheating and active evaporation phase. That is, high internal heating rate minimizes the dwell time needed to remove the moisture and therefore, conservation of energy cumulatively.

In Figure 7b, GEC relies on sample loading. Unlike TEC, GEC tended to fall with the increase of power at microwave frequencies on a constant mass sample, which means that more power contributed to greater efficiency of energy utilization. It can be seen through this decrease that a unit mass of water needed less energy to be removed when the drying process was accelerated. This has been improved by enhanced dielectric heating, quicker internal vapor creation and enhanced adoption of absorbed microwave energy to change phases rather than long sensible heating.

Sample mass has a more complicated effect on GEC. GEC was relatively high in low loadings (10–20 g) of feedstock, especially at lower microwave powers. Despite the high drying rate of these samples, the quantity of the evaporated water was low, and this augmented the normalized energy cost per unit of mass of the removed moisture. GEC on the other hand was minimum at intermediate loading particularly at the range of 30 g, under a variety of power conditions. This finding of this research indicates that an intermediate feedstock mass is more beneficial regarding the microwave absorption, water removal capacity, and minimization of heat loss.

GEC rose once again as mass sample rose (40–50 g) although the overall moisture content rose. This shows that overloading leads to further internal resistance to mass transfer and heat, which restrain the performance of microwave energy. Increased sample beds will tend to decrease the uniformity of heating and slow down the escape of vapor. This will cause the drying times to be longer, and the amount of energy spent in drying a unit of water to be removed to increase.

These findings suggest that there is an obvious trade-off between absolute energy demand and specific energy efficiency. TEC increases with larger sample loads because more energy is required to dry the samples, while GEC is less favorable with very small or very large loads. When the rate of internal vapor generation is well matched to the permeability and moisture transport capacity of the material bed, the lowest GEC values are observed at intermediate loadings and moderate-to-high microwave power levels. This suggests that energy efficiency is maximized at intermediate loading levels. The minimum GEC observed at 700 W with a 30 g load indicates an optimal power density (23.3 W/g). At this level, the driving force provided by internal vapor pressure is perfectly equilibrated with the bed's moisture diffusion resistance, avoiding excessive heat loss.

As a result of the energy analysis, it has been demonstrated that microwave drying efficiency is determined by the interaction between power intensity and feedstock loading, rather than by either parameter alone. It appears that operating at moderate-to-high microwave power with an intermediate sample mass provides the best balance between rapid drying and efficient energy consumption from the perspective of process optimization.

According to previous studies on microwave drying sludge and lignocellulosic biomass, higher microwave power generally reduces the specific energy consumption by shortening the drying time, whereas excessive sample loading reduces process efficiency and increases internal transport limitations [2,14]. Based on the present results, it is confirmed that the power-to-mass relationship is a critical design parameter for improving the energy efficiency of microwave-based drying systems.

3.6. Proposed Mechanism

According to the proposed mechanism (Figure 8) moisture transport, volumetric dielectric heating, and internal vapor generation contribute to the drying behavior during the preheating, constant rate, falling rate phases. When the microwave power is increased during the preheating stage, the internal heating is accelerated, and the heating time is shortened. During the constant rate stage, the temperature stabilizes between 95 °C and 100 °C, where absorbed energy is mainly used for water evaporation, and internal vapor pressure drives rapid moisture removal. As the moisture decreases, the dielectric absorption decreases and drying becomes diffusion controlled [27]. Increased heating and drying rates are achieved with the use of microwave power, but higher feedstock loading decreases efficiency because of a reduced specific energy input and an increase in internal resistance. A mass loss takes place between 90 and 110 °C and this is equivalent to removal of free water, and the final products are mostly the same.

Overall, the process is regulated by the ratio power-to-mass, which regulates the level of heating, transport of moisture, and energy efficiency.

