Evaluation of the drying process and toxic metal contents in yerba mate cultivated in southern Brazil

Evaluación del proceso de secado y contenido de metales tóxicos en la yerba mate cultivada en el sur de Brasil

Caroline Gieseler Dornelles[1] and Matheus Poletto[2*]

ABSTRACT

The drying kinetics of yerba mate leaves from southern Brazil was investigated theoretically and experimentally in a drying oven at 70°C. The effect of drying conditions on the moisture ratio, drying rate, and effective diffusivity of yerba mate leaves was evaluated. Five drying models were fitted to experimental data. Additionally, the concentrations of As, Cd, Pb, Ni, Cr, and Hg in the yerba mate leaves were determined using inductively coupled plasma optic emission spectrometry (ICP-OES). The results revealed that all samples only showed a falling rate period without a constant rate of drying. The Midilli model showed the best fit of experimental data. All samples showed levels of Hg higher than those permitted by Brazilian legislation. Monitoring programs and other studies are required to prevent the intake of yerba mate products contaminated with toxic metals.

Key words: diffusion, drying, modelling, *Ilex paraguariensis*.

RESUMEN

La cinética del secado de hojas de yerba mate del sur de Brasil se investigó experimental y teóricamente en un horno de secado a 70°C. Se evaluó el efecto de las condiciones de secado sobre la proporción de humedad, la velocidad de secado y la difusividad efectiva de las hojas de yerba mate. Se ajustaron cinco modelos de secado a los datos experimentales. Además, se determinó la concentración de As, Cd, Pb, Ni, Cr y Hg en las hojas de yerba mate mediante espectrometría de emisión óptica de plasma de acoplamiento inductivo (ICP-OES). Los resultados revelaron que todas las muestras solo presentaron un período de tiempo de velocidad decreciente sin periodo de velocidad constante de secado. El modelo Midilli mostró el mejor ajuste de los datos experimentales. Todas las muestras presentaron niveles de Hg superiores a los permitidos por la legislación brasileña. Se requieren programas de monitoreo y otros estudios para prevenir la ingesta de productos de yerba mate contaminados con metales tóxicos.

Palabras clave: difusión, secado, modelado, *Ilex paraguariensis*.

Introduction

Several studies have been recently conducted on yerba mate (*Ilex paraguariensis*) because of its effects on human health (Kahmann *et al*., 2017; Zielinski *et al*., 2020; Croge *et al*., 2021). The alkaloids, terpenes, polyphenols, and essential oils, among other compounds present in its chemical composition are responsible for pharmacological activities that have anti-inflammatory, anti-obesity, and antioxidant effects (Croge *et al*., 2021). The most common use of yerba mate consists of an infusion of its leaves, such as *chimarrão* (a hot infusion of yerba mate leaves), *tereré* (a cold infusion of leaves) and mate tea (Zielinski *et al*., 2020). However, in the last years, yerba mate has been used as raw material in non-traditional uses that include the production of beers, soft drinks, sweets, and functional cheeses (Croge *et al*., 2021).

Yerba mate production is particularly favored in eastern Paraguay, north-eastern Argentina and southern Brazil, where its cultivation and processing are an important economic activity, not only for South America but also for international trade (Heck & De Mejia, 2007; Frizon *et al*., 2017). The geographical origins associated with environmental conditions, soil composition, harvest time, and processing and cultivation can affect the levels of the bioactive compounds (Kahmann *et al*., 2017; Zielinski *et al*., 2020). Additionally, other anthropogenic activities can influence the chemical composition of yerba mate by introducing compounds harmful to health (Toppel *et al*., 2018; Valduga *et al*., 2019).

The drying is a vital stage in the processing of the yerba mate leaves. This process involves simultaneous mass

Received for publication: 10 June, 2021. Accepted for publication: 18 December, 2021. Doi: 10.15446/agron.colomb.v39n3.96535

[1] Exact Sciences and Technology, Chemical Engineering, University of Caxias do Sul (UCS), Caxias do Sul (Brazil).
[2] Postgraduate Program in Engineering of Processes and Technologies (PGEPROTEC), University of Caxias do Sul (UCS), Caxias do Sul (Brazil).
[*] Corresponding author: mpolett1@ucs.br

and heat transfer through the leaves, which may cause significant changes in yerba mate characteristics. The drying stage influences the product quality as well as its cost (Timm *et al*., 2019; Siqueira *et al*., 2020). These concerns could be addressed by using mathematical simulations of the drying process (Siqueira *et al*., 2020). Hence, knowing the drying characteristics of biological materials is essential to design, optimize, and control the drying process (Pilatti *et al*., 2016).

