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Infrared radiation drying of *Moringa oleifera* grains for use in water treatment

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ABSTRACT: This study aimed to evaluate the effects of using infrared radiation in the hot-air drying of *Moringa oleifera* grains on the inner dryer and grain temperatures, energy consumption, and grain quality. An experiment was conducted in a factorial scheme in 2013 to identify the optimum values of the air temperature (30 to 58 ºC) and infrared radiation application time (2.0 to 4.8 min) on moisture content, drying time, drying rate, inner dryer air temperature, grain temperature, energy consumption and quality of grains used as a natural coagulant for water treatment. The results obtained were moisture content from 4.40 to 4.76% wet basis; drying time from 0.50 to 2.00 h; drying rates from 0.70×10^{-3} to 2.05×10^{-3} kg_{water} $kg^{-1}_{dry\ matter}$ min^{-1}; inner dryer air temperatures from 42.24 to 61.82 ºC; grain temperatures from 56.32 to 76.19 ºC; energy consumptions of the fan from 0.05 to 0.20 kWh, electrical resistances from 1.41 to 4.49 kWh; resistances of the infrared heaters from 0.48 to 1.56 kWh; water turbidities from 1.36 to 5.76 NTU; grain protein contents from 34.93 to 37.93%; and peroxide value of grains from 0.009 to 0.052 meq kg^{-1}. Both evaluated factors increased the inner dryer air temperature and grain temperature. The electrical resistances contributed the most to the energy consumption. However, the infrared radiation reduced this consumption. The drying performed with air temperature of 44 °C and infrared radiation time of 3.4 min resulted in the highest protein concentration in the *Moringa oleifera* L. grains and in greater removal of the water turbidity in the water treatment.

Key words: convective drying, energy consumption, water turbidity, natural coagulant

Secagem com radiação infravermelha de grãos de *Moringa oleifera* para utilização em tratamento de água

RESUMO: Este estudo teve como objetivo avaliar os efeitos da utilização da radiação infravermelha na secagem convectiva de grãos de *Moringa oleifera* sobre a temperatura no secador e no grão, consumo de energia e qualidade dos grãos. Um experimento no esquema fatorial foi conduzido em 2013 para determinar os valores ótimos da temperatura do ar (30 a 58 ºC) e do tempo de radiação infravermelha (2,0 a 4,8 min) sobre as respostas: teor de água, tempo e taxa de secagem, temperatura no secador e no grão, consumo de energia, e qualidade dos grãos usados como coagulante no tratamento de água. Os resultados obtidos foram: teor de água (4,40 a 4,76% b.u.), tempo de secagem (0,50 a 2,00 h), taxa de secagem (0,70 x 10^{-3} a 2,05 x 10^{-3} $kg_{água}$ $kg^{-1}_{matéria\ seca}$ min^{-1}), temperatura dentro do secador (42,24 a 61,82 ºC), temperatura do grão (56,32 a 76,19 ºC), consumo de energia do ventilador (0,05 a 0,20 kWh), resistências elétricas (1,41 a 4,49 kWh), resistências do aquecedor (0,48 a 1,56 kWh), turbidez da água (1,36 a 5,76 NTU), teor de proteína dos grãos (34,93 a 37,93%), e índice de peróxido dos grãos (0,009 a 0,052 meq kg^{-1}). Ambos os fatores avaliados aumentaram a temperatura no secador e nos grãos. O maior consumo de energia foi devido às resistências elétricas. Por outro lado, a radiação infravermelha diminuiu esse consumo. A secagem realizada com temperatura do ar de 44 ºC e tempo de radiação infravermelha de 3,4 min proporcionou maior teor de proteína nos grãos e maior remoção da turbidez no tratamento de água.

Palavras-chave: secagem convectiva, consumo de energia, turbidez de água, coagulante natural

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Introduction

The combined use of infrared radiation and hot-air drying is more effective than using them alone because of the synergistic effect (Puente-Díaz et al., 2013). This is because the infrared radiation directly heats the product, with little heat losses to the surrounding air, which leads to high energy efficiency and low drying time due to high heating rates. The convection-heated air removes the evaporated water and replaces the saturated air by drying the air with a high specific volume (Sakai & Mao, 2006; Kocabiyik, 2011).

