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Microwave drying of yerba mate leaves: kinetics modeling and techno-economic analysis

Secagem de micro-ondas de folhas de yerba mate: modelagem cinética e análise tecno-econômica

Secado por microondas de hojas de yerba mate: modelado cinético y análisis tecnoeconómico

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ABSTRACT

Ilex paraguariensis, known as yerba mate, is a native species from South America widely used in the preparation of drinks, with several bioactive compounds. Its industrial drying process is archaic and associated to the contamination of the leaves with carcinogenic compounds. Previous study reported microwave drying of yerba mate as a potential alternative for its drying, but there are no studies on the techno or economic aspects of this process. Hence, this study aims to determine the drying kinetics on the yerba mate leaves (YML) using the microwave assisted drying method, and to provide a techno-economics analysis for different production and rate of return of investment scenarios. Microwave drying (MWD) of yerba mate was conducted at different powers (675, 945, and 1,215 W), and conventional kinetics models were fitted to the experimental data. A techno-economics analysis was conducted considering the processing of 10 – 100 kg YML/h in an agribusiness located in South Brazil. As results, the different microwave powers resulted in different equilibrium moisture content, and only the MWD at 1,215 W achieved Brazilian's legislation requirement of 10 % of moisture (wet basis). Page's drying kinetics model presented the best fitting to the experimental data, and its parameters were used in the study of economic viability. Finally, a required selling price of 19.88 US$/kg was calculated for the selling of the dried YML, resulting in a time of return of investment of 1 year for an agribusiness processing 100 kg YML/h.

Keywords: *Ilex paraguariensis*, drying kinetic, production cost, scale-up.

RESUMO

Ilex paraguariensis, conhecida como yerba mate, é uma espécie nativa da América do Sul amplamente utilizada na preparação de bebidas, com vários compostos bioativos. Seu processo de secagem industrial é arcaico e associado à contaminação das folhas com compostos cancerígenos. Estudo anterior relatou a secagem por micro-ondas de erva-mate como uma alternativa potencial para a sua secagem, mas não há estudos sobre o techno ou aspectos econômicos deste processo. Assim, este estudo visa determinar a cinética de secagem nas folhas de erva-mate (YML) usando o método de secagem assistida por micro-ondas, e fornecer uma análise tecno-econômica para diferentes cenários de produção e taxa de retorno do investimento. A secagem por micro-ondas (MWD) da erva-mate foi conduzida em diferentes potências (675, 945 e 1.215 W), e os modelos cinéticos convencionais foram ajustados aos dados experimentais. Uma análise tecno-econômica foi realizada considerando o processamento de 10 - 100 kg YML/h em um agronegócio localizado no Sul do Brasil. Como resultado, as diferentes potências de micro-ondas resultaram em diferentes teores de umidade de equilíbrio, e apenas o MWD a 1,215 W atingiu o requisito da legislação brasileira de 10 % de umidade (base úmida).

O modelo de cinética de secagem da Page apresentou o melhor ajuste aos dados experimentais, e seus parâmetros foram usados no estudo da viabilidade econômica. Finalmente, foi calculado um preço de venda exigido de 19,88 US$/kg para a venda do YML seco, resultando em um tempo de retorno do investimento de 1 ano para um processamento de agronegócio de 100 kg YML/h.

Palavras-chave: *Ilex paraguariensis*, cinética de secagem, custo de produção, scale-up.