In this context, this study evaluated the drying characteristics of yerba mate leaves cultivated in southern Brazil and proposed a mathematical model of the drying process. This research also determined the concentrations of diverse toxic metals, such as As, Cd, Pb, Ni, Cr and Hg since studies about the presence of toxic metals in yerba mate leaves are scarce.

Materials and methods

Plant material

Yerba mate leaves were evaluated from three different geographical locations from Brazil. The samples from Cruz Machado (26°1'0" S, 51°21'0" W) located in Paraná state, Brazil were identified as PR. Samples from Santiago (29°11'30" S, 54°52'2" W), located in Rio Grande do Sul state, Brazil were identified as RS. Finally, leaves from Antônio Prado (28°50'13" S, 51°17'45" W) also located in Rio Grande do Sul state, Brazil were identified as NT.

Drying equipment and experimental setup

Leaves of each sample were cut with dimensions of 2 x 2 cm to be used in the drying experiments. The initial moisture content of each sample was determined using a convection oven at 70 ± 2°C. The drying was carried out in a Gibertini Eurotherm thermobalance (Novate Milanese, Italy) with 350W power, using approximately 1 g of sample. The temperature used was 70°C. The sample mass was determined at 5 min intervals, directly by the thermobalance front display, until a constant mass was reached.

Modelling of the drying process

To evaluate the drying characteristics of yerba mate, the moisture ratio (MR) values were determined from the moisture content data (kg water/kg dry matter) at time *t* from Equation 1:

$$MR = \frac{Mt-Me}{Mo-Me} \qquad (1)$$

where M_t, M_o, and M_e are the moisture content at any time of drying (kg water/kg dry matter), the initial moisture content (kg water/kg dry matter), and the equilibrium moisture content (kg water/kg dry matter), respectively. M_e was neglected since its values were relatively small compared to M_t and M_o (Mewa *et al*., 2019; Yilmaz *et al*., 2019).

The drying rate of yerba mate leaves was obtained according to Equation 2:

$$DR = \frac{M_t - M_{t+dt}}{dt} \qquad (2)$$

where DR is the drying rate (kg water/kg dry matter per min), M_{t+dt} is the moisture content at t + dt time (kg water/kg dry matter) and *t* is the drying time (min).

The drying data obtained were fitted to five different drying models detailed in Table 1.

TABLE 1. Mathematical models applied to the drying curves.

Model's name	Model's equation
Newton (Yilmaz *et al*., 2019)	MR = exp(-kt)
Page (Mewa *et al*., 2019)	MR = exp(-kt^n)
Henderson and Pabis (Kouhila *et al*., 2020)	MR = a exp(-kt)
Midilli *et al.* (2002)	MR = a exp(-kt^n) + bt
Parabolic (Darvishi *et al*., 2013)	MR = at^2 + bt + c

MR - Moisture ratio; t - time; a, b, c, k, n: constants.

The nonlinear least-squares regression analysis was used to estimate model parameters using the software Origin® 2018 (OriginLab Corporation, Northampton, MA, USA). The coefficient of determination (R^2) was the primary parameter used for selecting the best model to define the drying curves (Darvishi *et al*., 2013). However, to better determine the quality of the fit, reduced chi-square (χ^2) and root mean square error (RMSE) were also calculated. These two statistical features were calculated according to Equations 3 and 4, respectively:

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]^{\frac{1}{2}} \qquad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\left(MR_{exp,i} - MR_{pre,i}\right)^2\right.}{N-Z} \qquad (4)$$

where $MR_{exp,i}$ is the experimental moisture ratio, $MR_{pre,i}$ is the predicted moisture ratio, *N* is the number of observations, and *Z* is the number of constants. The model that best described the drying characteristics was chosen as the one with the highest R^2, followed by the lowest χ^2 and RMSE values (Sarimeseli, 2011; Yilmaz *et al*., 2019).

Effective moisture diffusivity

The effective moisture diffusivity can be determined from the slope of the normalized plot of MR, ln(MR) versus time, when the drying time is abundant (Darvishi *et al*., 2013; Incedayi, 2020; Kouhila *et al*., 2020), using Equation 5:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2\ D_{eff}}{4\,L^2}\right) t \quad (5)$$

where (D_{eff}) is the effective moisture diffusivity (m^2/s) and L is the half thickness of the sample (m).

