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Research Article

Valorization of Arabica Coffee Grounds through Infrared Drying for Efficient Resource Utilization

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Keywords: Coffea arabica; Spent coffee grounds; Infrared drying; Drying kinetics; Energy efficiency

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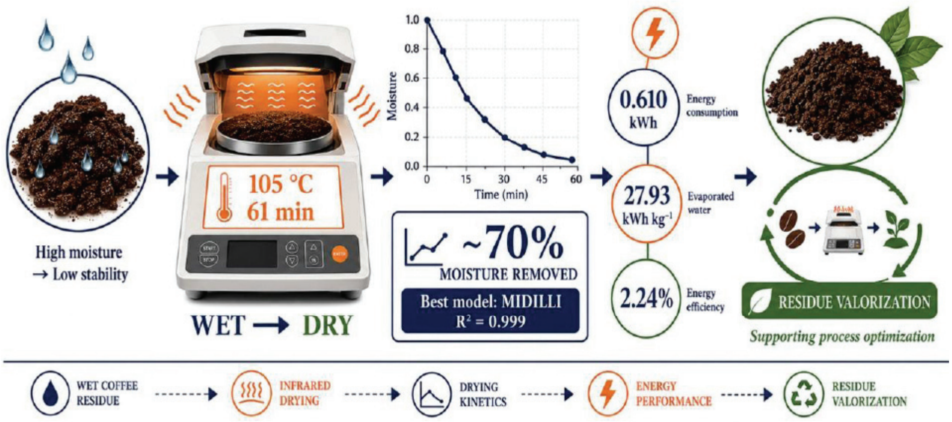
Abstract

Introduction: Spent coffee grounds are an abundant agro-industrial residue with high moisture content, which limits their storage, handling, and subsequent utilization. Infrared drying may improve residue stability while reducing the moisture load for further valorization. This study evaluated the drying kinetics and energy performance of Arabica coffee grounds subjected to infrared radiation and identified the mathematical model that best described the drying process.

Methods: Drying experiments were performed in triplicate using an infrared moisture analyzer (IV2000) at 105 °C until mass stabilization. Experimental moisture data were fitted by nonlinear regression using the Newton, Page, Henderson-Pabis, Logarithmic, Midilli, and Two-Term models. Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), chi-square (χ^2), and mean absolute error (MAE).

Result: The Midilli model provided the best fit, with $R^2 = 0.999$, RMSE = 0.0078, and $\chi^2 = 0.0001$. Drying reduced the sample mass from 31.216 to 9.377 g within 61 min, corresponding to 70% reduction in sample mass. Total energy consumption was 0.610 kWh, with a specific energy consumption of 27.93 kWh kg^{-1} of evaporated water and an energy efficiency of 2.24%.

Conclusion: Infrared drying effectively reduced the moisture content of Arabica coffee grounds and provided a suitable kinetic model for describing the process. The results provide useful information for optimizing drying conditions and supporting the stabilization and subsequent valorization of coffee-derived biomass residues.



Graphical abstract:

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Introduction

The expansion of global coffee production and consumption has been accompanied by an increase in the generation of by-products and waste throughout the production chain, highlighting the need for strategies capable of promoting their utilization and reducing the impacts associated with their improper disposal [1,2]. During processing and beverage preparation, different residual materials are generated, including coffee husk, pulp, mucilage, parchment, silver skin, and spent coffee grounds, which exhibit chemical compositions and physicochemical characteristics that enable a wide range of applications [1,3]. In this context, the valorization of these materials from a circular economy and biorefinery perspective represents an alternative for transforming residual streams into higher-value resources, promoting more efficient biomass utilization [2,4].

Among the residues generated throughout the coffee production chain, spent coffee grounds are of particular interest due to their high availability and the presence of fibers, proteins, lipids, and bioactive compounds, such as caffeine, phenolic compounds, and chlorogenic acids [2,5]. The increasing generation of this residue represents both a management challenge and an opportunity for resource recovery, as different valorization pathways have been investigated for its use in the production of biofuels, materials, food products, adsorbents, and other higher-value products [2,4,6]. When disposed of in landfills, spent coffee grounds may contribute to greenhouse gas emissions during decomposition, while improper disposal also represents the loss of a potentially valuable biomass resource [5,7].

The valorization of spent coffee grounds, however, is limited by their storage characteristics, particularly their high moisture content, which may range approximately from 55 to 80%, depending on the conditions under which the residue is obtained [8,9]. The high water content hinders storage and transportation and may favor microbiological changes, making drying an important step for stabilizing the material and enabling its use in subsequent processes [8,9]. In addition, reducing the moisture content can decrease the mass to be transported and facilitate the incorporation of spent coffee grounds into different valorization pathways [9].

Among drying technologies, the use of infrared radiation has potential for the rapid removal of moisture from agro-industrial materials due to the direct transfer of energy to the material exposed to radiation. Recent studies on spent coffee grounds have demonstrated that infrared drying parameters directly influence water removal kinetics, energy consumption, and the characteristics of the resulting product [8]. Therefore, the simultaneous evaluation of drying kinetics and energy performance is relevant for understanding the feasibility of the process as a biomass preparation step for subsequent valorization.

Mathematical modeling of drying kinetics is an important tool for describing the evolution of moisture removal and comparing experimental behavior with different mathematical models. Studies on spent coffee grounds have shown that drying is influenced by factors such as temperature, layer thickness, and internal moisture transfer, with effective diffusion being one of the mechanisms associated with the drying process [8]. The use of empirical and semi-empirical models allows the variation in moisture content over time to be mathematically represented and provides relevant information for the design and optimization of drying processes [8,11].

Thus, integrating drying kinetics characterization with the assessment of energy-related parameters represents an important approach for planning and optimizing processes aimed at the valorization of agro-industrial residues, contributing to more efficient resource use and the utilization of residual biomass streams [11,12]. In addition, different dehydration technologies, such as refractance window drying and convective drying, have been investigated as alternatives for reducing the high moisture content of spent coffee grounds and increasing their stability and utilization potential [13,14].

