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ORIGINAL PAPER

# Drying behavior, powder morphology, and technofunctional properties of edible flower flours of *Clitoria ternatea* and *Malvaviscus arboreus*: a comparative study

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## Abstract

The edible flowers of *Clitoria ternatea* and *Malvaviscus arboreus*, cultivated under agroecological principles, represent promising sources of functional ingredients. This study evaluated their convective drying behavior (50–80 °C), powder morphology, and technofunctional properties. The experiments involved convective drying under controlled airflow, with moisture ratio data fitted to mathematical models. The Page model provided the best fit ($R^2$ >0.99). Thermodynamic parameters were determined to assess the energy nature of moisture diffusion, while scanning electron microscopy (SEM) characterized powder microstructure. Multivariate analysis (PCA) was applied to differentiate samples based on their physical and functional traits. *M. arboreus* required longer drying times (150–840 min) and exhibited higher activation energy (57,753 J $mol^{-1}$) than *C. ternatea* (44,806 J $mol^{-1}$), indicating greater resistance to moisture transfer. Both processes were endothermic ($\Delta H > 0$) and non-spontaneous ($\Delta G > 0$). Microstructural analysis by scanning electron microscopy showed clear differences between the species. *C. ternatea* powders exhibited higher solubility (12.8%) and better flowability, making them suitable for instant food applications, while *M. arboreus* powders showed greater cohesiveness, suggesting use in structured formulations. Multivariate analysis (PCA) effectively distinguished the two species based on their physical and thermodynamic profiles. These findings demonstrate that *C. ternatea* holds stronger potential for functional powder production, whereas *M. arboreus* requires further process optimization. This work highlights the value of agroecological edible flowers as sustainable ingredients with distinct technological functionalities.

**Keywords** Edible flowers · Drying · Technofunctional properties · Agroecology

## Introdução

The growing demand for sustainable food ingredients, with functional properties and added nutritional value, has driven the exploration of unconventional plant sources as strategic alternatives for food diversification and technological innovation [1]. Among these sources, unconventional edible plants stand out, often neglected by traditional food systems, but which bring together relevant characteristics such as high phytochemical diversity, agroecological adaptability, and productive viability in local contexts [2]. Its use represents an opportunity to strengthen agricultural biodiversity, develop sustainable production chains, and promote more resilient food systems [3].

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In this context, edible flowers have been attracting increasing interest due to their sensory characteristics, nutritional value, and functional composition. Species such as *Clitoria ternatea* (butterfly pea) and *Malvaviscus arboreus* (Turkish hat) are particularly promising, as in addition to presenting profiles rich in bioactive compounds, they also have vibrant colors and potential for technological use in food. *C. ternatea*, belonging to the Fabaceae family, is a perennial plant widely known for its traditional use in Ayurvedic medicine [4]. Its extracts present antioxidant, anti-inflammatory, hepatoprotective, analgesic, and antipyretic activity, attributed to the presence of flavonoids, anthocyanins, and other secondary metabolites [5]. Its intense blue flowers are particularly rich in polyacylated anthocyanins, which makes them attractive for applications as a natural colorant and pH indicator in food systems, including the development of smart sensors for monitoring food quality [6].

Similarly, *Malvaviscus arboreus*, a perennial shrub of the Malvaceae family, also has both nutritional and pharmacological relevance [7]. Traditionally used in folk medicine for the treatment of conditions such as bronchitis, cough, gastrointestinal and renal disorders, this species has been the subject of studies that confirm antioxidant, antibacterial, antifungal, hepatoprotective, and antitussive activities associated with its extracts [8, 9]. The presence of phenolic compounds and flavonoids contributes to its functional potential and justifies its use in food and nutraceutical formulations.

These species, cultivated under agroecological principles, align with the growing emphasis on environmentally sustainable and socially equitable food production [10]. Agroecological agriculture, characterized by low-input, biodiversity-driven practices, not only supports ecological resilience but also strengthens family farming systems, fostering local economies and food sovereignty [11]. The valorization of edible flowers through innovative processing technologies, such as drying and powder production, represents a strategic way to increase their market potential, thus contributing to the economic viability of family farming.

The drying process is a critical step in transforming perishable floral materials into stable, value-added products, such as powders, which can be incorporated into functional foods, nutraceuticals, or natural colors. However, drying efficiency and the quality of the resulting powders depend on factors such as drying kinetics, plant morphology, and technofunctional properties, which vary between plant species and processing conditions [12]. The optimization of the drying process of these products, when used with mathematical simulations, allows us to understand the behavior during the thermodynamic processes and unit operations that occur until the final product, which is essential for industrial applications and to guarantee product quality [13].

Despite the growing interest in edible flowers and the vast literature on drying processes, comparative studies that systematically evaluate the drying behavior, powder morphology, and technofunctional properties of *C. ternatea* and *M. arboreus* produced under agroecological conditions are scarce, representing a significant knowledge gap. This study is pioneering in performing an integrated analysis of the drying kinetics, thermodynamic properties, and morphological characterization of these species, using mathematical modeling and multivariate analysis (PCA) to differentiate their functional profiles and highlight their potential in sustainable food systems. These species offer unique biochemical compositions that warrant detailed investigation to unlock their potential in food systems.

This study addresses this knowledge gap by systematically evaluating the drying kinetics, powder morphology, and technofunctional properties of *C. ternatea* and *M. arboureus* powders produced under controlled drying conditions. Using mathematical modelling, thermodynamic analysis, and morphological characterization of the powders, we provide a comprehensive assessment of how drying temperatures influence the quality and functionality of these powders. The research highlights the originality of combining thermodynamic and multivariate statistical approaches to optimize the processing of agroecological edible flowers, offering insights for industrial applications and strengthening technological innovation in supporting family farming communities.

## Materials and methods

### Materials

The flowers of *C. ternatea* L. were collected in the municipality of Areia, Paraíba state, Brazil (6°57 × 46 ′′ S and 35°41 × 31′′W). The flowers of *M. arboreus* Cav. were collected in the municipalities of Borborema (6°47 × 57 ′′ S and 35°37 × 15′′W) and Bananeiras (6°45 × 00 ′′ S and 35°38 × 00′′W), also located in Paraíba. The collections were carried out in February 2023, a period in which the average rainfall recorded was 25 mm in Areia, 65 mm in Borborema, and 45.5 mm in Bananeiras. For each species, a sample composed of approximately 250 flowers was collected.

### Drying kinetics of *C. ternatea* and *M. arboreus* flowers

For the drying experiments, the flower petals of both species were manually separated and subjected to dehydration in an oven with forced air circulation and controlled temperature.