RESUMEN

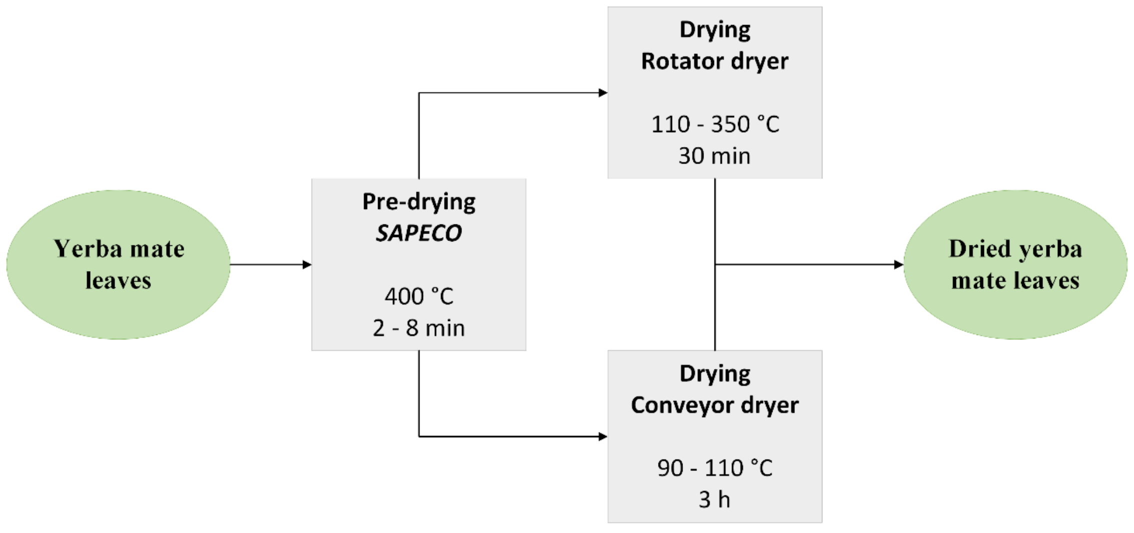
Ilex paraguariensis, conocida como yerba mate, es una especie nativa de Sudamérica ampliamente utilizada en la preparación de bebidas, con varios compuestos bioactivos. Su proceso de secado industrial es arcaico y se asocia a la contaminación de las hojas con compuestos cancerígenos. Estudios previos reportaron el secado por microondas de yerba mate como una alternativa potencial para su secado, pero no existen estudios sobre los aspectos técnicos o económicos de este proceso. Por lo anterior, el presente estudio tiene como objetivo determinar la cinética de secado en las hojas de yerba mate (LMA) mediante el método de secado asistido por microondas, y proporcionar un análisis tecno-económico para diferentes escenarios de producción y tasa de retorno de inversión. El secado por microondas (DMS) de yerba mate se realizó a diferentes potencias (675, 945 y 1,215 W), y se ajustaron modelos de cinética convencional a los datos experimentales. Se realizó un análisis tecno-económico considerando el procesamiento de 10 - 100 kg YML/h en una agroempresa ubicada en el sur de Brasil. Como resultado, las diferentes potencias de microondas resultaron en diferente contenido de humedad de equilibrio, y solo el MWD a 1,215 W alcanzó el requisito de la legislación brasileña de 10 % de humedad (base húmeda). El modelo de cinética de secado de Page presentó el mejor ajuste a los datos experimentales, y sus parámetros se utilizaron en el estudio de viabilidad económica. Finalmente, se calculó un precio de venta requerido de 19,88 US$/kg para la venta del YML desecado, resultando en un tiempo de retorno de inversión de 1 año para una agroindustria procesadora de 100 kg YML/h.

Palabras clave: *Ilex paraguariensis*, cinética de secado, costo de producción, escalado.

1 INTRODUCTION

Yerba mate (*Ilex paraguariensis*) is a native South American plant widely used in the preparation of beverages (teas, *chimarrão* and *tererê*) (TOMASI et al., 2021). Its leaves are rich in bioactive compounds (e.g., chlorogenic and caffeic acids, caffeine, theobromine) (GERKE et al., 2018; RODRIGUEZ et al., 2023), resulting in a crescent interest in developing new products from this matrix. Industrial processing of yerba mate leaves (YML) is essential on the inactivating of its oxidase enzymes (NABECHIMA et al., 2014), its procedure is dated from the 19th century and consists in a two-step mechanism (TOMASI et al., 2021), summarized in the block diagram (Figure 1). Although it is widely used in the mate industry, the *sapeco*-step may be harmful to the final product due to the direct contact of the smoke and the leaves, which results in the contamination of the dried yerba mate with carcinogenic compounds such as polyciclic aromatic hydrocarbons (PAHs) and anthraquinones (ATQ) (GARCÍA LONDOÑO; POK; RESNIK, 2020; NABECHIMA et al., 2014; TOMASI et al., 2021).

Figure 1. Block diagram on the industrial drying of yerba mate leaves.



Source: The Authors, 2024.