Within this context, the objective of this study was to evaluate the drying kinetics of Arabica spent coffee grounds under infrared radiation at 105 °C, compare mathematical models for describing water removal, and quantify the energy consumption and energy efficiency of the process. The study aims to provide information that contributes to the stabilization and valorization of this residual biomass stream, considering aspects related to resource-use efficiency and the utilization of by-products from the coffee production chain.

Materials and methods

Arabica coffee grounds (*Coffea arabica* L.) were obtained after beverage preparation and used as the raw material for the drying experiments. Approximately 10 g of SCG were collected for each experimental replicate, placed in airtight containers, and transported to the Laboratory of the Department of Agricultural Engineering at the Federal University of Viçosa (UFV), Viçosa, Minas Gerais, Brazil, where the experiments were conducted.

The drying experiments were performed at laboratory scale using an infrared moisture analyzer (IV2000) to evaluate the removal of water from the SCG under controlled conditions. Three independent drying runs were performed, using approximately 10.4 g of SCG per run, corresponding to a total initial sample mass of 31.216 g across the three replicates. In each run, the sample was evenly distributed over the analytical pan to provide uniform exposure to infrared radiation.

The IV2000 analyzer heats the sample through infrared radiation, enabling direct energy transfer to the material and subsequent evaporation of water. Infrared heating is commonly employed for rapid moisture determination in food and agro-industrial materials [15]. In the present study, the drying temperature was set at 105 °C. This temperature was selected as a fixed experimental condition to promote extensive removal of water from the SCG within a relatively short drying period, based on the temperature used as a reference for gravimetric moisture determination by oven-drying procedures. The use

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of a fixed temperature also allowed the drying behavior and energy consumption of the SCG to be characterized under a controlled and reproducible experimental condition.

Drying was continued until mass stabilization was reached. Mass stabilization was defined as a mass variation of less than 0.01% between two consecutive measurements. The initial and final sample masses were recorded for each experimental run and used to determine the moisture removal during the drying process. The data obtained during the experiments were organized and processed in a Python environment (version 3.x) using the Google Colab platform. Initially, the moisture content values were converted to a dry basis and used to determine the moisture ratio (MR), calculated from the relationship between the moisture content of the material at a given time, the initial moisture content, and the equilibrium moisture content. Subsequently, the experimental MR data as a function of drying time were used to fit the mathematical models of Newton, Page, Henderson–Pabis, Logarithmic, Midilli, and Two-Term, presented in Table 1.

The models were fitted by nonlinear regression using the Levenberg-Marquardt algorithm through the curve_fit function available in the optimize module of the SciPy library. Data processing and organization were performed with the aid of the NumPy and Pandas libraries, allowing manipulation of the experimental datasets, estimation of model parameters, and calculation of statistical goodness-of-fit indicators.

The most suitable model was selected based on a joint assessment of the coefficient of determination (R^2), root mean square error (RMSE), chi-square (χ^2), mean absolute error (MAE), and percentage error [12,16]. Model performance was evaluated according to its ability to adequately represent the experimental data, with higher R^2 values and lower RMSE, χ^2, MAE, and percentage error values indicating better fit. Based on these criteria, the model with the best overall performance was selected to describe the drying kinetics of the coffee grounds under the experimental conditions evaluated.

The rate of water removal during dehydration was quantified by the drying rate (DR), which represents the amount of water removed from the material per unit of time. Determination of the DR is an important parameter for characterizing process evolution and identifying changes in moisture removal behavior, thereby contributing to the understanding of the mass transfer mechanisms involved in drying [17,18]. The drying rate was calculated according to Equation (7):

Table 1: Mathematical models used to predict the drying kinetics.

Model	Mathematical equation	
Newton	$e^{(-kt)}$	(1)
Page	$e^{(-kt^n)}$	(2)
Henderson-Pabis	$ae^{(-kt)}$	(3)
Logarithmic	$ae^{(-kt)}+c$	(4)
Midilli	$ae^{(-kt^n)}+bt$	(5)
Two-Term	$ae^{(-k_0t)}+be^{(-k_1t)}$	(6)

$$TS=\frac{U_{ant}-U_{at}}{\Delta t} \quad (7)$$

where DR is the drying rate (g water g^{-1} dry matter min^{-1} or kg water kg^{-1} dry matter h^{-1}); M_{t-1} is the moisture content on a dry basis at the previous time interval (g water g^{-1} dry matter); M_t is the moisture content on a dry basis at the current time (g water g^{-1} dry matter); and Δt is the time interval between successive measurements (min or h). In coffee-derived residual materials, the drying rate tends to be higher during the initial stages of the process, when readily available moisture is removed more rapidly, and progressively decreases as the remaining water becomes more difficult to remove because of increasing internal resistance to mass transfer [17,18].

For process performance evaluation, the characterization of drying kinetics was complemented by an energy consumption analysis. Since the experiments were conducted using a laboratory-scale infrared moisture analyzer, the energy assessment was based on the electrical energy associated with the operation of the equipment during the drying period. Energy consumption analysis is commonly used to characterize the energy demand of drying processes and to compare the performance of different drying conditions [19,20]. The calculated energy parameters were therefore used to characterize the energy demand of the experimental system under the evaluated condition and were not intended to represent the energy performance of industrial-scale infrared drying systems. The electrical energy consumed during drying was estimated according to Equation (8):

$$E=\frac{P}{t} \quad (8)$$

where E is the electrical energy consumed by the equipment (kWh), P is the nominal power of the infrared moisture analyzer (kW), and t is the active drying time (h). The IV2000 used in the experiments had a nominal power of 0.600 kW.

Based on the electrical energy consumed and the amount of water removed from the sample, the specific energy consumption (SEC) was calculated. This parameter represents the amount of energy required to remove a unit mass of water during the drying process and allows the energy performance of different drying conditions to be assessed [19,20]. The SEC was determined according to Equation (9):

$$SEC=\frac{E}{m} \quad (9)$$

where SEC is the specific energy consumption (kWh kg^{-1} evaporated water), E is the estimated electrical energy demand of the equipment (kWh), and M_v is the mass of water removed from the sample (kg).