The efficiency of the drying process was evaluated according to the plant species, under different operating temperatures (50, 60, 70, and 80 °C) and with a fixed air speed of 1.0 m/s. The drying kinetics were monitored by periodically weighing the samples, starting at 5-minute intervals; subsequently, these intervals were gradually increased to 60 min, as the mass loss rate reduced. The process continued until the samples reached constant mass, indicating the end of drying. Based on the data obtained, the moisture content (dimensionless) was calculated over time, allowing the construction of drying kinetic curves for each experimental condition evaluated.

## Mathematical modelling of drying kinetics

Drying curves were constructed based on the relationship between moisture content and drying time. To fit the mathematical models to the experimental drying data, nonlinear regression analysis was performed using the Quasi-Newton method, using Statistica 7.0 software [14]. The following models were evaluated: Henderson and Pabis (Eq. 1 [15], Lewis (Eq. 2 [16], Page (Eq. 3 [15], and Logarithmic (Eq. 4 [17]),.

$$X^* = a \cdot \exp\left(-k \cdot t\right) \tag{1}$$

$$X^* = \exp\left(-k \cdot t\right) \tag{2}$$

$$X^* = \exp\left(-k \cdot t^n\right) \tag{3}$$

$$X^* = a \cdot \exp\left(-k \cdot t\right) + c \tag{4}$$

Where $a$, $k$, $n$, and $c$ are model parameters, $X^*$ is the ratio between the moisture content (dimensionless) and $t$ is the time (min).

The adjustment of the empirical models to the experimental data on the drying kinetics of the flowers of the two species was evaluated using widely used statistical criteria: the coefficient of determination ($R^2$), chi-square ($\chi^2$), and the root mean square deviation (MSD). These parameters provide a quantitative analysis of the goodness of fit, allowing a comprehensive assessment of the adequacy of the proposed models to the experimental data.

## Diffusion model

Assuming that flower petals behave similarly to a homogeneous and isotropic solid, with a uniform initial moisture distribution, and that water transport within them occurs exclusively by liquid diffusion, an idealized theoretical model was adopted to describe moisture diffusion in flower petals. It was also assumed that the convective mass transfer coefficient remained constant throughout the drying process [18].

Since the thickness of the petals was significantly smaller than the other characteristic dimensions of the system, the geometry of the body was approximated to a plane wall of finite thickness, assuming conditions of an infinite wall. Based on this simplification, the diffusion equation was solved analytically using a first-kind (prescribed) boundary condition, Eq. 5:

$$X\left(t\right) = X_e - \left(X_e - X_0\right) \sum_{n=0}^{200} \frac{8}{(2n+1)^2\pi^2} \exp\left[-\left(2n+1\right)^2 \pi^2 \frac{Def}{L^2}\right] \tag{5}$$

Where X is the water content at time t; Xe is the water content for $t \to \infty$; $X_0$ is the water content for $t = 0$. $L$ is half the thickness of the sample; $D_{ef}$ corresponds to the diffusivity, $t$ is the time.

The determination of the prescribed boundary condition was performed through a numerical optimization procedure, implemented in the "Prescribed" software [19].

## Activation energy and thermodynamic properties

The Arrhenius equation can be defined to associate diffusivity with drying temperature (Eq. 6).

$$Def = D_0 \cdot \exp\left(-\frac{E_a}{R\left(T + 273.15\right)}\right) \tag{6}$$

Where $D_0$ is the pre-exponential factor, $R$ is the universal ideal gas constant (8.314 J mol/K), $T$ is the temperature (°C), and $E_a$ is the activation energy (J/mol). $E_a$ and $D_0$ can be determined by adjusting $D_{ef}$ after linearization (Eq. 7).

$$\ln Def = \ln D_0 - \frac{E_a}{R} \cdot \left(\frac{1}{\left(T + 273.15\right)}\right) \tag{7}$$

The thermodynamic properties involved in the drying process, including specific enthalpy (ΔH, kJ/mol) (Eq. 8), specific entropy (ΔS, Jmol) (Eq. 9) and Gibbs free energy (ΔG, kJ/mol) (Eq. 10), were determined based on classical thermodynamic equations, using the method based on the universal gas constant, as described by [20].

$$\Delta H = E_a - R\left(T + 273.15\right) \tag{8}$$

$$\Delta S = R\left[\ln D_0 - \ln\left(\frac{k_b}{h_p}\right) - \ln\left(T - 273.15\right)\right] \tag{9}$$

$$\Delta G = \Delta H - \left(T + 273.15\right)\Delta S \tag{10}$$

Where $k_b$ is Boltzmann's constant ($1.38 \times 10^{-23}$ J/K), $h_p$ is Planck's constant ($6.626 \times 10^{-34}$ J/s), and $T$ is temperature (°C).

### Water content and physical properties of *C. ternatea* and *M. arboreus* flower powders

The water content of the flower powders after drying was determined following method 934.06 [21]. Flowability and cohesion were evaluated using the Carr Index (CI) [21] and the Hausner coefficient (HR) [22]. Solubility determination was performed based on the method described by Cano-Chauca et al. [23]. To prepare the mixture, 1 g of the dried flower sample was added to a flask containing 100 mL of distilled water. The mixture was stirred for 5 min, ensuring complete dispersion. After this process, the suspension was transferred to appropriate tubes and centrifuged at 3000×g for 5 min. Then, a 25 mL aliquot of the supernatant was carefully transferred to previously weighed Petri dishes and placed in an oven at 105 °C for 5 h, until the water had completely evaporated. Solubility was then calculated based on the residual mass obtained after drying, expressed as a percentage of the initial mass of the sample.

### Scanning electron microscopy (SEM)

The particle morphology of the flower powders was evaluated by scanning electron microscopy (SEM). The samples were fixed on aluminum supports (stubs) covered with conductive double-sided carbon tape and subsequently subjected to gold metallization for 200 s using a sputter metallizer (Ion Sputter Coater G20, Italy). Micrographs were obtained with a scanning electron microscope (VEGA4, TESCAN, Portugal) operating under the following conditions: accelerating voltage of 3 keV, chamber pressure of 0.07 Pa, exposure time of 10 s, and working distance of 50 mm. Images were recorded at magnifications of 500× and 1000× to characterize the surface morphology and particle structure.

### Principal component analysis (PCA)

A principal component analysis (PCA) was performed to explore the multivariate relationships between the physical, functional, and thermodynamic properties of powder samples derived from *C. ternatea* and *M. arboreus* flowers subjected to convective drying at four temperatures (50, 60, 70, and 80 °C). The variables considered included water content, Carr index, Hausner factor, solubility, drying time, activation energy ($E_a$), enthalpy change (ΔH), entropy change (ΔS), Gibbs free energy change (ΔG), and effective diffusivity ($D_{ef}$). Each combination of species and drying temperature was treated as a single sample, totalling eight observations.

Before analysis, all variables were standardized (z-scores) to ensure comparability and minimize the influence of scale differences. PCA was conducted using the prcomp() function in R (v4.x), with centering and scaling enabled (center = TRUE, scale = TRUE). The factoextra and ggplot2 packages were used for data visualization.