Alternative drying techniques for YML have been exploited, but according to (TOMASI et al., 2021), the microwave assisted drying (MWD) is the most promising method, for it preserves the most the green color on the leaves and is efficient on the maintenance of the bioactive compounds. Studies on the MWD of other leaves have also presented it as a propitious technique, once it promotes higher drying rates, and consequently shorter drying times, better quality for the dried leaves and lower energy consumption (BAHAMMOU et al., 2022; KUSUMA; IZZAH; LINGGAJATI, 2023).

Although exploratory studies indicate the microwave assisted drying for the yerba mate leaves, there are no reports on the drying kinetics of the leaves using this method, which is an essential data for the industrial sizing or scaling-up. Hence, the objective of the present work is to determine the microwave assisted drying kinetics for the yerba mate leaves, to establish the model that presents the best fitting to the experimental data and to provide a techno-economic analysis for a simulated plant for the processing of YML with the MWD technique.

2 MATERIAL AND METHODS

2.1 MATERIALS

Yerba mate leaves (YML) were collected in the summer (Jan. 2024) in Colombo, Paraná, Brazil (-25.3217023, -49.1698741). The leaves were quickly washed in distilled water, and the water excess was removed with filter paper. The samples were stored in room temperature (20 °C) for up to 3 h until the drying essays were performed.

In natura moisture of the YML was determined in triplicate (3 x 2 g) with gravimetric method after drying in oven (105 °C) until constant mass (AOAC, 2016). Leaves were measured on their thickness using a digital caliper (Fowler IP67, USA) to determine the average thickness of the sample.

2.2 EVALUATION OF THE YERBA MATE LEAVES DRYING TECHNIQUE

Part of the leaves was dried using three different drying techniques: oven drying at 60 °C (OD60), oven drying at 105 °C (OD105), and microwave assisted drying (MWD). For the OD60 and OD105, a laboratory oven was used, whereas for the MWD, a commercial microwave oven (Electrolux MEP37, Brazil) was used, with a drying chamber of 288 x 483 x 377 mm, a capacity of 27 L and a rotating glass plate with a diameter of 284 mm.

Na amount of 15 g of leaves was used for each methodology, and the drying was continued until constant mass of the samples. The dried materials were stored in plastic bags for further color characterization analyses, in order to determine the best drying methodology.

2.3 COLOR CHARACTERIZATION OF DRIED YERBA MATE LEAVES

Dried YML at the different techniques (OD60, OD105, and MWD) were characterized on their color (n = 15) using a Miniscan XE Plus colorimeter (Hunterlab), considering CIE's L*a*b color scale. ΔE was calculated using *in natura* YM leaves as reference.

2.4 MICROWAVE DRYING OF YERBA MATE LEAVES

Microwave drying kinetics were obtained as described: YM leaves were dried in batches (10.0 ± 0.5 g per batch) in triplicate under three powers (675, 945, and 1,1215 W) using a commercial microwave oven. The mass of the leaves was periodically determined in an analytical balance for 5 minutes.

Drying kinetics modeling was conducted according to (RICHTER REIS; IVAHASHI; GUÉNIAT ROSA, 2017): moisture content was expressed as moisture ratio (MR), calculated according to Eq. 1.

$$MR(t) = \frac{M(t) - M_e}{M_o - M_e} \qquad (1)$$

Where

$MR(t)$ is the moisture ratio at time t (s), and $M(t)$, M_e, and M_o (g water/g dry matter) are the moisture content at time t, equilibrium and time zero, respectively. Three thin-layer drying kinetics models were evaluated on the fitting to the experimental data: the models of Henderson-Pabis (Eq. 2) (HENDERSON; PABIS, 1961), Newton (Eq. 3) (LEWIS, 1921), and Page (Eq. 4) (PAGE, 1949).

$$MR(t) = a * \exp(-k\,t) \qquad (2)$$

$$MR(t) = \exp(-k\,t) \qquad (3)$$

$$MR(t) = \exp(-k\,t^n) \qquad (4)$$

Where

a, *k* (s^{-1}) and *n* are the models' constants. The models' fitting was conducted in the software Excel, by minimizing the objective equation (Eq. 5).

$$RMSD = 100 * \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR^{calc} - MR^{exp})^2} \tag{5}$$

Where

RMSD (%) is the root mean square deviation, *N* is the number of experimental points, and MR^{calc} and MR^{exp} are the calculated and experimental moisture ratio, respectively.