Moringa oleifera L. is a multiple-use plant (Mendieta-Araica et al., 2011; Alabi et al., 2017); one of its main use is on water clarification. Studies have reported that the grains of this species are a potential alternative to chemical coagulants for water clarification (Lédo et al., 2009). This is due to their benefits, such as biodegradability, low toxicity, low rate of residue production (Madrona et al., 2012), and no significant effects on water pH and electrical conductivity after treatment (Ndabigengesere et al., 1995).

Water clarification is usually performed using *M. oleifera* extracts combined with coagulation, flocculation, sedimentation, and/or filtration processes. *M. oleifera* grains are subjected to drying, prior to milling process, to obtain a grain powder for preparation of the coagulant solution. However, studies on drying conditions and their effects on quality of *M. oleifera* grains as natural coagulant for water treatment are scarce in the literature.

The objective of the present study was to evaluate the effects of air temperature and application time of infrared radiation on *Moringa oleifera* grains subjected to drying process, considering their maximum response of drying efficiency, energy consumption, and use of these grains as a natural coagulant for water treatment.

Material and Methods

The experiment was performed in 2013 at the Drying Laboratory of the Faculdade de Engenharia Agrícola of the Universidade Estadual de Campinas, Campinas, SP, Brazil (22º 48' 57" S, 47º 3' 33" W, and altitude of 640 m). *Moringa oleifera* grains were harvested in the experimental field of the University, with initial moisture content of 9.40% wet basis.

A 2^2 central composite rotatable design with two factors was used to define the drying conditions. The factors were: drying air temperature (T) and infrared radiation application time (t), including four axial points and three repetitions at the central point, totaling eleven trials (Table 1).

The dryer used consisted of a cylindrical chamber equipped with a centrifugal fan (2.2 kW, WEG, Brazil), electrical resistance (6 kW), and infrared radiant heater (4500 W, CQZ model 10, Corel, Brazil), with an energy flux of 0.75 W cm^{-2}, which was placed at the top of the dryer chamber at a fixed height of 0.42 m in relation to the sample tray.

Sensors were installed inside the grain layer and inside the drying chamber to evaluate the increases in the dryer and grain temperatures due to the use of infrared radiation. The dryer temperature was monitored using type T thermocouples and grain temperature was monitored with type J thermocouples (TFIR 005, Omega Engineering, Brazil), both connected to a data acquisition system (FieldLogger, TECNAL, Brazil).

Analyzers of electrical magnitude with mass memory were installed at each component of the dryer to measure energy consumption. The electrical parameters of the infrared and electrical resistance were measured using a multimeter (Mult-K Plus, Kron, Brazil), and the Landis & Gyr meter (SAGA 4000 model, ESB/Brazil) was used to measure the fan energy.

The drying operations were carried out with air velocity of 0.93 m s^{-1}, infrared radiant heater power of 4500 W, air temperature and infrared radiation application time according to the trials (Table 1). Samples were evenly distributed in a thin layer on a perforated metal tray (0.30 x 0.60 m). Each sample weighed 50 ± 1 g; weight loss was monitored by weighing the samples with 15-min intervals.

For the drying procedures, the fan and electrical resistances were adjusted to heat the air up to the temperature established for the experiment (Table 1). After the air temperature stabilizes, a thin layer of grains was manually placed on the perforated tray inside the dryer. Then, the dryer was closed and infrared radiant heaters were manually activated for the time set in the trials (Table 1). Subsequently, the radiant heaters were turned off and, after 15 min, the grains were weighed to evaluate the decreases in moisture content in the samples. This procedure was repeated until the moisture content reached 4.5% (w.b.), which is the suitable grain moisture for the storage of this product.

The evaluated response variables to the drying processes were: moisture content, drying time, and drying rate. The water turbidity, grain protein content, and peroxide value of grains were used as parameters to evaluate the quality of the *M. oleifera* grains. The air and grain temperatures were used to assess the temperature inside the chamber and inside the grain layer. The energy parameters evaluated were: power consumptions of the fan, electrical resistances, and infrared heaters.

Moisture content was determined gravimetrically at the beginning and at the end of the drying experiments by oven drying method at 105 ± 3 °C for 24 h.