Metal content determination

The arsenic, cadmium, lead, nickel, chromium, and mercury contents in yerba mate leaves were analyzed using ICP-OES equipment (ICAP 7000, Thermo Scientific, Cambridge, UK). The samples were previously dried in a convection oven at 70°C until constant weight. The samples were prepared according to the EPA method 3050B (EPA, 1996) and the APHA method 3120B (Gottler, 2017), and analyzed in triplicate.

Results and discussion

Drying characteristics

The evolution of moisture content as a function of time can be represented by the drying curve. Figure 1A shows the variations in the moisture ratio (MR) with the drying time for all leaves studied. According to Kouhila *et al.* (2020), the drying curve can be separated in three main phases. In the first phase, a transition between transient to permanent regime of drying takes place. The sample temperature reaches the wet bulb temperature. The main part of energy is used to increase the sample's surface temperature through a sensible heat input which will result in water evaporation. As seen in Figure 1A, before the initial 1000 s, all samples show very similar behavior, which is consistent with the first stage of drying.

The second drying phase corresponds to a more prominent drying since the steady state phase begins. At this stage, the free water present in the sample's surface is evaporated. The saturation vapor pressure inside the oven is equal to the vapor pressure at the sample's surface (Kouhila *et al.*, 2020). The drying rate is constant during this stage and only depends on the external conditions, such as temperature, air humidity and flow characteristics (Darvishi *et al.*, 2013; Kouhila *et al.*, 2020). It was not possible to identify the steady state phase in Figure 1A. After the first period, all samples only showed a falling rate period. A similar behavior was observed by Pilatti *et al.* (2016) for yerba mate leaves.

Phase 3 corresponds to the falling drying rate period. As shown in Figure 1A, this period can be identified approximately from 1000-6000 s. At this period, the energy is used to evaporate the water from the inside of the sample. In organic materials, such as yerba mate, the water evaporates from the inner layers of the sample generally by a diffusion-controlled process. Consequently, the drying rate decreases increasing the drying time, as can be seen in Figure 1B. Thus, the constitution of each yerba mate leaf may influence the mass and heat transfer that may cause the decrease in the drying rate. Pilatti *et al.* (2016) reported that, at this stage, the drying is governed by the water diffusion in the solid that agrees with the results of this study. After 6000 s, the moisture ratio was reduced, indicating that the drying process was near reaching the equilibrium moisture content.

Modelling of the drying curves

The best model for describing the drying characteristics of the leaves studied was selected according to the highest R^2 and the lowest χ^2 and RMSE values. The statistical results for the models tested are summarized in Table 2.

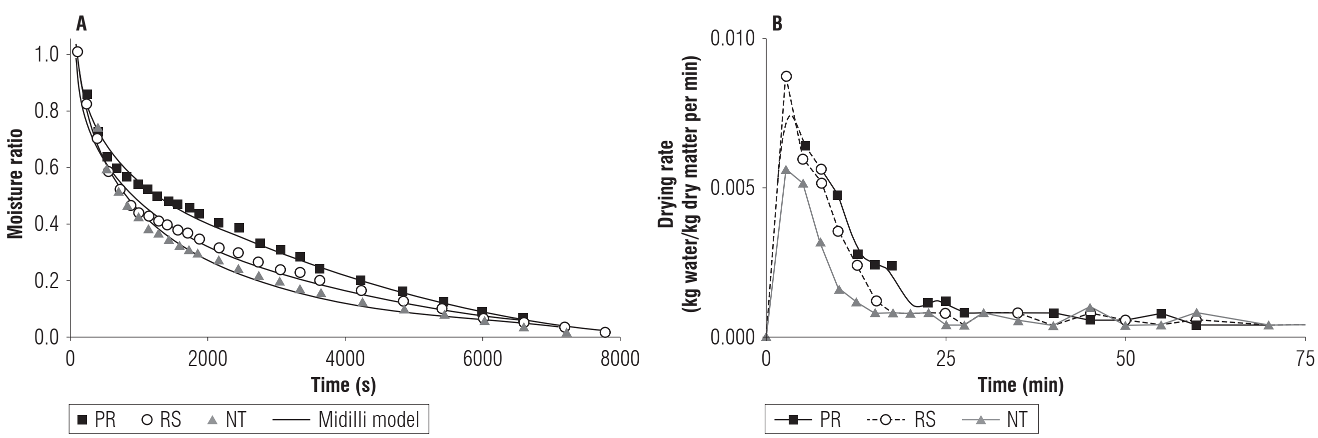

FIGURE 1. Evolution of A) moisture ratio and B) drying rate of the yerba mate leaves versus drying time. PR: Samples from Paraná; RS: samples from Rio Grande do Sul; NT: samples from Antônio Prado.