A biplot of the first two principal components (PC1 and PC2) was generated to visualize the sample projection and the loadings of each variable. Ellipses representing 95% confidence intervals were added around the groups corresponding to each floral species to assess clustering potential. Clustering and color-coding were based on species identity for ease of interpretation. PCA allowed dimensionality reduction while maintaining maximum variance and provided insights into the key variables driving differentiation between samples.

### Statistical analysis

Experimental data were expressed as mean ± standard deviation of at least three independent replicates. To compare the effects of drying temperatures within each floral species, analysis of variance (ANOVA) followed by Tukey's multiple comparison test was applied, considering a significance level of $p < 0.05$. To compare between floral species under the same drying condition, the Sidák test was used, also with a significance level set at $p < 0.05$. Statistical analyses and post hoc tests were performed using GraphPad Prism software (version 10.4.2, GraphPad Software, San Diego, CA, USA), which was also used to prepare graphs and visual representations of the results.

## Results and discussion

### Mathematical modelling of drying

In this study, experimental moisture content values were transformed into moisture ratios and analyzed using four empirical mathematical models. The adequacy of the models to the experimental data, obtained for all drying temperatures and for both floral species, was assessed using the coefficient of determination ($R^2$), root mean square deviation (MSD), and chi-square ($\chi^2$) as statistical criteria. Detailed results are presented in Table S1 of the supplementary material. Mathematical models considered adequate to describe the drying characteristics of a plant product should present $R^2$ close to 1.0 and low values for DQM and $\chi^2$ [24]. Figure 1 presents a heat map with the $R^2$ values for the evaluated

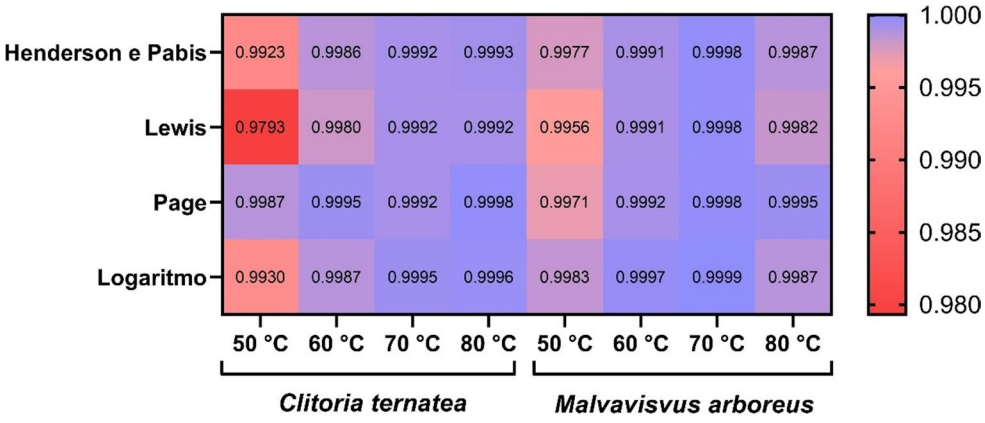



**Fig. 1** Heat map of the coefficients of determination ($R^2$) obtained for different mathematical models applied to the drying kinetics of *C. ternatea* and *M. arboreus* flours, subjected to convective drying at temperatures of 50, 60, 70, and 80 °C. The colors indicate the adjustment performance of each model, with blue tones associated with higher $R^2$ values

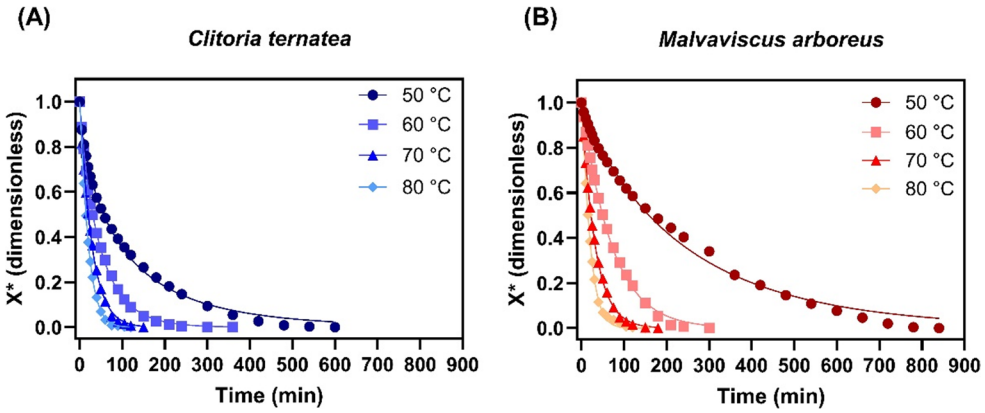



**Fig. 2** Drying curves of *C. ternatea* (**A**) and *M. arboreus* (**B**) flowers fitted using the page model. Symbols represent experimental data at different temperatures, while solid lines indicate model predictions

models, at different drying temperatures of *C. ternatea* and *M. arboreus* flowers.

Among the models tested, the Page model stood out for presenting, in all drying conditions, for both flower species, high values of $R^2$ >0.99 (0.9971–0.9998) and low values of DQM (0.0054–0.0249) and $\chi^2$ (0.00003–0.0007) (Table S1). These results indicate that Page's two-parameter model was highly satisfactory in describing the drying behavior of flowers at different temperatures compared to other models with more tuning parameters. Page's model assumes that the drying rate decreases exponentially over time, which is consistent with the observed behavior for both flower species [25]. The good performance of Page's model on experimental data on flower drying kinetics is in line with previous studies that demonstrated its effectiveness under different drying conditions, such as the study by Alcântara et al. [12], which showed the best fit of Page's model to experimental data on the drying of *Pereskia* sp. Lima et al. [25] also observed a good estimate of the model when describing the drying of papaya in a forced air oven at a temperature of 60 °C.

For the Page model, it is observed that there is a progressive increase in the drying constant $k$ with increasing drying temperature for both flower species, except for *C. ternatea* at 50 °C, which presented a higher $k$ value than at the other temperatures. The increase in the constant $k$ with increasing temperature is proportional to the reduction in drying time. Regarding the parameter $n$, Albuquerque et al. [26] indicated that, for the Page model, the parameter n is related to the type of diffusion and the microstructure of the material. When $n$ >1, the process is characterized as superdiffusive, while $n$ < 1 indicates a subdiffusive process. This suggests that the drying process of *C. ternatea* flowers at temperatures of 50 and 60 °C and of *M. arboreus* flowers at 50 °C was subdiffusive; however, from 70 °C for *C. ternatea* flowers and 60 °C for *M. arboreus* flowers, the process was superdiffusive. At lower temperatures, the system exhibits subdiffusive behavior ($n$ < 1) because water molecules are more likely to be trapped or hindered by the environment, resulting in slower diffusion. As the temperature increases, thermal energy increases, reducing the effect of barriers. This can increase water evaporation in the material, leading to superdiffusive behavior [27].