The evaporation energy efficiency was subsequently estimated by relating the theoretical latent energy required to evaporate the water removed from the sample to the estimated electrical energy demand of the equipment, according to Equation (10):

$$\eta evap=\frac{Mv\lambda}{E}x100 \quad (10)$$

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where ηevap is the evaporation energy efficiency (%), M_v is the mass of water removed from the sample (kg), λ is the latent heat of vaporization of water (kWh kg^{-1}), and E is the estimated electrical energy demand of the equipment (kWh). A latent heat value of 0.627 kWh kg^{-1}, equivalent to approximately 2257 kJ kg^{-1}, was adopted for the calculation. This parameter represents the ratio between the theoretical latent energy associated with water evaporation and the estimated electrical energy demand based on the nominal power of the laboratory-scale equipment. It should not be interpreted as the overall thermal efficiency of the drying system, since sensible heating of the material and water, heat losses, and other energy-transfer mechanisms were not independently quantified [19,20].

Results

The infrared radiation drying process promoted a substantial reduction in the mass of the Arabica coffee grounds, which decreased from 31.216 to 9.377 g after 61 min of operation. This variation corresponded to the removal of approximately 70% of the initial sample mass, demonstrating the capacity of infrared radiation to promote water removal from coffee grounds within a relatively short period. The drying process did not occur uniformly throughout the operation. A more pronounced mass reduction was observed during the initial stages, followed by a progressively smaller decrease as the sample approached stabilization (Figure 1).

This behavior is characteristic of the drying of materials with high initial water availability. At the beginning of the process, water present in the more accessible regions of the matrix can be removed more readily, resulting in a higher drying rate. As the process progresses, the amount of water available for removal decreases, and mass transfer tends to become more limited, resulting in a gradual reduction in the drying rate. Thus, the drying curve reflects not only the mass reduction promoted by the treatment but also the changes in the behavior of the sample throughout the drying process.

The mathematical description of this evolution was consistent among the models evaluated, although important differences were observed in the goodness of fit (Table 2). The Midilli model showed the best performance among the models tested, with an R^2 of 0.9994 and the lowest values of RMSE (0.0078), χ^2 (0.0001), MAE (0.0068), and percentage error (3.28%). These results indicate a high degree of agreement between the values estimated by the model and the experimental data, demonstrating that the equation was particularly suitable for describing the drying kinetics of coffee grounds under infrared radiation.

Table 2: Statistical indicators of the mathematical models fitted to the drying kinetics of Arabica coffee grounds under infrared radiation.

Model	R^2	RMSE	χ^2	MAE	P (%)
Newton	0.9648	0.0590	0.0035	0.0544	22.74
Page	0.9983	0.0128	0.0002	0.0116	4.47
Henderson & Pabis	0.9784	0.0462	0.0022	0.0419	17.34
Logarithmic	0.9934	0.0254	0.0007	0.0220	11.24
Midilli, et al.	0.9994	0.0078	0.0001	0.0068	3.28

The performance of the Midilli model was followed by that of the Page model, which presented an R^2 of 0.9983, RMSE of 0.0128, χ^2 of 0.0002, MAE of 0.0116, and percentage error of 4.47%. Both models met the criteria for statistical excellence, with R^2 values above 0.99. However, the lower errors associated with the Midilli model reinforce its superior performance under the experimental conditions investigated. The Logarithmic, Henderson & Pabis, Two Terms, and Newton models presented R^2 values of 0.9934, 0.9784, 0.9784, and 0.9648, respectively, accompanied by higher percentage deviations and absolute errors (Table 2). Therefore, the joint comparison of the statistical indicators reveals a clear performance hierarchy, with the Midilli and Page models standing out.

The superior fit of the Midilli model can also be observed visually by comparing the experimental and estimated values (Figure 2). The calculated curve consistently followed the trajectory of the experimental data throughout practically the entire drying period, reproducing both the more rapid reduction in the moisture ratio at the beginning of the process and the stabilization trend observed toward the end. The agreement between the two curves complements the statistical indicators presented in Table 2 and further supports the suitability of the

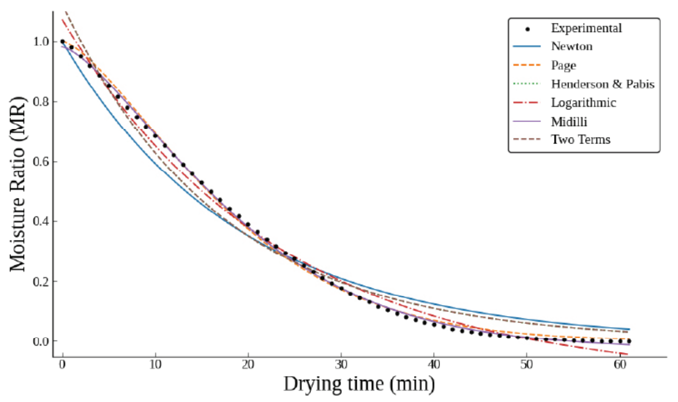

Figure 1: Experimental drying curve of Arabica coffee grounds subjected to infrared radiation and mathematical model fits. Source: Authors.

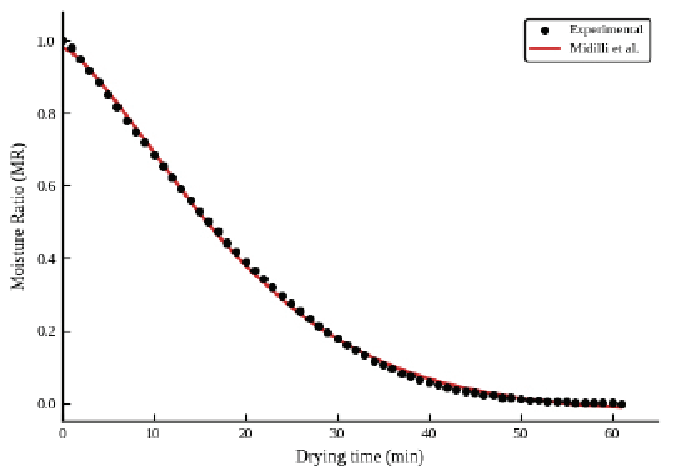

Figure 2: Moisture ratio experimentally determined and estimated by the Midilli model as a function of drying time for Arabica coffee grounds subjected to infrared radiation. Source: Authors.