TABLE 2. Results of the statistical analysis on the modelling of moisture content versus drying time for the samples of yerba mate leaves studied.

Model name	Samples	R^2	χ^2	RMSE	Coefficients				
					a	b	c	n	k
Newton	PR	0.8837	0.0068	0.1641	---	---	---	---	0.00049
	RS	0.8623	0.0081	0.2017	---	---	---	---	0.00067
	NT	0.9217	0.0050	0.1207	---	---	---	---	0.00077
Page	PR	0.9779	0.0013	0.0299	---	---	---	0.646	0.00731
	RS	0.9850	0.0009	0.0211	---	---	---	0.597	0.01289
	NT	0.9892	0.0006	0.0159	---	---	---	0.662	0.00878
Henderson and Pabis	PR	0.9520	0.0028	0.0648	0.8318	---	---	---	0.00037
	RS	0.9286	0.0042	0.1004	0.8053	---	---	---	0.00047
	NT	0.9458	0.0035	0.0800	0.8668	---	---	---	0.00063
Midilli	PR	0.9925	0.0004	0.0093	1.009	-0.000029	---	0.462	0.02409
	RS	0.9894	0.0006	0.0137	1.016	-0.000015	---	0.507	0.02353
	NT	0.9888	0.0007	0.0151	1.024	-0.000002	---	0.635	0.01088
Parabolic	PR	0.9281	0.0042	0.0929	0.78495	-0.00019	0.0002	---	---
	RS	0.8759	0.0073	0.1672	0.72184	-0.00022	0.0002	---	---
	NT	0.8698	0.0084	0.1840	0.74416	-0.00027	0.0003	---	---

PR: samples from Paraná; RS: samples from Rio Grande do Sul; NT: samples from Antônio Prado. R^2: coefficient of determination, χ^2: reduced chi-square; RMSE - root mean square error.

From all modes tested, the Midilli model seems to be the best model describing the drying characteristics of the three samples, as can be seen in the adjustment done in the experimental data shown in Figure 1A, and also verified by the highest R^2 and lowest χ^2 and RMSE values shown in Table 2. However, the Page model also showed similarity with the experimental data and could not be discarded. Pilatti *et al.* (2016) evaluated the drying of yerba mate leaves in a bench dryer and found that the Page model was suitable to predict the experimental data. Holowaty *et al.* (2018) also observed that the Page model better described the drying of yerba mate leaves.

Effective moisture diffusivity results

The values of effective moisture diffusivity are shown in Table 3. The D_{eff} values ranged from 2.96 x 10^{-12} to 3.69 x 10^{-12} $m^2\,s^{-1}$. The values obtained in this research are in the general range of other values found in the literature for yerba mate leaves ranging from 10^{-14} to 10^{-10} $m^2\,s^{-1}$ (Ramallo, 2001). Ramallo *et al.* (2001) found moisture diffusivity between 2.3 x 10^{-11} and 2.5 x 10^{-10} $m^2\,s^{-1}$ for yerba mate leaves cultivated in Argentina, drying the leaves at 100-130°C, while Pilatti *et al.* (2016) obtained moisture diffusivity ranging from 2.3 x 10^{-11} to 2.5 x 10^{-10} $m^2\,s^{-1}$ for yerba mate leaves from Brazil, when drying the samples at 55°C, 65°C and 75°C.

TABLE 3. Values of effective moisture diffusivity (D_{eff}) for the yerba mate leaves.

Sample	D_{eff} ($m^2\,s^{-1}$)	R^2
PR	3.65 x 10^{-12}	0.981
RS	2.96 x 10^{-12}	0.993
NT	3.69 x 10^{-12}	0.991

PR: Samples from Paraná; RS: samples from Rio Grande do Sul; NT: samples from Antônio Prado; R^2: coefficient of determination.