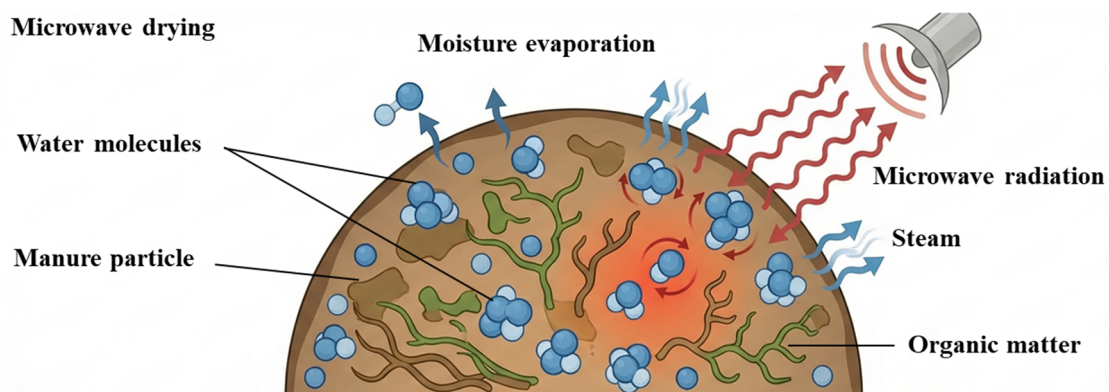


Figure 8. Schematics of microwave-assisted drying of dairy manure.

4. Conclusions

The current research examined the microwave-assisted drying of dairy manure at varying power (400–800 W) and load (10–50 g) whereby the impact of the two parameters on heating, drying kinetics, and energy efficiency were found to be significant. High levels of power in the microwave decreased preheating duration (to 67.8%) and enhanced drying rates (0.015 to 0.20 s^{-1}), whilst loading lessened drying results because of lower specific energy input and inner resistance.

Drying involves three steps that include rapid heating, constant rate phase which is dominated by water evaporation at a temperature of about 95 to 100 °C and falling-rate phase that is controlled by the fact that bound moisture is diffused. It was established that most of the mass loss was taking place at 90–110 °C, and the end solids were not significantly influenced by the conditions in which they were operated.

Given that an analysis of energy consumption was done, it was established that total energy consumption rose with load whereas specific energy consumption fell at higher powers. The inhibitory effect of surface hardening on moisture migration at a high microwave power of 800 W was observed. Consequently, 700 W was identified as the optimal power level for 30 g of dairy manure, where a synergistic balance is achieved between internal vapor pressure and bed permeability. Furthermore, the dual indicators (TEC and GEC) demonstrated that shortening the preheating phase enables enhanced efficiency without increased energy consumption, as TEC does not scale linearly with microwave power.

Generally, the drying performance is defined by the power-to-mass ratio. Microwave drying is a good valorization technique of manure, which has a high potential in managing waste in a sustainable manner. Future work should explore pilot-scale and integration with microwave-assisted pyrolysis.

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References

1. Wang, J.; Chen, S.; Lai, F.; et al. Microwave-assisted hydrothermal carbonization of pig feces for the production of hydro-char. *J. Supercrit. Fluids* **2020**, *162*, 104858.
2. Luo, T.; Wang, Y.; Pandey, P. The removal of moisture and antibiotic resistance genes in dairy manure by microwave treatment. *Environ. Sci. Pollut. Res.* **2021**, *28*, 6675–6683.
3. Gao, Y.; Liu, Y.; Zhu, G.; et al. Microwave-assisted hydrothermal carbonization of dairy manure: Chemical and structural properties of the products. *Energy* **2018**, *165*, 662–672.
4. Zhang, Y.; Fu, W.; Cui, L.; et al. Experimental microwave-assisted air gasification of biomass for syngas production. *Fuel* **2023**, *339*, 126954.
5. Zhang, Y.; Zhao, W.; Xie, K.; et al. Studies on microwave heating performances of biomass. *Energy Conserv. Technol.* **2026**, *44*, 3–7.
6. Lozano, A.S.; Lozada, J.J.; Guerrero, C.A. Application of microwave energy to biomass: A comprehensive review of microwave-assisted technologies, optimization parameters, and the strengths and weaknesses. *J. Manuf. Mater. Process.* **2024**, *8*, 121.
7. Guo, J.; Zheng, L.; Li, Z. Effect and interrelationship of different influencing factors on drying performance and energy analysis of cow manure in microwave drying at pilot scale. *J. Clean. Prod.* **2023**, *413*, 137407.
8. Moukakis, I.; Gidarakos, E. Microwave-assisted hydrothermal carbonization of rabbit manure. *Waste Manage.* **2025**, *203*, 114836.
9. Palla, S.; Surya, D.V.; Pritam, K.; et al. A critical review on the influence of operating parameters and feedstock characteristics on microwave pyrolysis of biomass. *Environ. Sci. Pollut. Res.* **2024**, *31*, 57570–57593.