Effective moisture diffusivity was determined by applying Fick's law (Eq. 6), which is simplified to Eq. 7 by assuming a conformation of the leaves as infinite flat slabs.

$$\frac{\partial C_A}{\partial t} = -D_{AB}\,\nabla^2 C_A \tag{6}$$

$$\frac{\partial C_A}{\partial t} = D_{eff}\,\frac{\partial^2 C_A}{\partial z^2} \tag{7}$$

Where

C_A is the concentration of solute *A*, D_{AB} is the diffusivity coefficient of *A* in *B*, and D_{eff} ($m^2\,s^{-1}$) is the effective diffusivity of *A*.

When considering no volume changes, uniform moisture distribution, and negligible external resistance, Eq. (7) can be represented by Eq. (8) (CRANK, 1975):

$$MR(t) = \frac{8}{\pi^2}\sum_{n=o}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\,\pi^2\,\frac{D_{eff}\,t}{L^2}\right] \tag{8}$$

Where

n is a positive integer, and L (m) is the thickness of the slab.

When considering the whole drying kinetics data, Eq. (8) can be simplified by truncating its summation in the first term, resulting in Eq. (9) (RICHTER REIS; IVAHASHI; GUÉNIAT ROSA, 2017), which can be linearized to Eq. 10.

$$MR(t) = \frac{8}{\pi^2} \exp\left(-\frac{D_{eff}\,\pi^2\,t}{L^2}\right) \tag{9}$$

$$\ln\left(\frac{\pi^2\,MR(t)}{8}\right) = -\frac{D\,\pi^2}{L^2}t \tag{10}$$

The effective diffusivity coefficient of MWD at the different powers was determined by fitting Eq. (10) to the experimental data.

2.5 ECONOMIC ANALYSIS

An economic analysis was conducted to evaluate the economic viability of the microwave assisted drying process for the YM leaves. For the economic analysis, the following assumptions were made:

a. A medium-sized agribusiness for the microwave assisted drying of the YML was installed in the dependencies of the yerba mate producer's association in Três Barras, Santa Catarina, Brazil;
b. The agribusiness operates for 8 h/day, 300 day/year;
c. The agribusiness processes 10, 50 or 100 kg YM leaves/h;
d. All values used in the present study are in US dollar (US$), with a conversion rate of 4.87 R$/US$.

The economic analysis was conducted according to (KUSUMA; IZZAH; LINGGAJATI, 2023), considering the Rate of Return of Investment (ROI) as the main response variable. Equipment cost was determined considering the drying kinetics, a final moisture content of 10 % (wet basis), and a scale-up coefficient of 1,000 US$ per kilowatt of microwave power estimated for the industrial plant (RADOIU, 2020). The expressions for the estimation of each parameter are presented in Tables 3 – 4.

3 RESULTS AND DISCUSSION

3.1 PHYSICOCHEMICAL CHARACTERIZATION

Firstly, yerba mate leaves (YML) were characterized on their average *in natura* moisture (61.45 ± 0.59 g water/100 g leaf, 1.595 ± 0.040 g water/g dry matter). Such high water content, associated with the presence of enzymes such as polyphenoloxidase and peroxidase present in the leaves (NABECHIMA et al., 2014), reiterate the importance of drying the material and inactivating the enzymes for the preservation of the final product. The leaves presented an average thickness of 0.50 ± 0.06 mm (n = 60), which is an important parameter on the modelling of the mass transfer during the drying phenomenon.

To determine the best drying method among the evaluated ones in this study, the fully-dried yerba mate leaves on each technique (OD60, OD105, and MWD) were used on the evaluation of the color. The results are presented in Table 1.

As previously reported (TOMASI et al., 2021), the microwave drying technique maintains the most the color of the *in natura* yerba mate leaves, with the lowest total color difference for both adaxial and abaxial sides (ΔE equal to 13.54 and 9.28, respectively). MWD also maintains the leave’s green color (negative values of the *a* parameter), which is an important factor when considering the customer’s acceptance of mate leaves (NABECHIMA et al., 2014), while OD60 and OD105 promoted an increase on the red color (positive values of the *a* parameter). That being considered, the study on the drying kinetics and the economics analysis are essential on evaluating the economic viability of the process.