The NT showed the highest D_{eff} value followed by PR and RS. This result corroborated the moisture ratio showed in Figure 1A. When samples were dried, the activity of water molecules increased (Xiao *et al.*, 2010) since the energy was used to heat the sample; consequently, the movement and collisions between water molecules increased, which resulted in higher moisture diffusivity.

Metal content

The concentration of arsenic, cadmium, lead, chromium, mercury, and nickel found in the leaf samples is shown in Table 4. The maximum metal content permitted in yerba mate according to Brazilian legislation (Presidência da República - Brasil, 1965; Ministério da Saúde - Brasil, 2013) is shown in Table 4.

Based on the results shown in Table 4, the contents of As, Cd, Pb and Ni were below those permitted by Brazilian legislation, while the Hg content obtained in the three samples of yerba mate leaves was above that allowed by Brazilian legislation. The highest levels were obtained for the PR and NT samples, with contamination 3 times higher than the maximum content established by Brazilian legislation. The Hg contamination in the RS sample was 50% higher than that allowed by Brazilian legislation.

Mercury is present in the entire biosphere, although it is far from natural or anthropogenic sources. Mercury compounds such as chlorides, nitrates and sulphates are stable and are even more abundant in the environment (Xiao *et*

TABLE 4. Metal concentration (mg kg^{-1} DW) found in the yerba mate leaves.

Metal	Maximum concentration permitted	PR	RS	NT
As	0.60	0.0047 ± 0.0019	0.0186 ± 0.0005	0.0185 ± 0.0004
Cd	0.40	0.1989 ± 0.0015	0.1921 ± 0.0085	0.0458 ± 0.0011
Pb	0.60	0.3313 ± 0.0024	0.3072 ± 0.0158	0.1990 ± 0.0044
Cr	0.10	0.0431 ± 0.0250	0.1523 ± 0.0037	0.1307 ± 0.0018
Hg	0.01	0.0377 ± 0.0015	0.0155 ± 0.0005	0.0305 ± 0.0008
Ni	5.00	3.7791 ± 0.0209	0.5413 ± 0.0302	2.4941 ± 0.0071

Values in red are higher than the maximum permitted by Brazilian legislation (Presidência da República - Brasil, 1965; Ministério da Saúde - Brasil, 2013). PR: Samples from Paraná; RS: samples from Rio Grande do Sul; NT: samples from Antônio Prado.

al., 2010). Thus, contamination of soils and waters with Hg can generate leaf contamination during plant growth.

The Cr content was 50% above that established by Brazilian legislation for the RS leaf samples and 30% above for NT. Saidelles *et al*. (2010) evaluated yerba mate samples and verified higher levels of Cr. The authors obtained Cr content that ranged from 1.3 and 1.6 mg kg^{-1} for samples commercialized in the southern region of Brazil. According to Valduga *et al*. (2019), the elemental composition of the yerba mate leaves can be altered by the chemical properties of the soil, fertilization, and limestone use. Water used for soil irrigation may also contain toxic metals (Kosanić *et al*., 2017; Santos *et al*., 2018) and contribute to the higher levels of metals in the yerba mate leaves analyzed. Therefore, other studies need to be carried out to confirm these hypotheses.

Conclusions

Drying characteristics and concentrations of As, Cd, Pb, Ni, Cr, and Hg in the yerba mate leaves were investigated. The drying curve revealed only the presence of a falling drying rate period. The Midilli model seemed to be the best mathematical model to describe the drying process. The moisture diffusivity ranged from 2.96×10^{-12} to 3.69×10^{-12} $m^2 s^{-1}$. All samples studied showed Hg levels higher than those permitted by Brazilian legislation, while the RS and NT samples showed higher levels of Cr. The higher levels of Hg and Cr may be associated with soil composition, use of fertilizers, limestone addition to soil, or contamination of the water used for soil irrigation. However, new studies are required to confirm these hypotheses.

Acknowledgments

The authors would like to thank the University of Caxias do Sul (UCS) of Brazil for its contribution to this research.

Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this article.

Author's contributions

CGD and MP formulated the overarching research goals and aims. CGD carried out activities to annotate scrub data and maintain research data for initial use and later reuse. MP applied statistical, mathematical, computational techniques to analyze study data. CGD conducted the research and investigation process, specifically performing the experiments. CGD developed the methodology and created the models. MP managed and coordinated the research activity planning and execution. CGD provided the study materials, reagents, laboratory samples, instrumentation, and other analysis tools. CGD and MP verified the overall replication/reproducibility of results and other research outputs. CGD and MP prepared, created, and presented the published work and oversaw its visualization. CGD and MP wrote/translated the initial draft. MP carried out the critical review, commentary, and revision of the manuscript. All authors reviewed the manuscript.