In Fig. 2, the drying curves for the flowers of *C. ternatea* (Fig. 2A) and *M. arboreus* (Fig. 2B) can be seen at different drying temperatures, with the adjustment of the Page model.

*M. arboreus* flowers required more time to dry than *C. ternatea* flowers at all drying temperatures (Table 1). *M. arboreus* flowers require more time to dry than *C. ternatea* flowers, mainly due to their distinct morphological and biochemical characteristics. *M. arboreus* flowers have thick, fleshy, tightly wrapped petals that retain greater moisture

**Table 1** Drying time and water content of powders obtained from drying *C. ternatea* and *M. arboreus* flowers at different temperatures

| Flowers | Temperature (°C) | Drying time (min) | Water content (% w.b) |
|---|---|---|---|
| *C. ternatea* | 50 | 600 | 6,78 ± 1,44 a |
| | 60 | 360 | 4,60 ± 0,02 b |
| | 70 | 150 | 3,43 ± 0,76 bc |
| | 80 | 120 | 2,12 ± 0,87 c |
| *M. arboreus* | 50 | 840 | 8,35 ± 0,03 a |
| | 60 | 300 | 7,31 ± 0,01 b |
| | 70 | 180 | 4,49 ± 0,42 c |
| | 80 | 150 | 3,37 ± 0,19 d |

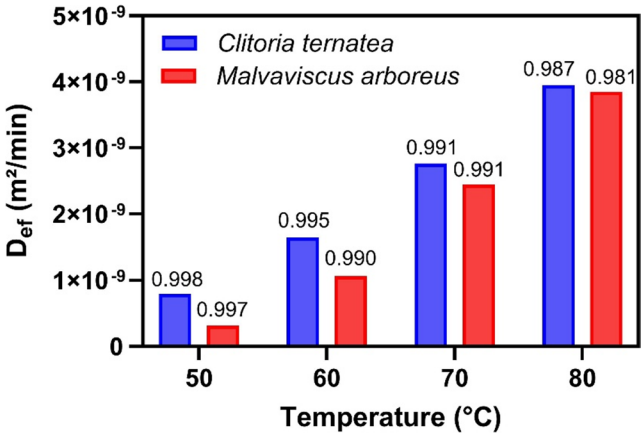



**Fig. 3** Effective moisture diffusivity of *C. ternatea* and *M. arboreus* flowers at different drying temperatures. The values above each bar represent the coefficient of determination ($R^2$) for the diffusion model fit

content and contain abundant bioactive compounds, such as flavonoids, phenolics, and glycosylated flavonoids [28]. These structural and chemical characteristics contribute to the slower evaporation of water during drying.

In contrast, *C. ternatea* flowers have thinner, more delicate petals with lower moisture retention, which causes their petals to lose moisture quickly upon drying, as corroborated by the study developed by Thuy et al. [29], which revealed that the drying time and yield of *C. ternatea* vary with temperature, but generally complete drying can occur in a few hours (approximately 6 h at 65 °C), similar to the drying time observed in our study.

Biochemically, *M. arboreus* contains complex phenolic and flavonoid glycosides, such as rutin and astragalin, which not only affect moisture retention but also potentially influence drying behavior through their interactions with water molecules in the petals [30]. The thicker flower morphology, combined with these chemical constituents, results in longer drying times compared to the more porous and chemically less complex petals of *C. ternatea*.

## Effective diffusivity

In parallel with the analysis of the moisture curves, the diffusion model was used to describe the drying kinetics of *C. ternatea* and *M. arboreus* flowers at temperatures of 50, 60, 70, and 80 °C. The effective diffusivity ($D_{ef}$) values, accompanied by the respective coefficients of determination ($R^2$), are presented in Fig. 3. $D_{ef}$ is a fundamental parameter for evaluating and optimizing processes involving moisture transfer within a product, encompassing mechanisms such as molecular diffusion, liquid and vapor diffusion, and hydrodynamic phenomena [31]. This parameter expresses, in an integrated way, the influence of multiple factors that affect mass transfer in plant material [32].

For agricultural products, the literature indicates that $D_{ef}$ values are generally in the range of $10^{-12}$ to $10^{-7}$ m²/s, varying according to the physical-chemical properties of the product and the drying conditions applied [33]. Studies with Prunus flowers, for example, indicated that increasing the drying temperature tends to increase $D_{ef}$ values, due to the increase in the kinetic energy of the water molecules, although different methods present different behaviors [34]. Sharifian et al. [35] found that increasing the drying temperature resulted in increased $D_{ef}$ values for saffron petals dried by infrared and hot air drying. The drying method can generate irregular $D_{ef}$ values, with higher values often observed for hot air drying processes, while processes such as freeze-drying generate lower $D_{ef}$ values [34].

In our study, the $D_{ef}$ coefficients determined for *C. ternatea* flowers ranged from $7.382 \times 10^{-10}$ to $4.083 \times 10^{-9}$ m²/min, while for *M. arboreus* flowers, the values ranged from $3.687 \times 10^{-10}$ to $3.714 \times 10^{-9}$ m²/min. These results are consistent with the order of magnitude reported for plant products and indicate that, as observed in other studies with flowers, there is a significant influence of drying conditions on effective diffusivity. The observed amplitude suggests that variations in temperature and possibly in the morphological structure of the petals impact moisture mobility, reinforcing the importance of fine-tuning process parameters to optimize drying kinetics.

## Activation energy and thermodynamic properties

The activation energy ($E_a$) required for drying reflects the ease with which water molecules can leave the flower tissue. Flowers with denser structures, thicker cell walls, or higher concentrations of compounds such as phenolics or flavonoids generally require more energy for moisture diffusion, resulting in higher $E_a$ values as the temperature increases [36, 37].

The $E_a$ of *M. arboreus* flowers was higher (57753.33 J/mol) than that required for *C. ternatea* flowers (44806.37 J/mol) (Table 2). Flowers with water more strongly bound to cellular components (such as proteins and polysaccharides) or with more complex cellular arrangements will present higher activation energies. Garnai et al. [36] showed that the yellow flowers of *Tagetes erecta* L. had a 35.57% higher $E_a$ than orange ones, probably due to differences in tissue structure or chemical composition. Results like these are confirmed in our study, where the divergent chemical composition and morphological structure between flower species resulted in significant changes in $E_a$.

Enthalpy (ΔH) and entropy (ΔS) changes during drying also varied by species (Table 2). Higher enthalpy values indicate that more energy is required to initiate moisture transfer, which is often seen in species with more robust or less porous tissues [37, 38]. As drying temperature increases, these thermodynamic properties change, but relative differences between species persist due to inherent biological differences [37].