Protein concentration of *M. oleifera* grains without the tegument and in powdered form was determined by the Kjeldahl method 960.52 (AOAC, 1998). Grain oxidation was

Table 1. Trials used to evaluate the drying of *Moringa oleifera* grains, considering real and encoded values of the air temperature and infrared radiation application time factors

Trial	Air temperature (ºC)	Infrared application time (min)
1	34 (-1)	2.4 (-1)
2	54 (+1)	2.4 (-1)
3	34 (-1)	4.4 (+1)
4	54 (+1)	4.4 (+1)
5	30 (-1.41)	3.4 (0)
6	58 (1.41)	3.4 (0)
7	44 (0)	2.0 (-1.41)
8	44 (0)	4.8 (+1.41)
9	44 (0)	3.4 (0)
10	44 (0)	3.4 (0)
11	44 (0)	3.4 (0)

evaluated by determining the peroxide value, according to the methodology described by Partanen et al. (2008).

After drying, the teguments were manually removed, and the grains were milled to obtain a powder, which was used to prepare the coagulant solution. Synthetic turbid water with 60 NTU (nephelometric turbidity units) was treated with the coagulant solution in static reactors (Jar-Test), using coagulation, flocculation and sedimentation processes. Treated samples were collected during sedimentation process to evaluate the water turbidity.

The coagulant solution (2% m/v) was prepared by dissolving 2 g of *M. oleifera* grain powder in 100 mL of distilled water. The mixture was homogenized for 2 min and filtered through a 125 µm mesh sieve (Arantes et al., 2014). The turbid water (60 NTU) was prepared by adding 3.2 g of bentonite in a container with 16 L of deionized distilled water, resulting in a concentration of 200 mg L^{-1}. The solution was stirred with velocity gradient of 400 s^{-1} for 30 min and left to rest for 24 h. Then, the supernatant was removed carefully, thus, obtaining the synthetic turbid water (Arantes, 2010).

Coagulation, flocculation and sedimentation assays were performed in static reactors (Jar-Test) to determine the efficiency of the solutions from the dried grains. The coagulant dosage was 10 mL L^{-1} of the 2% solution for initial turbidity of 60 NTU. During the treatment of the synthetic turbid water, the coagulation assay was performed at an average velocity gradient of 400 s^{-1} and rapid mixing for 60 s, while flocculation was performed at a velocity gradient of 40 s^{-1} and slow mixing for 10 min (Arantes, 2010).

The sedimentation consisted of a 60 min rest period and, then, water samples were collected to determine their residual turbidity. The remaining turbidity of the samples collected during sedimentation was determined by nephelometry, using a turbidimeter (2100 NA model, HACH).

The statistical analysis was performed using the Statistica 9.0 software, with application of the analysis of variance and regression. Experimental data were adjusted to a second-order polynomial equation, as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \quad (1)$$

where:

y - response;
β_0 - constant regression coefficient;
β_1 and β_2 - linear regression coefficients;
β_{11} and β_{22} - quadratic regression coefficients;
β_{12} - interaction regression coefficient; and,
x_1 and x_2 - coded values of the factors.

Results and Discussion

All the equations are presented in terms of encoded levels of the factors. Thus, the encoded values of the factors must be replaced in the equation to obtain the response. The real values of the factors can only be inserted in the real equations.

Figure 1 shows the temperature behavior inside the dryer and in the grains in the trials 1 and 8. The peaks coincide with the periods of infrared radiation application, which occurred intermittently at intervals of 15 min, and with a specific duration for each trial (Table 1). Different periods of radiation application affected the drying process, raising the inner dryer air temperature and, mainly, inside the layer of grains (Figure 1) since, according to the optics laws, infrared radiation passes through air and is absorbed by the product (Sakai & Mao, 2006).

The average air temperature was higher when using the infrared radiation, ranging from 2.16 °C (trial 2) to 14.63 °C (trial 3) when compared to the drying temperature provided by the electrical resistance (trial 2 = 54 °C and trial 3 = 34 °C) (Tables 1 and 2). The major differences between these temperatures were observed when longer infrared application times combined with lower air temperatures were used (trials 3, 5 and 8).