Literature cited

Croge, C. P., Cuquel, F. L., & Pintro, P. T. M. (2021). Yerba mate: cultivation systems, processing and chemical composition. A review. *Scientia Agricola*, *78*(5), Article e20190259. https://doi.org/10.1590/1678-992X-2019-0259

Darvishi, H., Azadbakht, M., Rezaeiasl, A., & Farhang, A. (2013). Drying characteristics of sardine fish dried with microwave heating. *Journal of the Saudi Society of Agricultural Sciences*, *12*(2), 121–127. https://doi.org/10.1016/j.jssas.2012.09.002

EPA. (1996). *Method 3050B: acid digestion of sediments, sludges, and soils*. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-06/documents/epa-3050b.pdf

Frizon, C. N. T., Dagostin, J. L. A., Nisgoski, S., Ribani, M., & Hoffmann-Ribani, R. (2017). Microwave drying and NIR spectroscopy for the rapid moisture measurement of yerba mate (*Ilex paraguariensis*) leaves during storage. *International Journal of Food Properties*, *20*(sup2), 1403–1412. https://doi.org/10.1080/10942912.2017.1343834

Gottler, R. A. (2017). 3120 - metals by plasma emission spectroscopy. In R. B. Baird, A. D. Eaton, & E. W. Rice (Eds.), *Standard methods for the examination of water and wastewater* (23rd ed., pp. 3–42). American Public Health Association, American Water Works Association, Water Environment Federation.

Heck, C. I., & De Mejia, E. G. (2007). Yerba mate tea (*Ilex paraguariensis*): a comprehensive review on chemistry, health implications, and technological considerations. *Journal of Food Science*, *72*(9), R138–R151. https://doi.org/10.1111/j.1750-3841.2007.00535.x

Holowaty, S. A., Thea, A. E., Alegre, C., & Schmalko, M. E. (2018). Differences in physicochemical properties of yerba maté (*Ilex paraguariensis*) obtained using traditional and alternative manufacturing methods. *Journal of Food Process Engineering*, *41*(8), Article e12911. https://doi.org/10.1111/jfpe.12911

Incedayi, B. (2020). Assessment of pretreatments on drying kinetics and quality characteristics of thin-layer dried red pepper. *Turkish Journal of Agriculture and Forestry*, *44*(6), 543–556.

Kahmann, A., Anzanello, M. J., Marcelo, M. C. A., & Pozebon, D. (2017). Near infrared spectroscopy and element concentration analysis for assessing yerba mate (*Ilex paraguariensis*) samples according to the country of origin. *Computers and Electronics in Agriculture*, *140*, 348–360. https://doi.org/10.1016/j.compag.2017.06.007

Kosanić, M., Ranković, B., Rančić, A., & Stanojković, T. (2017). Evaluation of metal contents and bioactivity of two edible mushrooms *Agaricus campestris* and *Boletus edulis*. *Emirates Journal of Food and Agriculture*, *29*(2), 98–103. https://doi.org/10.9755/ejfa.2016-06-656

Kouhila, M., Moussaoui, H., Lamsyehe, H., Tagnamas, Z., Bahammou, Y., Idlimam, A., & Lamharrar, A. (2020). Drying characteristics and kinetics solar drying of Mediterranean mussel (*Mytilus galloprovincilis*) type under forced convection. *Renewable Energy*, *147*, 833–844. https://doi.org/10.1016/j.renene.2019.09.055

Mewa, E. A., Okoth, M. W., Kunyanga, C. N., & Rugiri, M. N. (2019). Experimental evaluation of beef drying kinetics in a solar tunnel dryer. *Renewable Energy*, *139*, 235–241. https://doi.org/10.1016/j.renene.2019.02.067

Midilli, A., Kucuk, H., & Yapar, Z. (2002). A new model for single-layer drying. *Drying Technology*, *20*(7), 1503–1513. https://doi.org/10.1081/DRT-120005864

Ministério da Saúde - Brasil. (2013). *Resolução - RDC no. 42, de 29 de Agosto de 2013*. https://bvsms.saude.gov.br/bvs/saudelegis/anvisa/2013/rdc0042_29_08_2013.html