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model for describing the drying kinetics under the evaluated conditions.

The parameters fitted to the Midilli et al. model were foram a = 0,980531157, k = 0,012784511, n = 1,42922286 and b = -0,000357385. Based on these values, the mathematical equation describing the drying kinetics of Arabica coffee grounds is given by:

$$MR = 0{,}980531157 \cdot \exp\left(-0{,}012784511 \cdot t^{1{,}42922286}\right) - 0{,}000357385 \cdot t$$

This result is particularly relevant because kinetic models not only describe the observed behavior but can also provide a tool for estimating the evolution of the drying process at different processing times. In this regard, the high goodness of fit obtained with the Midilli model indicates its potential as a tool to support the analysis and design of infrared radiation drying processes for coffee grounds, although its application under other operating conditions still requires experimental validation.

In addition to the drying kinetics, the energy assessment provided a quantitative characterization of the energy demand associated with the infrared drying of Arabica coffee grounds (SCG). The drying process lasted 61 min, corresponding to approximately 1.02 h of equipment operation. Over this period, the estimated electrical energy demand reached 0.610 kWh, calculated from the nominal power of the equipment and the active operating time. The corresponding mass of water removed from the sample was 0.0218 kg. Based on the relationship between these two quantities, the specific energy consumption (SEC) was 27.93 kWh kg^{-1} of evaporated water. The energy productivity, expressed as the amount of water removed per unit of estimated electrical energy demand, was 0.0358 kg H_2O kWh^{-1}. The evaporation energy efficiency calculated from the theoretical latent energy associated with water removal was 2.24%.

The temporal evolution of water removal and estimated electrical energy demand is presented in Figure 3. The cumulative amount of evaporated water increased throughout the drying period, reflecting the continuous removal of moisture from the SCG. This increase was not uniform over time. A more pronounced accumulation of evaporated water was observed during the initial portion of the drying process, whereas the increment in water removal became progressively smaller as drying approached its final stage. Thus, although water continued to be removed throughout the experiment, the amount of additional water removed over successive periods of operation decreased with drying time.

In contrast to the cumulative water removal, the estimated electrical energy demand increased continuously throughout the experiment as a function of operating time. Because the equipment operated continuously during the drying period, the energy demand accumulated with each additional unit of drying time. Consequently, the relationship between cumulative water removal and estimated energy demand was progressively altered as drying proceeded. During the initial stage, increases in energy demand were accompanied by comparatively greater increments in water removal. Toward the end of the process, however, additional energy demand was associated with comparatively smaller increments in cumulative water removal.

The temporal evolution of the moisture ratio (MR) in relation to the estimated electrical energy demand is shown in Figure 4. The MR decreased continuously throughout the 61-min drying period, indicating a progressive reduction in the moisture content of the SCG. At the beginning of the process, the MR decreased more rapidly, falling from an initial value of 1.00 to approximately 0.50 within the first 13 - 14 min. After this initial period, the rate of reduction became progressively smaller, and the MR curve exhibited a more gradual decline as drying proceeded. At approximately 30 min, the MR was close to 0.20, decreasing further to approximately 0.10 at around 43 - 44 min and reaching a final value close to 0.04 at the end of the drying period. Thus, the experimental curve presented a continuous, non-linear reduction in MR, with the magnitude of the decrease between successive time intervals becoming progressively smaller toward the end of drying.

In contrast to the behavior observed for MR, the estimated electrical energy demand increased continuously with drying time. The energy demand followed an approximately linear progression throughout the experiment, increasing from values close to zero at the beginning of drying to approximately 0.61 kWh after 61 min of operation. Therefore, the two variables exhibited distinct temporal patterns: while MR decreased progressively at a decreasing rate, the estimated electrical energy demand increased continuously as a function of operating time. The simultaneous evolution of these variables shows that the largest reductions in MR occurred during the period in which the cumulative estimated energy demand was still relatively low, whereas progressively smaller reductions in MR were observed as the energy demand accumulated toward the end of the drying process.

The trends observed in Figures 3 and 4 were consistent with the experimental drying-rate profile. The initial stage of the process presented a greater rate of moisture removal, followed by a progressive reduction in the drying rate as the process advanced. Thus, although water removal continued throughout the experiment, the quantity of water removed

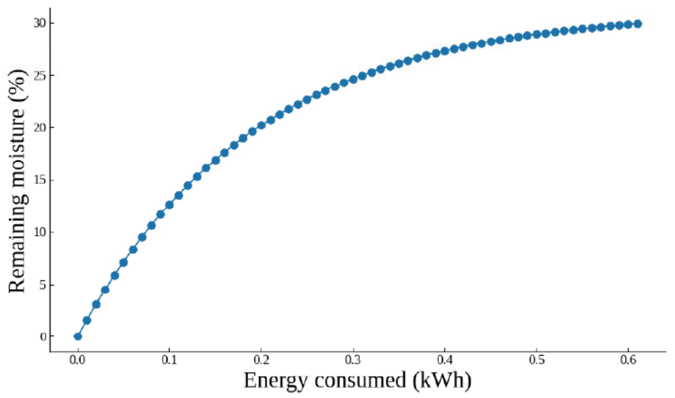

Figure 3: Evaporated water as a function of energy consumption during the drying of Arabica coffee grounds under infrared radiation. Source: Authors.

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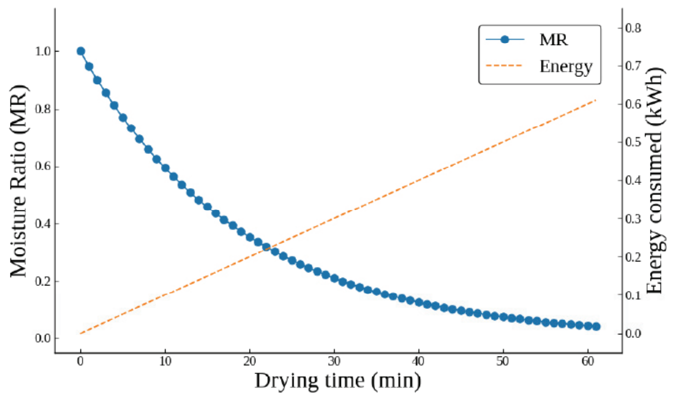

Figure 4: Moisture ratio (MR) and energy consumption as a function of time during the drying of Arabica coffee grounds under infrared radiation. Source: Authors.

over each successive unit of drying time decreased toward the end of the process. At the same time, the estimated electrical energy demand continued to accumulate as a function of the operating time.