The positive ΔH values for both species confirm that drying is an endothermic process [39]. For *C. ternatea*, ΔH ranged from 42,119.70 to 41,870.28 kJ/mol, while for *M. arboreus* the values ranged from 55,066.66 to 54,817.24 kJ/mol (Table 2). This difference reinforces that *M. arboreus* requires a greater heat supply to overcome water-matrix interactions, corroborating the findings of drying processes in plant matrices with greater structural complexity [40].

ΔS showed negative values for both species, indicating a reduction in molecular disorder during the process. This trend is consistent with the transition from liquid water (high entropy) to vapor, leaving the solid matrix more organized and with less translational freedom of the remaining water molecules [41]. However, *C. ternatea* presented a lower ΔS (−279.41 to −280.14 J/mol) than *M. arboreus* (−243.03 to −243.76 J/mol), suggesting that moisture loss in this species is associated with a more pronounced reorganization of the internal structure, possibly resulting from the presence of phenolic compounds and pigments, such as anthocyanins, which interact with the cellular matrix during dehydration [4].

The Gibbs free energy (ΔG) remained positive under all conditions, increasing with increasing temperature (132409.35–140802.73 kJ/mol for *C. ternatea* and 133600.30–140902.29 kJ/mol for *M. arboreus*). Positive ΔG values indicate that the process does not occur spontaneously under standard conditions, requiring energy input [40]. The increase in ΔG with temperature is directly related to the negative ΔS, since the term -TΔS contributes positively to the total variation in free energy, a fact already reported in plant systems with high cohesion of the cellular matrix after partial loss of water [18].

Overall, the results indicate that *C. ternatea* flowers are thermodynamically more favorable for drying in terms of energy (lower Ea and ΔH), while *M. arboreus* exhibits greater internal resistance and temperature dependence for increasing the drying rate. These differences likely originate from anatomical, chemical, and structural variations intrinsic to each species and should be considered when designing industrial processes to optimize energy consumption and preserve bioactive quality.

**Table 2** Thermodynamic properties of drying *C. ternatea* and *M. arboreus* flowers at different drying temperatures

| Flowers | Parameters | Temperature (°C) | | | |
|---|---|---|---|---|---|
| | | 50 | 60 | 70 | 80 |
| *C. ternatea* | $E_a$ (J/mol) | 44806.37 | | | |
| | ΔH (J mol/K) | 42119.70 | 42036.56 | 41953.42 | 41870.28 |
| | ΔS (J mol/K) | −279.41 | −279.66 | −279.90 | −280.14 |
| | ΔG (J mol/K) | 132409.35 | 135204.67 | 138002.49 | 140802.73 |
| *M. arboreus* | $E_a$ (J/mol) | 57753.33 | | | |
| | ΔH (J mol/K) | 55066.66 | 54983.52 | 54900.38 | 54817.24 |
| | ΔS (J mol/K) | −243.03 | −243.28 | −243.53 | −243.76 |
| | ΔG (J mol/K) | 133600.30 | 136031.82 | 138465.85 | 140902.29 |

## Physical and functional properties of *C. ternatea* and *M. arboreus* powders

Table 3 presents the physical and functional characteristics of the powders obtained from *C. ternatea* and *M. arboreus* flowers dried at different temperatures. Moisture reduction occurred progressively in both species with increasing drying temperature, being more pronounced in *C. ternatea*, which reached values of 2.12% at 80 °C, compared to 3.37% for *M. arboreus* under the same conditions. These results indicate greater water removal efficiency in *C. ternatea*, possibly related to the lower structural density of its petals and greater cellular permeability, as seen in the powder micrographs, which may have facilitated moisture diffusion.

The Carr index and Hausner factor, parameters associated with powder flow behavior, showed contrasting responses among species. For *C. ternatea*, the Carr index varied between 37.29% and 50.96%, while the Hausner factor ranged from 0.49 to 0.62. These values indicate powders with acceptable to good flow, according to the classification proposed by Carr [21], suggesting that drying did not severely compromise the material's fluidity. On the other hand, *M. arboreus* presented a similar Carr index (36.40–50.95%), but the Hausner factor values were substantially

**Table 3** Physical and functional characteristics of flower powders of *C. ternatea* and *M. arboreus* subjected to drying at different temperatures

| Flowers | Parameters | Temperature (°C) | | | |
|---|---|---|---|---|---|
| | | 50 | 60 | 70 | 80 |
| *C. ternatea* | Water content (% w.b) | 6.78 ± 1.14aA | 4.60 ± 0.02bB | 3.43 ± 0.76bcA | 2.12 ± 0.87cA |
| | Carr Index (%) | 37.29 ± 0.19cA | 50.88 ± 0.13aA | 40.76 ± 0.06bA | 50.96 ± 0.01aA |
| | Hausner factor | 0.62 ± 0,01aB | 0.49 ± 0.01cB | 0.59 ± 0.01bB | 0.49 ± 0.01cB |
| | Solubility (%) | 10.57 ± 0.46bA | 9.91 ± 0.06bA | 12.18 ± 0.33aA | 12.80 ± 0.3aA |
| *M. arboreus* | Water content (% w.b) | 8.34 ± 1.11aA | 7.31 ± 0.09bA | 4.48 ± 0.11cA | 3.37 ± 0.10dA |
| | Carr Index (%) | 36.40 ± 0.98bA | 49.33 ± 0.81aA | 38.44 ± 1.33bB | 50.95 ± 1.34aA |
| | Hausner factor | 1.57 ± 0.02bA | 1.97 ± 0.03aA | 1.62 ± 0.04bA | 2.03 ± 0.06aA |
| | Solubility (%) | 9.98 ± 0.52aA | 9.17 ± 0.19abA | 8.54 ± 0.87bB | 9.48 ± 0.31abB |

a,b - Different lowercase letters in the same row indicate a statistically significant difference between drying temperatures, according to Tukey's test ($p < 0.05$).

A, B - Different uppercase letters between flower species indicate a significant difference between species, according to Sidák's test ($p < 0.05$).

higher (1.57–2.03), indicating poor to very poor flow behavior [21]. This discrepancy between the parameters may be related to the greater cohesiveness of the *M. arboreus* particles, possibly associated with adhesive components in the floral matrix, hindering the free flow of the powder [9].

The solubility of the powders also showed significant differences between species. In *C. ternatea*, the values ranged from 9.91% to 12.80%, being higher than those obtained for *M. arboreus* (8.54% − 9.98%). The greater solubility of *C. ternatea* suggests greater availability of hydrophilic compounds and less structural compaction, desirable factors for applications in instant beverages or food formulations that require rapid dispersion in aqueous media [42]. In contrast, the relatively lower solubility of *M. arboreus* may reflect the greater presence of insoluble fibers and structural polysaccharides, which reduce particle dissolution [43].