Pilatti, D., Johann, G., Palú, F., & Silva, E. A. (2016). Evaluation of a concentrated parameters mathematical model applied to drying of yerba mate leaves with variable mass transfer coefficient. *Applied Thermal Engineering*, *105*, 483–489. https://doi.org/10.1016/j.applthermaleng.2016.02.139

Presidência da República - Brasil. (1965). *Decreto no. 55871 de 26 de março de 1965*. https://www.gov.br/agricultura/pt-br/assuntos/inspecao/produtos-vegetal/legislacao-1/biblioteca-de-normas-vinhos-e-bebidas/decreto-no-55-871-de-26-de-marco-de-1965.pdf/view

Ramallo, L. A., Pokolenko, J. J., Balmaceda, G. Z., & Schmalko, M. E. (2001). Moisture diffusivity, shrinkage, and apparent density variation during drying of leaves at high temperatures. *International Journal of Food Properties*, *4*(1), 163–170. https://doi.org/10.1081/JFP-100002194

Saidelles, A. P. F., Kirchner, R. M., Santos, N. R. Z., Flores, E. M. M., & Bartz, F. R. (2010). Análise de metais em amostras comerciais de erva-mate do sul do Brasil. *Alimentos e Nutrição*, *21*(2), 259–265.

Santos, A. C., Barbosa, S., Pessoa, M. F., Leal, N., Reboredo, F., Lidon, F., & Almeida, J. (2018). Speciation, mobility and adsorption effects of various metals in sediments in an agricultural area surrounding an uranium ore deposit (Nisa, Portugal). *Emirates Journal of Food and Agriculture*, *30*(6), 503–514.

Sarimeseli, A. (2011). Microwave drying characteristics of coriander (*Coriandrum sativum* L.) leaves. *Energy Conversion and Management*, *52*(2), 1449–1453. https://doi.org/10.1016/j.enconman.2010.10.007

Siqueira, V. C., Leite, R. A., Mabasso, G. A., Martins, E. A. S., Quequeto, W. D., & Isquierdo, E. P. (2020). Drying kinetics and effective diffusion of buckwheat grains. *Ciência e Agrotecnologia*, *44*, Article e011320. https://doi.org/10.1590/1413-7054202044011320

Timm, T. G., Pasko, R. Z., Campos, C. S. G., Helm, C. V., & Tavares, L. B. B. (2019). Drying process of *Lentinula edodes*: influence of temperature on β-glucan content and adjustment of mathematical models. *Ciência e Agrotecnologia*, *43*, Article e025719. https://doi.org/10.1590/1413-7054201943025719

Toppel, F. V., Maccari Junior, A., Motta, A. C. V., Frigo, C., Magri, E., & Barbosa, J. Z. (2018). Soil chemical attributes and their influence on elemental composition of yerba mate leaves. *Floresta*, *48*(3), 425–434. https://doi.org/10.5380/rf.v48i3.56677

Valduga, A. T., Gonçalves, I. L., & Magri, E. (2019). Analysis of the presence of toxic metals in yerba mate samples: a case study from south Brazil. *Water, Air, & Soil Pollution*, *230*, Article 153. https://doi.org/10.1007/s11270-019-4204-z

Xiao, H. W., Pang, C. L., Wang, L. H., Bai, J. W., Yang, W. X., & Gao, Z. J. (2010). Drying kinetics and quality of Monukka seedless grapes dried in an air-impingement jet dryer. *Biosystems Engineering*, *105*(2), 233–240. https://doi.org/10.1016/j.biosystemseng.2009.11.001

Yilmaz, M. S., Şakiyan, O., Mazi, I. B., & Mazi, B. G. (2019). Phenolic content and some physical properties of dried broccoli as affected by drying method. *Food Science and Technology International*, *25*(1), 76–88. https://doi.org/10.1177/1082013218797527

Zielinski, A. A. F., Alberti, A., Bona, E., Bortolini, D. G., Benvenutti, L., Bach, F., Demiate, I. M., & Nogueira, A. (2020). A multivariate approach to differentiate yerba mate (*Ilex paraguariensis*) commercialized in the southern Brazil on the basis of phenolics, methylxanthines and *in vitro* antioxidant activity. *Food Science and Technology*, *40*(3), 644–652. https://doi.org/10.1590/fst.15919