The initial sample mass decreased substantially during the 61-min drying period. Considering the initial and final masses recorded for the experimental material, the sample mass decreased from 31.216 to 9.377 g, corresponding to a reduction of approximately 70% in the initial sample mass. The calculated water removal over the drying period was 0.0218 kg. The experimental drying curve showed a continuous reduction in moisture throughout the process, with a more pronounced change during the initial stage and a progressively smaller change as the drying endpoint was approached.

The mathematical modeling of the experimental drying data showed differences among the models evaluated. The Midilli model provided the best representation of the experimental drying behavior, presenting the highest coefficient of determination and the lowest error among the models tested. For this model, the coefficient of determination was R^2 = 0.999 and the root mean square error (RMSE) was 0.0078. For comparison, the Newton model presented R^2 = 0.965 and RMSE = 0.0590, whereas the Page model presented R^2 = 0.998 and RMSE = 0.0128. Therefore, among the models evaluated, the Midilli model showed the closest agreement with the experimental drying data according to the statistical criteria considered.

The energy indicators obtained under the experimental condition are summarized by an estimated electrical energy demand of 0.610 kWh, a water removal of 0.0218 kg, an SEC of 27.93 kWh kg^{-1} of removed water, an energy productivity of 0.0358 kg H_2O kWh^{-1}, and an evaporation energy efficiency of 2.24%. These parameters were calculated from the operating time, nominal equipment power, and amount of water removed during the drying process and represent the energy and moisture-removal behavior observed under the fixed infrared drying condition evaluated in the present study.

Discussion

The approximately 70% reduction in sample mass within 61 min demonstrates the capability of infrared radiation to promote water removal over a relatively short period. This behavior is primarily associated with the high availability of moisture in the outer and more accessible regions of the material at the early stages of drying, combined with the direct transfer of electromagnetic energy to the matrix, which favors rapid volumetric heating and subsequent water evaporation. Beyond accelerating the stabilization of the residue, this feature is particularly relevant when drying is considered as a pretreatment step for coffee grounds intended for storage or subsequent valorization, as shortening the processing time contributes to limiting the overall energy demand of the process [1,2].

The evolution of the drying rate throughout the experiment further supports this interpretation. Following the rapid initial removal of surface moisture, a progressive decrease in the drying rate was observed, reflecting a transition to a regime where internal mass transfer resistance governs the process. As the readily available water is depleted, the remaining moisture, predominantly retained within the porous structure of the matrix, exhibits higher resistance to migration, rendering subsequent removal progressively less efficient. This behavior is characteristic of the falling-rate period, which is widely reported during the drying of biomass and agro-industrial residues [2,3].

This trend is consistent with findings from different drying configurations applied to coffee grounds, although the overall process duration varies considerably depending on operating parameters. During infrared drying, the highest rate of water removal occurs during the initial stages, followed by a gradual decrease in the drying rate as the process progresses [2]. Under isothermal drying conditions, the predominance of the falling-rate period is also associated with increased internal resistance to moisture transfer [9], whereas fluidized-bed drying exhibits a similar behavior, with drying times depending on air temperature and particle movement dynamics [10]. This convergence among different technologies indicates that the decrease in drying rate observed in the present study is not a specific characteristic of the infrared system, but is related to the intrinsic characteristics of the matrix and the availability of water throughout the process.

The 61-min drying time obtained in this study should also be interpreted in light of these differences among drying systems. Convective drying of coffee grounds in a 0.7-cm-thick layer at 80 °C required approximately 150 min, whereas the use of refractance window technology reduced this period to approximately 75 min [5]. In fluidized-bed drying, approximately 60, 40, and 30 min were required at temperatures of 60, 75, and 90 °C, respectively [10]. Although these results do not allow a direct comparison of efficiency because of differences in temperature, load, layer thickness, power input, and equipment configuration, they demonstrate that drying time results from the interaction between operating conditions and heat and mass transfer mechanisms. In this context, the relatively short drying time obtained with infrared radiation represents a relevant characteristic; however, its

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contribution to process sustainability should be assessed in conjunction with the energy consumption required to reach the desired moisture level.

Mathematical modeling complements this interpretation by demonstrating that, although all evaluated models were capable of representing the general trend of the experimental data, important differences were observed in the goodness of fit. The Midilli model showed the best performance, characterized by the highest coefficient of determination (R^2) and the lowest values of RMSE, χ^2, and SSE. The ability of this model to incorporate different curve behaviors is particularly relevant to the present dataset, in which a pronounced reduction in the water removal rate occurs during the final stages of drying. Thus, the superior fit of the Midilli model not only mathematically describes the trajectory of the moisture ratio but also provides a tool for estimating material behavior and identifying operating conditions that can prevent unnecessary extension of the drying process.

The suitability of the Midilli and Page models for describing the drying kinetics of coffee grounds is also supported by studies conducted under different drying conditions. R^2 values higher than 0.99 were obtained for these models during the infrared drying of coffee grounds under different power conditions, demonstrating their ability to represent the dynamics of water removal [2]. The satisfactory performance of semi-empirical models has also been reported in fluidized-bed drying [10], whereas the modified Henderson and Pabis model provided the best fit for coffee husks [6]. These differences reinforce that model selection should not be dissociated from the physical characteristics of the material and the heat and mass transfer conditions employed. Therefore, in the present study, the performance of the Midilli model is directly related to the experimentally observed drying behavior, particularly the rapid initial reduction in moisture followed by a deceleration during the subsequent stages.