The average grain temperature (Table 2) was higher with the application of infrared radiation, which varied from 13.88 °C (trial 2) to 34.82 °C (trial 3) when compared to the initial drying air temperature. The highest grain temperature (trial 3 = 68.82 °C, trial 5 = 58.90 °C and trial 8 = 73.22 °C, Table 2) was found in the trials with lower air temperature and longer infrared radiation application times (trial 3 = 34 °C and 4.4 min, trial 5 = 30 °C and 3.4 min, trial 8 = 44 °C and 4.8 min, Table 1).

The increase in air and grain temperature due to the application of infrared radiation, as previously described, caused an increase of the drying rate, with consequent reduction of drying time and energy consumption (Table 2).

Table 3 presents the linear, quadratic and interaction effects of the air temperature and infrared application time. The linear effects of the both factors and the quadratic effect of the infrared application time were significant for the inner dryer air temperature ($p \leq 0.05$). Regarding grain temperature,

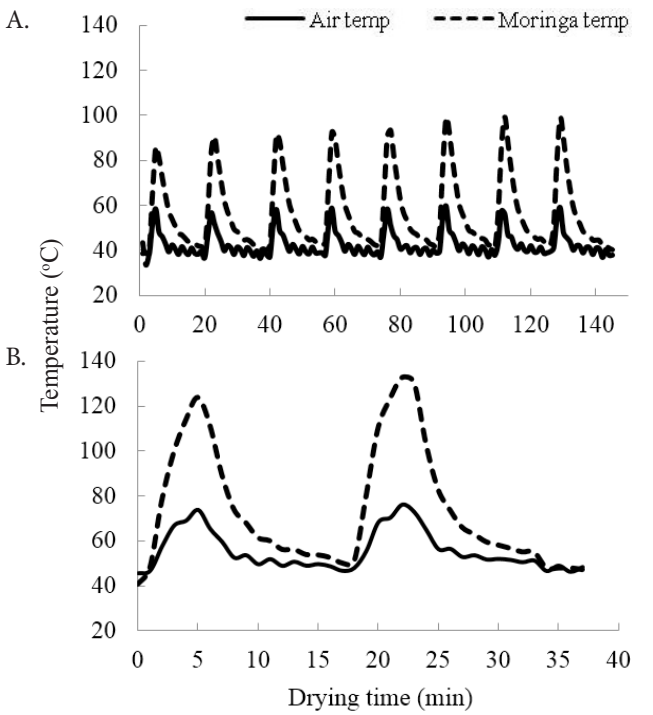

Figure 1. Inner dryer temperature (Air temp) and grain temperature (Moringa temp) in the experimental trials 1 (A) and 8 (B), as function of drying time

Table 2. Mean values of inner dryer temperature and grain temperature, energy consumption, moisture content, drying time, drying rate, grain protein content, water residual turbidity and peroxide value of grains in the trials evaluated

Trial	Inner dryer temperature (°C)	Grain temperature (°C)	Energy (kWh)	Moisture content (% w.b.)	Drying time (h)	Drying rate (kg_{water} $kg_{dry\ matter}^{-1}$ min^{-1})	Protein content (%)	Turbidity (NTU)	Peroxide (meq kg^{-1})
1	42.65	56.32	4.93	4.40	2.00	0.70×10^{-03}	34.93	5.76	0.012
2	56.16	67.88	5.28	4.55	1.00	1.14×10^{-03}	36.33	1.91	0.021
3	48.63	68.82	2.55	4.65	0.75	1.63×10^{-03}	35.80	1.36	0.015
4	60.89	76.19	2.70	4.54	0.50	2.05×10^{-03}	37.06	1.51	0.024
5	42.24	58.90	3.48	4.39	1.50	0.97×10^{-03}	35.65	5.20	0.009
6	61.82	73.79	3.07	4.41	0.50	1.97×10^{-03}	36.62	1.45	0.052
7	50.27	62.59	4.54	4.76	1.25	1.01×10^{-03}	36.85	2.49	0.009
8	55.59	73.22	2.19	4.57	0.50	1.77×10^{-03}	36.19	1.49	0.013
9	51.45	70.45	3.12	4.53	0.75	1.54×10^{-03}	37.93	1.55	0.009
10	49.84	64.14	3.02	4.47	0.75	1.55×10^{-03}	37.19	1.50	0.009
11	50.17	67.29	3.30	4.54	0.75	1.66×10^{-03}	37.66	1.54	0.009