10. Cui, L.; Zhang, Y.; Shi, C.; et al. Describing the microwave heating performances of the main constituents of biomass. *Energy* **2024**, *302*, 131873.
11. Dehghannya, J.; Habibi-Ghods, M. Microwave Drying of Food Materials: Principles, Hybrid Techniques, Modeling Approaches, and Emerging Innovations. *Compr. Rev. Food Sci. Food Saf.* **2025**, *24*, e70312.
12. Divyabharathi, R.; Komalabharathi, P.; Subramanian, P. Microwave-assisted hydrothermal carbonization for biochar production: Potential application and limitations. In *Biochar Production for Green Economy: Agricultural and Environmental Perspectives*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 43–56.
13. Mahmoud, A.; Mohamed, N.; Mahmoud, A.; et al. The effect of microwave drying pretreatment on dry torrefaction of agricultural biomasses. *Bioresour. Technol.* **2019**, *286*, 121400.
14. Wulyapash, W.; Phongphiphat, A. Comparative study of hot air drying and microwave drying for dewatered sludge. *Clean Technol. Environ. Policy* **2022**, *24*, 423–436.
15. Cui, Y.; Zhang, Y.; Cui, L.; et al. Microwave-assisted fluidized bed reactor pyrolysis of polypropylene plastic for pyrolysis gas production towards a sustainable development. *Appl. Energy* **2023**, *342*, 121099.
16. Huang, G.; Han, L.; Yang, Z.; et al. Evaluation of the nutrient metal content in Chinese animal manure compost using near infrared spectroscopy (NIRS). *Bioresour. Technol.* **2008**, *99*, 8164–8169.
17. Zhao, W.; Cao, W.; Cui, L.; et al. Energy and exergy performances of corn straw and SiC during the microwave heating process. *J. Therm. Sci.* **2025**, *34*, 1857–1866.
18. Wang, G.; Zhang, K.; Huang, B.; et al. Microwave drying of sewage sludge: Process performance and energy consumption. *Processes* **2024**, *12*, 432.
19. Fu, W.; Zhang, Y.; Liu, Z.; et al. Kinetic and thermodynamic insights into the catalytic pyrolysis of PP with Fe/Ni catalysts. *Energy* **2025**, *330*, 136809.
20. Khodifad, B.C.; Dhamsaniya, N.K.; Rathod, P.J. Effect of microwave drying on sensory attribute of coriander leaves. *Int. J. Chem. Stud.* **2020**, *8*, 1618–1623.
21. Xie, K.; Liu, Z.; Zhang, M.; et al. Understanding the Transient Microwave Drying Performances of Industrial Sewage Sludge Towards Green Fuel and Energy. *Green Energy Fuel Res.* **2025**, *2*, 174–186.
22. Liu, Z.; Luo, W.; Zhang, M.; et al. Evaluating the potential environmental impact of biomass combustion methods using quantitative universal exergy method. *Energy Environ. Nexus* **2026**, *2*, e005.
23. Dumpler, J.; Moraru, C.I. A process optimization approach for microwave vacuum drying of concentrated skim milk. *J. Dairy Sci.* **2022**, *105*, 8765–8781.
24. Srinivas, G.; Radhika, G.B.; Praveen, B.V. Experimental study on the effect of microwave heating power on the drying behavior of onion slices. *MethodsX* **2025**, *15*, 103479.
25. Wang, F.; Tian, N.; Ren, L.; et al. Quantitative investigation of moisture migration during microwave drying of coal slime dough through simulation and tracer analysis. *Sci. Rep.* **2025**, *15*, 11308.
26. Ling, W.; Feng, W.; Xing, Y.; et al. The impact of ambient-temperature deep drying on the surface characteristics of sewage sludge. *Dry. Technol.* **2025**, *43*, 980–992.
27. Li, J.; Tan, J.; Zhang, B.; et al. Microwave assisted pretreatment of urban green waste with more efficiency and less energy cost. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 1107–1122.