Table 1. Color characterization on the *in natura* and fully-dried yerba mate leaves on different drying techniques.

Sample	*In natura* leaves	OD60	OD105	MWD
a. Color parameters				
Adaxial side				
a	-9.71	-1.64	6.60	-6.40
b	22.55	13.35	15.93	26.28
L	36.53	45.21	36.42	49.13
ΔE*	-	15.00	17.60	13.54
Abaxial side				
a	-8.94	-0.11	3.43	-5.70
b	28.51	22.94	26.27	32.39
L	52.84	48.04	51.80	60.62
ΔE*	-	11.49	12.61	9.28

Drying techniques evaluated: oven drying at 60 °C – OD60; oven drying at 105 °C – OD105; and microwave assisted drying – MWD. ΔE* was calculated considering *in natura* yerba mate leaves as reference. Source: The Authors, 2024.

3.2 DRYING KINETICS

To the best understanding of the microwave assisted drying mechanism of yerba mate leaves, different mathematical models were evaluated. Table 2 presents the estimated coefficients (*a*, *k*, and *n*) and the root mean square deviation (*RMSD*) for the kinetics models fitted to the experimental data at the three microwave powers used in the study (675, 945, and 1,215 W).

Table 2. Estimated coefficient and error of the kinetics models fitted to the experimental data on the microwave assisted drying of yerba mate leaves.

Kinetic model	Parameter	Power (W)		
		675	945	1,215
	M_e (g water/g dry matter)	0.1546	0.1473	0.0842
Henderson-Pabis	a	1.041	1.063	1.067
	k (s^{-1})	0.026	0.029	0.031
	RMSD (%)	2.88	3.94	4.81
Newton	k (s^{-1})	0.025	0.028	0.029
	RMSD (%)	3.34	4.70	5.59
Page	k (s^{-1})	0.016	0.010	0.008
	n	1.129	1.276	1.337
	RMSD (%)	2.43	1.55	1.04
Diffusion	D ($m^2\ s^{-1}$)	5.72E-10	8.00E-10	1.06E-09
	R^2	0.982	0.996	0.978

M_e is the equilibrium moisture, *a*, *k*, and *n* are the models' coefficients, and *RMSD* is the root mean square deviation. Source: The Authors, 2024.

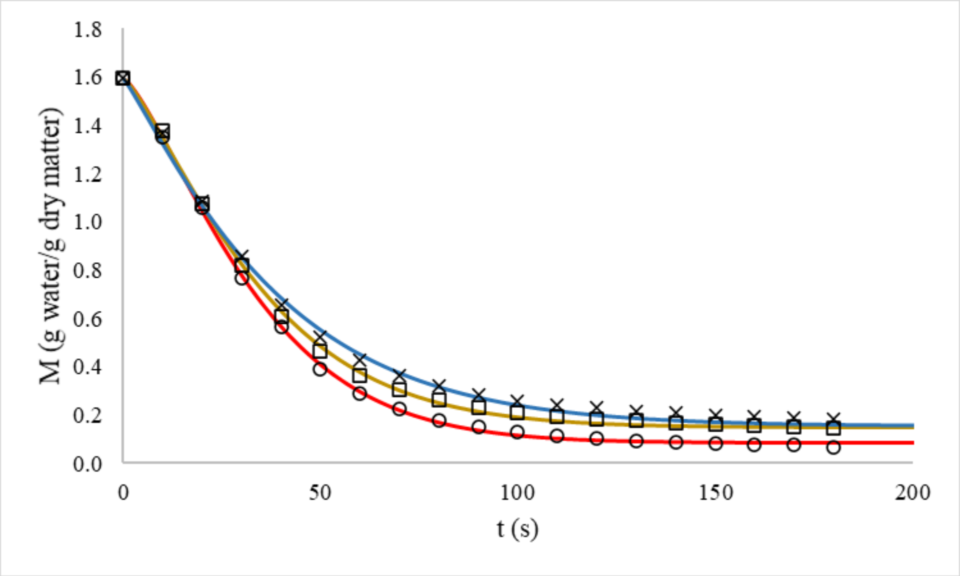
Page’s kinetics model showed the best fitting results for all evaluated drying conditions (675 – 1,215 W), with the lowest RMSD. Such result indicates that, regardless of the power utilized on the microwave assisted drying of yerba mate leaves, Page’s mathematical model fits well to the experimental data.