Trial - For description of the trials see Table 1

Table 3. Estimated effects and probability significance (p) of the terms for responses: inner dryer air temperature, grain temperature, energy consumption, drying time, drying rate, protein content, water residual turbidity and peroxide value of grains

Terms	Inner dryer temperature (°C)		Grain temperature (°C)		Energy consuption (kWh)		Drying time (h)		Drying rate (kg $kg^{-1}min^{-1}$)		Protein content (%)		Turbidity (NTU)		Peroxide (meq kg^{-1})	
	Effect	p	Effect	p	Effect	p	Effect	p	Effect	p	Effect	p	Effect	p	Effect	p
Average	50.49	0.00	67.29	0.00	3.15	0.00	0.75	0.00	1.58×10^{-3}	0.00	37.59	0.00	1.53	0.01	0.01	0.07
T (L)	13.36	0.00	10.00	0.00	-0.02	0.961	-0.67	0.00	5.68×10^{-4}	0.00	1.01	0.05	-2.25	0.00	0.02	0.01
T (Q)	1.35	0.11	-0.86	0.67	0.40	0.359	0.31	0.04	-1.38×10^{-4}	0.35	-1.60	0.02	1.78	0.02	0.02	0.02
t (L)	4.56	0.00	8.97	0.00	-2.07	0.002	-0.70	0.00	7.27×10^{-4}	0.00	0.17	0.69	-1.55	0.01	0.00	0.62
t (Q)	2.24	0.02	0.70	0.72	0.49	0.272	0.19	0.17	-2.22×10^{-4}	0.16	-1.22	0.04	0.45	0.41	0.00	0.96
T (L) x t (L)	-0.63	0.49	-2.10	0.39	-0.10	0.842	0.38	0.04	-7.57×10^{-6}	0.97	-0.08	0.90	2.00	0.02	0.00	0.97

T - Drying air temperature; t - Infrared radiation application time; L - Linear term; Q - Quadratic term

the linear terms of the factors presented significant effects. Considering that the effects were positive, the increase in both factors raised the dryer air temperature and grain temperature.

The analysis of variance in Table 4 shows that both dryer and grain temperatures presented significant regressions ($F_{calculated} > F_{tabulated}$), denoting the validation of the models regarding the determination coefficient (R^2). The models explained more than 90% of the variance, thus, it is predictive of the process.

The encoded models for the dryer air temperature and grain temperature during the drying of *M. oleifera* grains are shown by Eqs. 2 and 3. The equations are presented in terms of coded variables.

$$DT = 51.12 + 6.68^{*}T + 2.28^{*}t + 0.92^{*}t^{2} \quad R^{2} = 0.98 \quad (2)$$

$$GT = 67.23 + 4.50^{*}T + 4.48^{*}t \quad R^{2} = 0.92 \quad (3)$$

where:

DT - dryer temperature, °C;

GT - grain temperature, °C;

T - drying air temperature;

t - infrared radiation application time; and,

* - significant at $p \leq 0.05$ by F test.

The dryer components that required electricity were: fan, electrical resistances and radiant infrared heaters. Total electrical energy was calculated for each trial by summing the energy consumptions of the dryer components (Table 2).

The electrical resistance had the greatest contribution to the energy consumption, it was responsible for 50% (trial 5) to 85% (trial 2) of the total energy consumption of the drying experiments, probably due to the power of the electrical resistance (6 kW) and the time they were used to heat the air (Table 2).

The energy consumption of the infrared radiation heaters ranged from 0.48 kWh (trial 6) to 1.56 kWh (trial 5). Considering the percent of the energy consumption of the infrared heaters of each trial, its contribution ranged from 12.88% (trial 2) to 44.83% (trial 5). Therefore, despite the high power (4.5 kW) of the infrared heaters, their short use period generated less energy consumption than the electrical resistance.