Operating at a fixed temperature limit of 105 °C was necessary to prevent thermal degradation of the material; however, it restricts the evaluation of thermal effects on drying kinetics. Consequently, declarations of an "optimal temperature" cannot be strictly established based on the present data alone, as the absence of comparative trials at alternative temperatures represents a clear operational limitation of this study. Future investigations exploring a broader temperature range are required to fully elucidate thermal optimization pathways.

This change in drying dynamics has direct consequences for energy consumption. The estimated electrical energy demand of 0.610 kWh and the specific energy consumption (SEC) of 27.93 kWh kg^{-1} of evaporated water should be analyzed considering the laboratory scale and the configuration employed. Furthermore, the evaporation energy efficiency of 2.24%, representing the fraction of energy effectively converted into latent heat of vaporization relative to the total energy supplied, highlights that a significant portion of the input energy is dissipated. The application of a relatively small sample mass in equipment with high power tends to increase the calculated energy consumption per unit mass of water removed, since a significant portion of the supplied energy may not be directly converted into evaporation. In addition, heat losses to the surroundings and limitations related to radiation distribution may become more significant in small-scale systems [7].

The influence of scale becomes evident when the SEC obtained in this study is compared with higher-capacity systems. During the infrared drying of 500 g of coffee grounds, values ranging from approximately 5.68 to 5.80 kWh kg^{-1} of evaporated water were reported [8]. This difference compared with the 27.93 kWh kg^{-1} obtained in the present study should not be interpreted in isolation as evidence of lower intrinsic efficiency of infrared radiation, but rather as a result of the different processing conditions. In systems with a greater loading capacity, the relationship between the energy supplied and the amount of material processed may be more favorable, while equipment design and control of thermal losses may increase the fraction of energy effectively used for water removal [7,8].

Comparison with other technologies further reinforces the importance of system configuration. Fluidized-bed drying presented SEC values ranging from 1.63 to 4.28 kWh kg^{-1} of evaporated water, whereas the use of auxiliary materials with high thermal conductivity in an intensified system reduced the specific active energy consumption from 3.13 to 2.64 kWh per 1% of moisture removed, representing an energy saving of approximately 15.6% [10,20]. These results demonstrate that energy efficiency depends not only on the energy source employed but also on the system's ability to direct this energy toward effective water removal. From this perspective, the high SEC observed in the present study identifies an opportunity for optimization of the experimental system, particularly through increasing the processed mass, improving thermal insulation, adjusting the power input, and optimizing the distance and distribution of infrared radiation.

The relationship between water removal and cumulative energy consumption makes this issue even more evident. During the first few minutes, the rapid decrease in the moisture ratio indicates that a substantial fraction of the available water is removed while energy consumption is still relatively low. As drying progresses, however, energy consumption continues to increase, whereas the reduction in moisture becomes progressively smaller. This mismatch demonstrates that the energy efficiency of the process does not remain constant over time: the energy supplied during the initial stages provides a greater return in terms of water removal, whereas the energy supplied during the final period produces progressively smaller gains [3,4].

The origin of this behavior is related to the structure of the coffee grounds itself. The matrix contains lignocellulosic components, such as cellulose, hemicellulose, and lignin, as well as proteins, lipids, and other organic compounds, forming a heterogeneous and porous structure capable of retaining water with different levels of interaction with the solid matrix [5,6]. At the beginning of drying, the greater availability of free and weakly bound water favors mass transfer and results in a greater amount of water removed per unit of energy supplied. Subsequently, as this more readily removable fraction

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decreases, the remaining water encounters greater resistance to migrating from the interior of the particles to the surface, making internal diffusion an increasingly relevant mechanism [4]. Thus, the structural and hygroscopic evolution of the material itself explains the simultaneous reduction in drying rate and energy efficiency observed during the final stages.

The findings of this work must be interpreted within the inherent limitations of bench-scale equipment. Operating with small sample batches restricts direct extrapolation to industrial scales, where heat and mass transfer dynamics, radiation penetration, and thermal inertia differ significantly. Although comparisons with 500-g systems provide useful benchmarks, scale-up studies addressing continuous operation, spatial uniformity of the infrared source, and comprehensive heat recovery mechanisms are essential before industrial adoption.

This relationship between drying kinetics and energy is particularly important for defining processing conditions. Although the approximately 70% reduction in sample mass within 61 min demonstrates the effectiveness of infrared radiation in the initial stabilization of the coffee grounds, continued energy input after the stage of greatest water removal results in diminishing returns. In practical terms, this means that a longer processing time does not necessarily correspond to greater system efficiency. On the contrary, when the moisture content has already reached levels suitable for the intended application, extending the drying process may simply increase energy consumption, with only a minor additional contribution to moisture reduction.

This interpretation is particularly relevant from a sustainability perspective. The efficiency of a drying technology should be evaluated not only based on its ability to achieve low moisture contents but also on the balance among energy consumption, amount of water removed, processing time, and the stability required for subsequent utilization of the material [7]. For coffee grounds, this assessment is especially important because drying is not the final product-generating step but rather an intermediate stabilization stage required to enable storage, transportation, or conversion into higher-value products [6]. Therefore, the energy used in this stage should be commensurate with the technological benefit effectively achieved.

In this context, defining a drying endpoint constitutes an important strategy for avoiding the energy consumption associated with removing moisture beyond the required level. Reducing water activity to values close to or below 0.60, together with moisture contents below 10%, may provide more favorable conditions for storage stability and reduce the risk of microbiological and fungal deterioration [2,8]. Thus, the endpoint should not be established simply by achieving the lowest possible moisture content but by identifying a level at which material stability is ensured without unnecessarily extending the operation.

The results obtained in this study therefore indicate that the optimization of infrared drying should simultaneously consider the kinetics of water removal and the evolution of energy consumption. The rapid initial reduction in the moisture ratio, followed by the characteristic deceleration of the falling-rate period, indicates the existence of an operating window in which water removal occurs more efficiently. Beyond this point, continued heating increases cumulative energy consumption without producing a proportional reduction in moisture content. Identifying this transition, together with monitoring moisture content or water activity, may contribute to establishing a technically appropriate and more energy-efficient drying endpoint.