The different powers evaluated in the microwave assisted drying of the yerba mate leaves resulted in different equilibrium moisture contents (0.0842 – 0.1546 g water/g dry matter), which is reflected in the wet basis moisture content of the products obtained. Not all the dried yerba mate leaves obtained after drying under the three powers (675, 945, and 1,215 W) presented a wet basis moisture contents lower than 10 % (13.39, 12.84, and 7.77 %, respectively), which is an important parameter for the commercialization of the product (Brazil, 1998).

Although the powers of 675 and 945 W did not achieve the desired moisture content for the commercialization of the dried yerba mate, the yerba mate leaves obtained after MWD in these conditions presented no darkening and maintained the green color of the *in natura* leaves, which suggests that the MWD at such powers can be utilized as an alternative pre-drying step for the *sapeco*. The MWD at 1,215 W, on the other hand, can be utilized as a substitute to the whole conventional YML drying method at a single equipment.

Experimental data and the fitted Page’s kinetics model curves are shown in Figure 2. The moisture content decreases rapidly until an equilibrium-like state is reached. The increase on the microwave power results in an increase on the drying rates, which is induced by observing the inclination of the kinetics curves.

Figure 2. Microwave assisted drying kinetics of yerba mate leaves at 675 W (x, blue line), 945 W (□, yellow line), and 1,215 W (○, red line).



Source: The Authors, 2024.

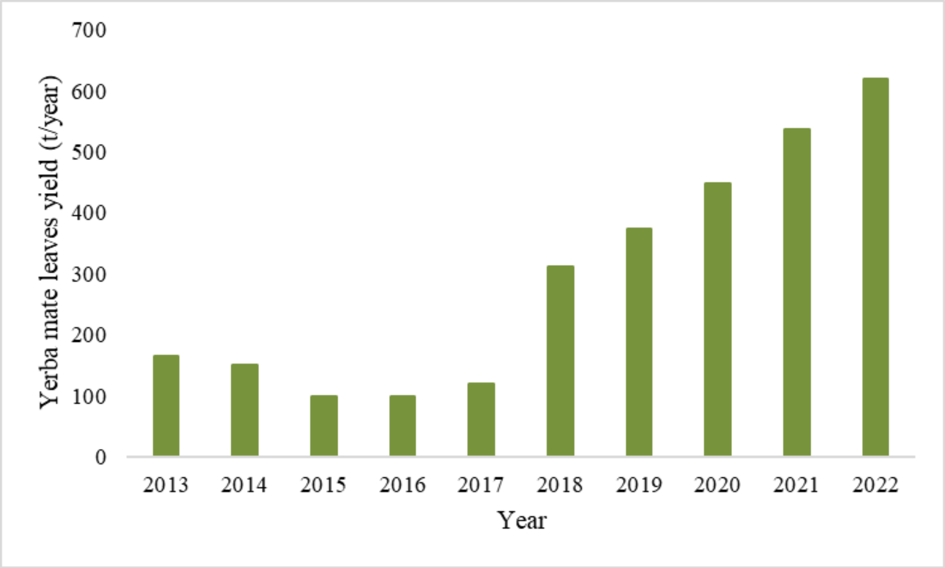
3.3 ECONOMIC ANALYSIS

Once the microwave assisted drying kinetics of the yerba mate leaves are known, it is possible to perform an economic analysis, in order to determine if the studied process is economically viable. The business goal considered for the analysis was to produce dried yerba mate leaves (wet basis moisture of 10 %) using the microwave assisted drying technique. Considering the previously obtained kinetics, such moisture content is achieved only using the power of 1,215 W, and the required time to achieve it, considering the estimated parameters on the Page's kinetics model fitting, is equal to 103 s.

The economic analysis was conducted according to (KUSUMA; IZZAH; LINGGAJATI, 2023), by calculating the Total Capital Investment (TCI, Table 3), composed by the Fixed Capital Investment (FCI) and the Working Capital Investment (WCI), and the Total Production Cost (TPC, Table 4), obtained by the sum of the General Expenses (GE) and the Manufacturing Cost (MC). Finally, the product selling price (Table 5) was estimated for different Rates of Return of Investment (ROI).