The fan was the component that required less electrical energy consumption in all trials. This was due to the low air

Table 4. The F and R^2 values calculated for inner dryer temperature and grain temperature, energy consumption, moisture content, drying rate, drying time, protein content, water residual turbidity and peroxide value of grains

Indexes	Inner dryer temperature	Grain temperature	Energy consuption	Moisture content	Drying rate	Drying time	Protein content	Turbidity	Peroxide
$F_{calculated}$	146.04	45.70	48.77	2.53^{ns}	33.24	22.11	9.92	17.11	22.05
$F_{tabulated}$	4.35	4.46	5.12	5.05	4.46	4.53	4.35	4.53	4.46
R^2	0.98	0.92	0.84	0.72	0.89	0.94	0.81	0.92	0.85

ns - Not significant at $p > 0.05$

velocity (0.93 m s^{-1}), which requires low power (0.086 kW), leading to less energy consumption while remaining engaged throughout the drying test. The energy consumption of the fan, in relation to the total consumption of each trial, varied from 1.73% in trial 6 (0.053 kWh) to 4.11% in trial 5 (0.143 kWh).

The 2, 1 and 7 trials consumed a higher amount of total energy, with values of 5.28, 4.93, and 4.54 kWh, respectively (Table 2). Considering the trials 2 and 7, this may be due to the high air temperature levels (54 and 44 °C, respectively, Table 1). The lower drying air temperature and short application time of infrared radiation in trial 1 increased drying time (2 h), which increased the energy consumption of the process.

The lowest energy consumption was observed in trial 8 (44 °C and 4.8 min); 64.38% from the total energy used (2.19 kWh) was spent on the electrical resistance, 33.79% on infrared radiation, and 2.10% on the fan (Table 2). Therefore, considering the evaluated drying conditions, trial 8 was more effective in drying *M. oleifera* grains, denoting that the combination of the highest air temperature and highest infrared application time leads to a reduction of drying time and a lower energy consumption.

Based on statistical analysis (Table 3), the linear term of the infrared application time was significant to the energy consumption, with a negative effect.

This was a similar result to other studies on infrared radiation drying. Krishnamurthy et al. (2008) reported that the use of infrared radiation for dehydrating foods has numerous advantages, such as use of an alternative energy source, decreasing of the drying time and increased energy efficiency. Wang et al. (2014) carried out an experimental study on drying shredded squid and found that the energy consumption of the hot-air drying was 28% higher than that of the infrared radiation drying. Onwude et al. (2018) used infrared drying on sweet potato and found low energy consumption; they attributed it to the higher heat flux rate and heat transfer coefficient of the infrared radiation drying when compared to the hot-air drying.

The analysis of variance (Table 4) showed that total energy presented significant regression ($F_{calculated} > F_{tabulated}$). The R^2 of the model explained more than 84% of the variability, which is suitable. The model that represents the energy consumption by drying of *M. oleifera* grains is presented by Eq. 4. The equation is presented in terms of coded variables.

$$EC = 3.47 - 1.04^{*} t \qquad R^2 = 0.84 \tag{4}$$

where:

EC - energy consumption, kWh;
t - infrared radiation application time; and,
* - significant at $p \leq 0.05$ by F test.

Similar results were found by Oliveira (2009), who studied the drying of yacon tubers and found that the application of infrared radiation significantly decreased the total energy consumption of the drying. They also observed that the increase in air temperature caused a proportional increase in energy consumption since a longer period for activation of the electrical resistances was required.

The initial grains moisture content was 9.40% (w.b.), which ranged from 4.39 to 4.76% (w.b.) at the end of the drying experiments (Table 2), with no significant difference between trials (Table 4). These results were expected, since the purpose of this study was to perform drying operations to reach moisture content of 4.5% (w.b.).

The lowest drying time (0.5 h) was found in trials 4, 6 and 8, with drying air temperature and infrared application time of 54 °C and 4.4 min; 58 °C and 3.4 min; 44 °C and 4.8 min, respectively. These trials used the highest air temperatures and infrared application times, thus, explaining the reasons of the more rapid drying in these trials when compared to the others. Contrastingly, trial 1 (34 °C and 2.4 min), corresponding to the lowest levels of these factors, required higher drying time (2 h) to achieve the desired grain moisture content (Table 2).