From the perspective of waste valorization, this approach makes it possible to integrate energy efficiency into the other stages of the coffee grounds utilization chain. Drying is necessary to reduce the instability associated with the high moisture content and to enable subsequent processing; however, it must be noted that a chemical and structural quality assessment of the dried spent coffee grounds (e.g., preservation of bioactive compounds, lipids, or functional properties) was beyond the scope of this work. Therefore, potential degradation risks or benefits to subsequent valorization routes remain to be systematically evaluated. Combining kinetic modeling, determination of the drying endpoint, thermal efficiency improvements, and downstream quality tracking constitutes a consistent strategy for making drying fully compatible with circular economy principles.

From a circular economy and biorefinery perspective, spent coffee grounds (SCG) represent an abundant lignocellulosic residue (≈60 million tons annually) rich in cellulose, hemicellulose, and lignin, qualifying them as a strategic raw material for value-added valorization [17]. Diverting SCG from landfills prevents severe environmental impacts and supports global waste-reduction targets under the 2030 Agenda by enabling the recovery of antioxidants, dietary fibers, and prebiotic oligosaccharides [18]. Incorporating SCG into food matrices enriches their nutritional profile [19], while advanced extraction and microencapsulation techniques further protect their sensitive bioactives [20]. However, because fresh SCG exhibits high initial moisture and biological instability, efficient primary dehydration is an essential preliminary step. Industrial processing strategies, such as rotary drum drying, have been explored to stabilize moisture below 5% while preserving thermosensitive compounds [21,22].

Beyond the food sector, SCG valorization encompasses innovative energy and material engineering routes. Integrated thermochemical and biochemical strategies enable the conversion of this residual biomass into biofuels, such as biodiesel, bioethanol, and bio-oil, effectively reducing carbon footprints [23]. Sequential cascade biorefineries integrate oil extraction, hemicellulose recovery, and solid-residue pyrolysis, yielding biochar with promising higher heating values around 22.7 MJ/kg [24,25]. Life cycle assessments (LCAs) corroborate the environmental and economic sustainability of these energy pathways by preventing uncontrolled greenhouse gas emissions [26]. Furthermore, modified SCG-derived biochar serves as an efficient adsorbent for phosphate recovery in environmental remediation [27], while upcycled SCG has been successfully utilized to manufacture energy-saving green geopolymeric materials and structural bio-composites [28, 29]. Nevertheless, industrial processing requires strict safety protocols due to the dust-explosion and flammability risks associated with dry SCG powders [30].

Within this technological framework, the findings of the present study demonstrate that infrared radiation acts as an efficient preparatory pretreatment for stabilizing Arabica spent coffee grounds. Achieving a 70% mass reduction within 61 min at 105 °C, supported by the reliable predictive performance of the Midilli kinetic model and quantified energy metrics (27.93 kWh kg^{-1}), establishes a solid baseline for moisture removal. By integrating precise kinetic modeling with practical energy performance data, this work provides foundational parameters to support the safe storage and subsequent transition of SCG into sustainable biorefinery chains..

Conclusion

Infrared radiation drying proved to be an efficient technology for the rapid stabilization of Arabica coffee grounds, promoting an approximately 70% reduction in the initial sample mass within 61 min and potentially favoring residue stabilization and storage. The high goodness of fit of the Midilli model in describing the drying kinetics, together with the behavior associated with the falling-rate period, enables rigorous process control.

By jointly considering the need for material stabilization and energy demand, the results provide relevant support for the sustainable management of by-products. Thus, this study strengthens the coffee grounds valorization chain by transforming an environmental liability into a potentially useful resource within strategies for the valorization of agro-industrial residues.

Conflict of interest

The authors declare that there is no conflict of interest of any kind associated with the conduct or publication of this study.