In the comparative context, the statistical analysis reveals significant differences between species and temperatures for several parameters, indicating that both the nature of the raw material and the drying conditions directly influence the technofunctional properties of the powders. From a technological perspective, the results suggest that *C. ternatea* presents advantages in terms of more efficient reduction of moisture content, better flowability (Hausner factor < 1), and greater solubility, characteristics that favor its application in powder formulations with better processability and reconstitution. In turn, *M. arboreus* showed greater flow difficulties and lower solubility, which may limit its direct use in instant products, although these characteristics can be exploited in applications requiring greater structural stability or incorporation into solid matrices.

## Scanning electron microscopy (SEM)

Figure 4 shows the micrographs of flours obtained from *C. ternatea* and *M. arboreus* flowers subjected to different drying temperatures. In Fig. 4A of the *C. ternatea* flower, it can be observed that the articulations present irregular geometry, heterogeneous size distribution, and a predominantly rough surface. The variation in drying temperature did not promote marked structural changes, and the outline of the leaf cellular structure remained visible in all samples, a characteristic also reported by Xu [44] in the analysis of the surface morphology of flowers and leaves of *Bauhinia variegata* L. Furthermore, capillary structures were identified in all powders, originating from the leaves of the floral receptacle. Similar structures have been described in rice leaves [45] and also in *Bauhinia variegata* L [44]., indicating that such formations are recurrent in leaf tissues.

Figure 4B shows the micrographs of powders obtained from *M. arboreus* flowers under the same drying conditions. Unlike what was observed in *C. ternatea*, the particles had a more compact and regular surface, although they maintained irregular geometry and heterogeneity in size. This characteristic suggests that the *M. arboreus* matrix has greater structural resistance to mechanical disintegration during the powder production process, possibly due to its higher cell density. As with *C. ternatea*, no significant changes attributable to the increased drying temperature were observed, and the cell contour remained preserved in all samples.

In comparison, while *C. ternatea* presented particles with a rougher and more heterogeneous surface, possibly related to the presence of phenolic pigments and greater cell wall fragility, *M. arboreus* revealed a more compact and homogeneous morphology, consistent with a more cohesive cellular matrix. These structural differences may have direct implications for the surface reactivity of the powders, the retention of bioactive compounds, and their storage stability.

## Principal component analysis

Principal component analysis (PCA) allowed a comprehensive assessment of the multivariate variation between *C. ternatea* and *M. arboreus* samples dried at different

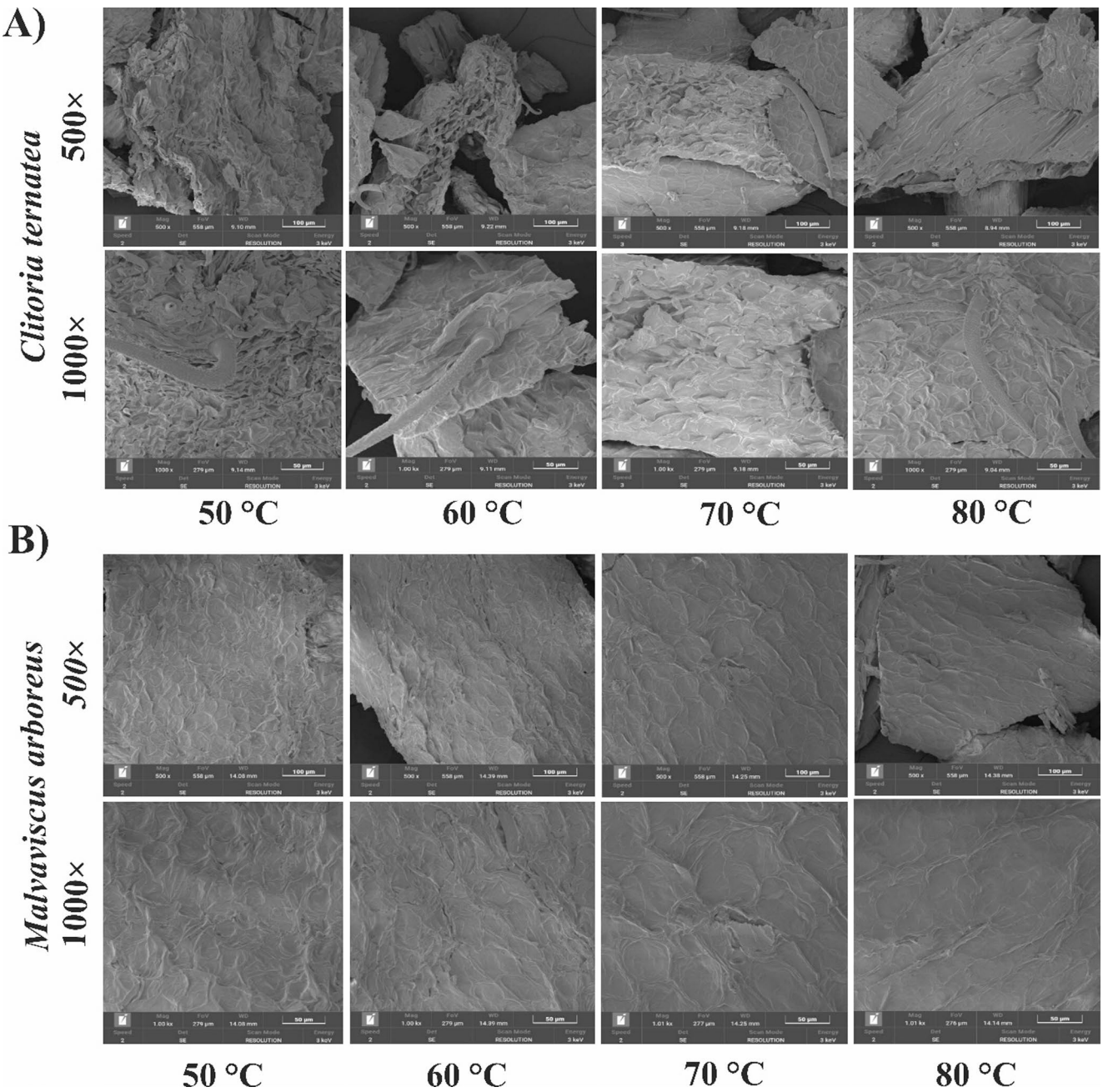



**Fig. 4** Micrographs of particles from flower powders of *C. ternatea* (**A**) and *M. arboreus* (**B**), with magnification of 500× and 1000×, at temperatures of 50, 60, 70, and 80 °C

temperatures. The Fig. 5 shows the projection of the samples onto the plane defined by the first two principal components, which jointly explain most of the total variance in the data.