The plant location (Três Barras, SC, Brazil) for this simulation was chosen due to the crescent yield of yerba mate over the last years (Figure 3), and the existence of a yerba mate producers' association in the region.

Figure 3. Yerba mate leaves yield through the last ten years (2013 – 2022) in the county of Três Barras, SC, Brazil.



Source: Data retrieved from (IBGE).

The YML inlet of 10, 50, and 100 kg YML/h for the simulation were specified, and they represent an annual processing of 24, 120, and 240 t YML/year, which represents 3.9, 19.3, and 38.7 %, respectively, of the YML yield in the year of 2022 in the municipality of Três Barras.

Total Capital Investment (TCI, Table 3) is the amount of money required to establish and operate a plant. It consists of the sum of the Fixed Capital Investment, capital needed to supply all the necessary plant facilities, and the Working Capital Investment, capital related to the operation of the plant (TIMMERHAUS; PETERS; WEST, 2004). The estimated TCI for the MWD of YML varies according to the amount of yerba mate leaves processed due to the required size for the equipment, and it is the lowest when processing 10 kg/h (92,701 US$).

Table 3. Estimated capital investment.

No	**Component**	**Estimating expression**	**Cost (US$)**		
			10 kg/h	**50 kg/h**	**100 kg/h**
		a. Direct cost			
1	Equipment cost (E)		35,235	173,745	347,490
2	Tool installation cost	0.30 * E	10,571	52,124	104,247
3	FOB fee (F)		45,806	225,869	451,737

4	Insurance fee	0.01 * F	458	2,259	4,517
5	Facility service fee	0.40 * E	14,094	69,498	138,996
6	Total direct cost (D)		60,358	297,625	595,250
		b. Indirect cost			
1	Engineering (Eng)	0.32 * E	11,275	55,598	111,197
2	Contingency	0.10 * (D+Eng)	7,163	35,322	70,645
3	Total indirect cost (I)		18,438	90,921	181,842
c. Fixed capital investment (FCI)		D + I	**78,796**	**388,546**	**777,092**
d. Working capital investment (WCI)		0.15 * TCI	**13,905**	**68,567**	**137,134**
e. Total capital investment (TCI)		FCI + WCI	**92,701**	**457,113**	**914,226**

Costs estimated for the processing at 1,215 W. Source: The Authors, 2024.

The Total Production Cost (TPC, Table 4), on the other hand, represents the annual costs to maintain the plant working. It involves the General Expenses, which represents the administrative, distribution and marketing, and research and development expenses, and the Manufacturing Cost, which represents all the expenses directly associated to the plant operating, such as the raw material buying, fixed charges, electricity, and payroll (TIMMERHAUS; PETERS; WEST, 2004). Similarly to the TCI, the TPC is the lowest at the highest lowest YML inlet of 10 kg/h (116,339 US$/year).

Table 4. Estimated production cost.

No	Component	Estimating expression	Cost (US$/year)		
			10 kg/h	**50 kg/h**	**100 kg/h**
		a. General expenses			
1	Administration cost	0.03 * TCI	2,781	13,713	27,427
2	Distribution and marketing cost	0.05 * TCI	4,635	22,856	45,711
3	Other expenses	0.05 * TCI	4,635	22,856	45,711
4	Total general expenses (GE)		12,051	59,425	118,849
		b. Direct manufacturing cost			
1	Raw material (RM)		72,000	360,000	720,000
2	Labor (L)		7,538	7,538	7,538
3	Maintenance	0.02 * FCI	1,576	7,771	15,542
4	Electricity		6,726	33,168	66,336

5	Total direct manufacturing cost (DMC)		87,841	408,477	809,416
c. Indirect manufacturing cost					
1	Payroll overhead	0.15 * L	1,131	1,131	1,131
2	Plant overhead	0.50 * L	3,769	3,769	3,769
3	Total indirect manufacturing cost (IMC)		4,900	4,900	4,900
d. Fixed manufacturing cost					
1	Depreciation	0.10 * FCI	7,880	38,855	77,709
2	Taxes	0.01 * FCI	788	3,885	7,771
3	Packaging	0.04 * RM	2,880	14,400	28,800
4	Total fixed manufacturing cost (FMC)		11,548	57,140	114,280
e. Manufacturing cost (MC)		**DMC + IMC + FMC**	**104,288**	**470,517**	**928,597**
f. Total production cost (TPC)		**GE + MC**	**116,339**	**529,942**	**1,047,446**

Costs estimated for the processing at 1,215 W. Source: The Authors, 2024.