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References

1. Andrade C, Perestrelo R, Câmara JS. Bioactive compounds and antioxidant activity from spent coffee grounds as a powerful approach for its valorization. Molecules. 2022;27(21):7504. Available from: https://dx.doi.org/10.3390/molecules27217504.
2. Mussatto SI, Machado EMS, Martins S, Teixeira JA. Production, composition, and application of coffee and its industrial residues. Food Bioprocess Technol. 2011;4(5):661–672. Available from: https://dx.doi.org/10.1007/s11947-011-0565-z.
3. Pérez-MerchánAM,Moreno-TostR,Malpartida-GarcíaI,García-SanchoC,Mérida-Robles JM, et al. An integrated biorefinery approach based on spent coffee grounds valorization. J Clean Prod. 2025;528:146716. Available from: https://dx.doi.org/10.1016/j.jclepro.2025.146716.
4. Al Balushi J, Al Saadi S, Ahanchi M, Al Attar M, Jafary T, et al. A comprehensive review on sustainable conversion of spent coffee grounds into energy resources and environmental applications. Biomass. 2025;5(3):55–85. Available from: https://dx.doi.org/10.3390/biomass5030055.
5. Sermyagina E, Mendoza Martinez CL, Nikku M, Vakkilainen E. Spent coffee grounds and tea leaf residues: Characterization, evaluation of thermal reactivity and recovery of high-value compounds. Biomass Bioenergy. 2021;150:106141. Available from: https://dx.doi.org/10.1016/j.biombioe.2021.106141.
6. Loaiza JM, Palma A, Garcia JC, Diaz MJ, Alfaro A. Sequential cascade biorefinery for the valorization of spent coffee grounds: Energy, biodiesel, furfural, and biochar production. Bioresour Technol Rep. 2026;34:102754. Available from: https://dx.doi.org/10.1016/j.biteb.2026.102754.
7. Bejenari V, Marcu A, Ipate AM, Rusu D, Tudorachi N, et al. Physicochemical characterization and energy recovery of spent coffee grounds. J Mater Res Technol. 2021;15:4437–4451. Available from: https://dx.doi.org/10.1016/j.jmrt.2021.10.064.
8. Wang SC, Tsai MJ, Tung CH, Wu PH. Evaluation of infrared drying parameters for spent coffee grounds: Effects on drying kinetics, quality, and energy consumption. Beverages. 2026;12(5):53. Available from: https://dx.doi.org/10.3390/beverages12050053.
9. Bejenari V, Lisa C, Cernătescu C, Mămăligă I, Lisa G. Isothermal drying kinetic study of spent coffee grounds using thermogravimetric analysis. Int J Chem Eng. 2022;2022:2312147. Available from: https://dx.doi.org/10.1155/2022/2312147.
10. Sa-adchom P. Drying kinetics and mathematical modeling of spent coffee grounds drying using the spouted bed technique. Eng Appl Sci Res. 2023;50(4):324–334. Available from: https://dx.doi.org/10.14456/easr.2023.35.
11. Silva WOA, Novaes FJM, Felix PHC, Martins E, Melo EC, et al. Drying kinetics, thermodynamic properties and volatile preservation of coffee husks from organic and conventional production systems. Processes. 2026;14(8):2582. Available from: https://dx.doi.org/10.3390/pr14082582.
12. Miano AC, Rojas ML. Drying strategies of spent coffee grounds using refractance window method. Food Res Int. 2024;178:114007. Available from: https://dx.doi.org/10.1016/j.foodres.2024.114007.
13. Sakare P, Prasad N, Thombare N, Singh R, Sharma SC. Infrared drying of food materials: Recent advances. Food Eng Rev. 2020;12(3):381–398. Available from: https://dx.doi.org/10.1007/s12393-020-09222-y.
14. Onwude DI, Hashim N, Abdan K, Janius R, Chen G. Modelling the mid-infrared drying of sweet potato: Kinetics, mass and heat transfer parameters, and energy consumption. Heat Mass Transf. 2018;54(10):2917–2933. Available from: https://dx.doi.org/10.1007/s00231-018-2379-3.
15. Martynenko A, Vieira GNAV. Sustainability of drying technologies: system analysis. Sustainable Food Technol. 2023;1(5):629–682. Available from: https://dx.doi.org/10.1039/d3fb00080j.
16. Lee K-T, Lu C-A, Chen W-H. Activated carbon filter offcuts as energy-saving drying enhancers to improve storability of spent coffee grounds and enable microwave torrefaction into solid biofuel. Energies. 2026;19(11):2606. Available from: https://dx.doi.org/10.3390/en19112606.
17. Sa-adchom P. Drying kinetics and mathematical modeling of spent coffee grounds drying using the spouted bed technique. Eng Appl Sci Res 2023; 50(4): 324–334. Available from: https://doi.org/10.14456/easr.2023.35
18. Silva WOA, Novaes FJM, Felix PHC, Martins E, Melo EC, Campos RC. Drying Kinetics, Thermodynamic Properties and Volatile Preservation of Coffee Husks from Organic and Conventional Production Systems. Processes 2026;14(8):2582. Available from: https://doi.org/10.3390/pr14082582
19. Miano AC, Rojas ML. Drying strategies of spent coffee grounds using refractance window method. Food Res Int 2024; 178: 114007. Available from: https://doi.org/10.1016/j.foodres.2024.114007

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20. Sakare P, Prasad N, Thombare N, Singh R, Sharma SC. Infrared drying of food materials: Recent advances. Food Eng Rev 2020; 12(3): 381–398. Available from: https://doi.org/10.1007/s12393-020-09222-y

21. Onwude DI, Hashim N, Abdan K, Janius R, Chen G. Modelling the mid-infrared drying of sweet potato: Kinetics, mass and heat transfer parameters, and energy consumption. Heat Mass Transf 2018; 54(10): 2917–2933. Available from: https://doi.org/10.1007/s00231-018-2379-3

22. Martynenko A, Vieira GNAV. Sustainability of drying technologies: system analysis. Sustainable Food Technol 2023; 1(5): 629–682. Available from: https://doi.org/10.1039/d3fb00080j

23. Lee K-T, Lu C-A, Chen W-H. Activated carbon filter offcuts as energy-saving drying enhancers to improve storability of spent coffee grounds and enable microwave torrefaction into solid biofuel. Energies 2026; 19(11): 2606. Available from: https://doi.org/10.3390/en19112606

24. Chavhan MP, Slovák V, Siddiqi H, Mucha M. Pyrolysis of household coffee vis-à-vis tea waste: a detailed insight into physicochemical properties, kinetics, and thermodynamics study. Chem Eng J Adv 2024; 17: 100587. Available from: https://doi.org/10.1016/j.ceja.2024.100587

25. Bhushan D, Hooda S, Chitransh S, Mondal P. Insights into catalytic co-pyrolysis of spent coffee grounds and high density polyethylene (HDPE) using acid mine drainage (AMD) treated sludge based catalyst: Analysis of kinetics, mechanism and thermodynamic properties. Sustain Chem Clim Action 2024; 5: 100051. Available from: https://doi.org/10.1016/j.scca.2024.100051

26. Solberg SB, Solberg SØ. Spent coffee grounds as a sustainable coffee flavouring ingredient in muffins. Explor Foods Foodomics 2025; 3: 101066. Available from: https://doi.org/10.37349/eff.2025.101066

27. Pinto GHA, Gil GA, Kakuda L, Campanharo SC, Chagas PAM, et al. Integrated Processing of Agro-Industrial By-Products into Functional Bioactive Ingredients for Sustainable Food and Health Applications. Discov Food 2026; 6: 175. Available from: https://doi.org/10.1007/s44187-026-01175-6

28. Pradhan S, Al-Awadhi YM, Alherbawi M, Mackey HR, Al-Ansari TA, McKay G. Economic and environmental life cycle assessment of spent coffee grounds valorization for bioenergy production. Discov Energy 2026; 6: 13. Available from: https://doi.org/10.1007/s43937-025-00118-z

29. Eraliev J, Ghosh A, Paul T, Yee JJ, Park SH. Valorization of waste mussel shells and spent coffee grounds into calcium-rich biochar for sustainable phosphate recovery for soil amendment. Environ Technol Innov 2025; 40: 104634. Available from: https://doi.org/10.1016/j.eti.2025.104634

30. Mansour Khodja A, Pliya P, Rehab Bekkouche S, Eslami J. Valorization of spent coffee grounds and casein for a new bio-composite material. Dev Built Environ 2026; 25: 100872. Available from: https://doi.org/10.1016/j.dibe.2026.100872

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