A clear separation between the groups of the two floral species is observed along the PC1 axis, indicating that the analyzed variables are effective in discriminating materials based on their botanical origin. Samples of *C. ternatea* (blue circles) are positioned in the right quadrant of the graph, being strongly associated with higher values of solubility, Carr's index, and effective diffusivity ($D_{ef}$). This grouping suggests that the powder and *C. ternatea* have characteristics of greater dispersibility in aqueous media and ease of moisture removal during drying, which may be related to lower matrix compaction and greater surface porosity.

On the other hand, *M. arboreus* samples (red triangles) are distributed to the left of the biplot, associated with higher values of water content, drying time, activation energy ($E_a$), entropy ($\Delta S$), enthalpy ($\Delta H$), Hausner factor, and Gibbs free energy ($\Delta G$).

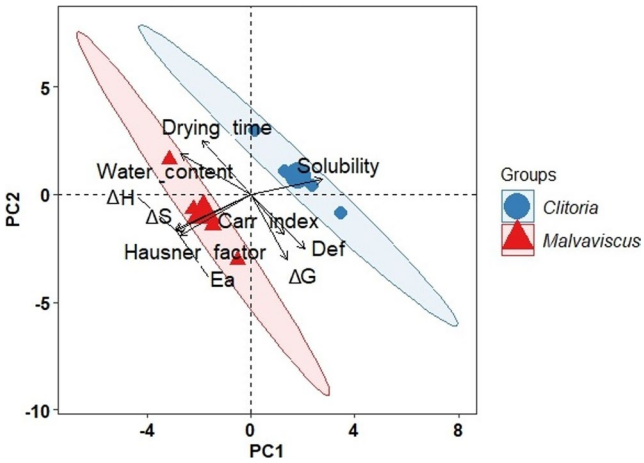



**Fig. 5** Principal Component Analysis (PCA) applied to the physical and technofunctional properties of flours obtained from *C. ternatea* (blue circles) and *M. arboreus* (red triangles). The ellipses represent the 95% confidence interval clusters for each species

The solubility and Carr index variables, located in the positive quadrant of PC1, contributed most to the separation of the *C. ternatea* group, suggesting greater dispersibility of this species' powders in aqueous media. This characteristic may be related to the specific chemical structure of the compounds present in the *C. ternatea* floral matrix, which favored greater interaction with water during rehydration. On the other hand, the clustering of thermodynamic variables such as ΔH, ΔS, and $E_a$ close to the *M. arboreus* samples indicates that this species requires greater energy input to promote water removal, reflecting greater resistance to drying, possibly attributed to a denser cellular structure or the presence of hydroscopic compounds.

Effective diffusivity ($D_{ef}$) proved to be an important discriminator, being consistent with that of *C. ternatea* samples. This indicates improved mass transfer during drying of these samples, a desirable result in industrial processes because it translates into shorter time and lower energy expenditure to achieve safe residual moisture levels.

The drying time vector, oriented toward the upper quadrant, reinforces this hypothesis by indicating a longer time required to reach thermodynamic equilibrium when drying *M. arboreus* samples. The proximity between ΔG and samples of this same species suggests that, despite the greater energy demand, the drying process remains spontaneous, albeit less efficient in terms of entropy reduction.

The addition of thermodynamic and transport parameters (such as $D_{ef}$) to the data matrix proved crucial in expanding the discriminant power of PCA, providing a more integrated perspective on the behavior of materials during the drying process. The presence of non-overlapping 95% confidence ellipses confirms the statistical robustness of the separation between groups and suggests that the multivariate profiles of each species are significantly distinct.

## Conclusion

This study revealed significant differences in drying kinetics, structural characteristics, and functional properties between *C. ternatea* and *M. arboreus* flowers grown under agroecological conditions. The drying behavior was most accurately modeled by the Page equation, with *M. arboreus* exhibiting longer drying times and greater resistance to moisture loss compared to *C. ternatea*. Functional evaluation showed that *C. ternatea* powders possess superior solubility and flowability, making them well-suited for instant food products. In contrast, *M. arboreus* powders demonstrated higher cohesiveness, suggesting their applicability in formulations requiring a structured texture. These results emphasize the critical role of botanical source in determining powder properties and support the utilization of edible flowers as sustainable, value-added ingredients that bridge agroecological cultivation practices and food technology advancement.

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**Data availability** Dataset available on request from the authors.