Finally, after considering the estimated TCI and TPC, the required selling price of the products was calculated to achieve different Rate of Return of Investment (ROI) scenarios of 10, 20 and 100 %, which results in an investment return time of 10, 5 and 1 year, respectively. The investment return time is an important parameter, for it represents the time required for the plant to pay its FCI.

Although the plant for the processing of the highest inlet of YML (100 kg/h) requires the highest investment in both TCI and TPC, it also results in the highest yield of product, and it requires, consequently, the lowest selling price for the same ROI: the required selling prices for the different inlet YML (10, 50, and 100 kg/h) to achieve a ROI of 10 % are 12.30, 11.28, and 11.16 US$/kg.

Such association of the required selling price and the YML inlet is also observed for the different ROI (50 and 100 %), with the lowest required selling price for the highest YML inlet. The relative difference, however, decreases with the increase on the ROI: the relative difference of the required selling price for the processing of 100 kg YML/h and 50 kg YML/h is 1.1, 1.0 and 0.6 % for the ROI of 10, 50 and 100 %, respectively.

Table 5. Estimated product price for different Rate of Return of Investment (ROI) and inlet mass flow scenarios.

ROI (%)	Parameter	10 kg/h	50 kg/h	100 kg/h
10	Selling price (US$/kg)	12.30	11.28	11.16
	Profit after taxes (US$/year)	7,880	38,855	77,709
20	Selling price (US$/kg)	13.28	12.25	12.13
	Profit after taxes (US$/year)	15,759	77,709	155,418
100	Selling price (US$/kg)	21.15	20.00	19.88
	Profit after taxes (US$/year)	78,796	388,546	777,092

Product prices estimated for the processing at 1,215 W. Source: The Authors, 2024.

As expected, the required selling price for the dried yerba mate leaves increases with the increasing of the ROI: for the processing of 100 kg/h, the required selling price is equal to 11.16, 12.13, and 19.88 US$/kg for the ROI of 10, 20 and 100 %, respectively. When compared to the roasted yerba mate selling price of 19.99 – 33.50 R$/kg (4.10 – 6.88 US$/kg) (MANUFACTURERS, 2024), the microwave dried yerba mate presents a considerably higher price. This higher price, however, must be competitive when considering the higher quality of the product's chemical composition, with the maintenance of its bioactive compounds and the absence of the PAHs and ATQ, which are associated to the *sapeco*-step on the conventional drying mechanism.

4 CONCLUSIONS

The present study presents the kinetics for the microwave assisted drying (MWD) of yerba mate leaves (YML) at different powers (675, 945, and 1,215 W). MWD resulted in small changes to the leaves' color when compared to the *in natura* ones, with a high conservation of the green color. The kinetics model with the best fitting to the experimental data was Page's thin-layer model, which presented the lowest RMSD values (1.04 – 2.43 %).

Different microwave power results in different drying rates and equilibrium moisture of the yerba mate leaves: the highest power promotes a faster drying and results in a wet basis moisture of 7.77 %, value acceptable for the commercialization of dried yerba mate leaves according to Brazilian legislation, whereas the lowest powers promote a slower drying and result in an equilibrium moisture content higher than the upper limit presented in the legislation. Such results suggest that the MWD at 1,215 W is an alternative substitute for the whole conventional drying process of YML, while the MWD at 675 and 945 W are potential substitutes for the pre-drying *sapeco*-step.

Economic viability of a MWD plant for the processing of YML was evaluated at different scenarios, and a required selling price of 19.88 US$/kg dried YML was achieved when processing 100 kg YML/h with a rate of return of investment of 100 %, which implies in a time of investment return of 1 year. Such price is approximately 3 times the commercial price of conventional dried yerba mate, but the final product presents physicochemical attributes of higher quality, with the maintenance of the in natura leaves' color and the absence of carcinogenic compounds.

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