## Declarations

**Competing interest** The authors declare no conflicts of interest.

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## References


1. C.S. Giuliani, C.A.A. Farias, P.K. Marquezan, K.L. de Aguiar, P.H.F. Guerim, E.A.S. Musachio, N.C. de Bonotto, F. Barbisan, M.T. Barcia, A.L.S.S. Mateus, A.S. Bezerra, J.L. Nörnberg, Food Chem. **492**, 145526 (2025)
2. T. Ulian, M. Diazgranados, S. Pironon, S. Padulosi, U. Liu, L. Davies, M.R. Howes, J.S. Borrell, I. Ondo, O.A. Pérez-Escobar, S. Sharrock, P. Ryan, D. Hunter, M.A. Lee, C. Barstow, Ł Łuczaj, A. Pieroni, R. Cámara-Leret, A. Noorani, C. Mba, R. Nono Womdim, H. Muminjanov, A. Antonelli, H.W. Pritchard, E. Mattana, Plants, People, Planet **2**, 421 (2020)
3. C.P. Ferreira, M. da C. Lima, J.G. da Silva, N.M. Peixoto Araujo, Food Res. Int. **191**, 114643 (2024)
4. S. Chowdhury, B. Das Gupta, S. Ghosh, S. Gayen, A. Kar, P.K. Mukherjee, P.K. Haldar, Fitoterapia. **185**, 106772 (2025)
5. L.K. Raju, G.K. Mana, S. Cheruthazhakkatt, S.K. Sarojini, I. Balachandran, J. Herbs Spices Med. Plants **28**, 217 (2022)
6. Y. Yun, X. Jin, X. Cheng, Y. Wang, H. Jin, J. Li, L. Wang, Int. J. Biol. Macromol. **304**, 140933 (2025)
7. S. Rodríguez-Morales, B. Ocampo-Medina, N. Romero-Ceronio, C. Alvarado-Sánchez, M.Á. Vilchis-Reyes, L. F. Roa de la Fuente, R. Ortiz-Andrade, O. Hernández-Abreu, Chem. Biodivers. **18**, (2021)
8. M.B. Adassi, G.T. Ngoupaye, F.B. Yassi, A.F. Foutsop, T.D. Kom, E. Ngo Bum, J. Ethnopharmacol. **303**, 115995 (2023)
9. Y. Campos-Vidal, M. Herrera-Ruiz, G. Trejo-Tapia, M. Gonzalez-Cortazar, A.J. Aparicio, A. Zamilpa, J. Ethnopharmacol. **268**, 113633 (2021)
10. P. Antwi-Agyei, E.M. Abalo, A.J. Dougill, F. Baffour-Ata, Reg. Sustain. **2**, 375 (2021)
11. K. Aghaloo, A. Sharifi, Curr. Res. Environ. Sustain. **6**, 100230 (2023)
12. C.M. Alcântara, I.S. Moreira, M.T. Cavalcanti, R.P. Lima, H.V. Moura, R. da S. Neves, C.A.L. Cassimiro, J.J.A. Martins, F.R.C. Batista, E.M. Pereira, Processes. **12**, 2077 (2024)
13. B.M.C. Silva, D.E.C. de Oliveira, B. de L. Farias, V.S. Costa, V.B. Ferreira, M.R.G. Nunes, O. Resende, Research, Society and Development **9**, e975974789 (2020)
14. https://www.statsoft.com (2004)
15. L.M. Diamante, R. Ihns, G.P. Savage, L. Vanhanen, Int. J. Food Sci. Technol. **45**, 1956 (2010)
16. W.K. Lewis, J. Ind. Eng. Chem. **13**, 427 (1921)
17. A. Yagcioglu. In proceedings of the 7^< Th>international congress on agricultural mechanization and energy, 1999 Faculty of Agriculture, Cukurova University. 565–569 (1999)
18. S.S. Monteiro, W.P. da Silva, S.S. Monteiro, J.P. Gomes, E.M. Pereira, J.P. de Ferreira, J. Food Process. Preserv. **46**, (2022)
19. W.P. Silva, C. M. D. P. S. Silva, (2009)
20. H.W. da Silva, R.S. Rodovalho, M.F. Velasco, C.F. Silva, L.S.R. Vale, Rev. Bras. Eng. Agrícola Ambient. **20**, 174 (2016)
21. R.L. Carr, (1965)
22. H.H. Hausner, *Friction Conditions in a Mass of Metal Powder* Polytechnic Inst. of Brooklyn (Univ. of California, Los Angeles, 1967)
23. M. Cano-Chauca, P.C. Stringheta, A.M. Ramos, J. Cal-Vidal, Innov. Food Sci. Emerg. Technol. **6**, 420 (2005)
24. N.C. Santos, R.L.J. Almeida, G.M. da Silva, V.M. de A. Silva, V.H. de A. Ribeiro, A.C. de O. Brito, L.M. de S. Rodrigues, R.M. S. Santos, M.M. T. Saraiva, J. Sci. Food Agric. **103**, 125 (2023)
25. T.L.B. Lima, N.C. Santos, R.L.J. Almeida, S.S. Monteiro, J.G. da S. Figueira, K.A. Bomfim, M.A. de B. Pasquali, J.P. Gomes, A.P.T. Rocha, J Food Process Eng. **48,** (2025)
26. J.C. Albuquerque, R.M.F. de Figueirêdo, A.J. de Queiroz, F.S. dos Santos, N.C. Santos, R. de Carvalho, H.V. Moura, N. de Albuquerque, A.P. Júnior, de F. Silva, M.G. Gregório, J.Q. Farias, A. C. O. de Brito, and L. A. da Silva, Waste biomass valorization. (2025)
27. T. Kosztołowicz, Phys. Rev. E. **107**, 064103 (2023)
28. O. Abdelhafez, J. Fahim, U. Abdelmohsen, S. Desoukey, J. Adv. Biomedical Pharm. Sci. **0**, 0 (2020)
29. N.M. Thuy, V.Q. Minh, T.C. Ben, H.T.N. Ha, N.V. Tai, Food Res. **5**, 197 (2021)
30. H.S.S. Gazwi, N.A. Shoeib, M.E. Mahmoud, O.I.A. Soltan, M.M. Hamed, A.E. Ragab, Antibiotics (2022). https://doi.org/10.3390/antibiotics11111652
31. N. de Macedo Albuquerque Junior, W.P. da Silva, D.A. Lima, R. dos Santos Silva, H.V. Moura, A.P. de F. Silva, R. de Oliveira Carvalho, F.S. Andrade, L.T.S. Amadeu, J. Therm. Anal. Calorim. **150**, 5213 (2025)
32. J. Dehghannya, M. Pourahmad, B. Ghanbarzadeh, H. Ghaffari, J. Food Eng. **238**, 164 (2018)
33. N. Dibagar, R. Amiri Chayjan, Drying Technol. **37**, 1097 (2019)
34. A.N. Dundar, O.I. Sahin, M.E. Parlak, F.T. Saricaoglu, J. Food Process. Eng. (2023). https://doi.org/10.1111/jfpe.14405
35. F. Sharifian, Z.R. Gharkhloo, A.A. Yamchi, M. Kaveh, J. Food Process. Eng. (2023). https://doi.org/10.1111/jfpe.14342
36. M. Garnai, D.D. Borda, C. Vizireanu, L.I. Mihalcea, J. Agroaliment. Process. Technol. **1**, 52 (2017)
37. M. Kaveh, S. Zomorodi, B. Ghaysari, H.S. El-Mesery, F. Sharifian, A.H. ElMesiry, A. Salem, Sci. Rep. **15**, 9245 (2025)
38. Hicham el Ferouali, A. Zoukit, F. Benkhalti, N. Zehhar, H. Bouamama, Disse Doubabi, and Naji Abdenouri. J. Appl. Bot. Food Qual. **91**, 14 (2018)
39. F.S. dos Santos, R.M.F. de Figueirêdo, A.J. de Queiroz, E.T. de Silva, Y.F. Paiva, H.V. Moura, A.R.N. Campos, De B. A. Carvalho, M. dos S. Lima, and A. D. B. de Macedo. J. Food Meas. Charact. **17**, 6452 (2023)
40. M.G. Gregório, A.J. de Queiroz, R.M.F. Figueirêdo, F.S. dos Santos, J.P. Gomes, J.O. de Oliveira Neto, M.M. de Gomes, M.A. Araújo, R. de Carvalho, V.L.M. Silva, H.V. Moura, N.M.H. Mascarenhas, B.F. Silva, Y.F. Paiva, E.Z. Lara, Appl. Food Res. **5**, 101096 (2025)
41. L.T.S. Amadeu, A.J. de Queiroz, R.M.F. de Figueirêdo, J.P. de Ferreira, W.P. da Silva, J.P. Gomes, Y.F. Paiva, C.C. Costa, H.V. Moura, D.and, H.A. Silva, Processes. **10**, 1460 (2022). da C. Santos, A. R. C. de Lima
42. N.F. Jaafar, M.E. Ramli, R. Mohd. Salleh, Trop. Life Sci. Res. **31**, 1 (2020)
43. J.R. Fahim, O.H. Abdelhafez, U.R. Abdelmohsen, S.Y. Desoukey, J. Adv. Biomedical Pharm. Sci. **4**, 12 (2021)
44. Y. Xu, Micron. **177**, 103575 (2024)
45. L. Zheng, C. Cao, Z. Chen, L. Cao, Q. Huang, B. Song, Pest Manag. Sci. **77**, 3198 (2021)


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