The air temperature and infrared application time were significant ($p \leq 0.05$) for the drying time of *M. oleifera* grains (Table 3). The linear effects of these factors had a negative effect on the drying time. Thus, the increase in both factors affected the reduction of drying time. Nowak & Lewicki (2004) evaluated apple slices dried by infrared radiation and hot-air dryings under similar conditions and found that the process time was reduced up to 50% when infrared energy was used.

The highest drying rate was found in trial 4 (2.05 x 10^{-3} kg_{water} $kg^{-1}_{dry\ matter}$ min^{-1}), which was performed with the highest levels of the factors (54 °C and 4.4 min). Contrastingly, the lowest drying rate was found in trial 1 (0.70 x 10^{-3} kg_{water} $kg^{-1}_{dry\ matter}$ min^{-1}, Table 2), which was carried out using 30 °C and 2.4 min (Table 1). The linear term of the factors was significant and had a positive effect on the drying rate, showing that increasing air temperature and infrared radiation time leads to an increase in the drying rate of *M. oleifera* grains (Table 3). Puente-Díaz et al. (2013) found higher drying rates in the drying of murta berries using infrared radiation when compared to hot-air drying.

The analysis of variance shows that, for drying time and drying rate, the $F_{calculated}$ regression in relation to the residues was higher than the $F_{tabulated}$, denoting the validation of the models. The R^2 of the drying rate and drying time were suitable, since they explained 89 and 94% of the variability, respectively (Table 4).

The encoded models for drying time and drying rate, considering the significant and predictive parameters of each model, are presented in Eqs. 5 and 6, respectively. The equations are presented in terms of coded variables.

$$DT = 0.838 - 0.333^{*} T + 0.129^{*} T^2 - 0.351^{*} t + 0.188^{*} Tt \qquad R^2 = 0.94 \tag{5}$$

$$DR = 1.45\ x10^{-3} + 2.84\ x10^{-4^{*}} T + 3.64\ x10^{-4^{*}} t \qquad R^2 = 0.89 \tag{6}$$

where:

DT - drying time, h;
DR - drying rate, kg_{water} $kg^{-1}_{dry\ matter}$ min^{-1};
T - drying air temperature;
t - infrared radiation application time; and,
* - significant at $p \leq 0.05$ by F test.

The grain protein content ranged from 34.93% (trial 1) to 37.93% (trial 9) (Table 2). This is a similar result to that found

by Compaoré et al. (2011) - 35.37 ± 0.07%. The linear and quadratic effects of the air temperature were significant for grain protein concentration ($p \leq 0.05$); the linear term had a positive effect and the quadratic term had a negative effect. The quadratic term of the infrared application time was also significant ($p \leq 0.05$) on grains protein concentration, with a negative effect (Table 3).

These effects can be graphically explained by the response surface for grains protein content (Figure 2A). Increasing the air temperature to a certain extent (approximately 47 °C) led to an increase in sample protein concentrations, which reduced from that point. Similar result was observed for the infrared application time. Thus, the most favorable condition for grain protein concentration is in the central point region of the experimental design, corresponding to 44 °C and 3.4 min.

Similar results were described by Tejavath & Nadimpalli (2014) and Jain et al. (2019), who presented higher values of protein extraction and enzymatic activity, respectively, at temperature of 50 °C; below 50 °C, protein extraction and enzymatic activity increased with increasing temperature. Increases in temperature are responsible for protein folding and structural changes, which are processes that may have affected the protein concentration.

However, according to Ghebremichael et al. (2005), protein is thermoresistant after treatment for 5 h at 95 °C. A recent study showed a drastic reduction in protein extraction at temperatures from 70 °C (Jain et al., 2019) and in enzymatic activity at temperatures from 80 °C (Tejavath & Nadimpalli, 2014). According to Jain et al. (2019), this is due to protein denaturation.

The residual turbidity of the synthetic water (initial turbidity of 60 NTU) subjected to coagulant solution made with dried *M. oleifera* grains ranged from 1.36 NTU (trial 3) to 5.76 NTU (trial 1) (Table 2); these values correspond to a turbidity removal of 97.7 and 90.4%, respectively. Arantes et al. (2014), used *M. oleifera* grain processed in a machine, followed by powder sieving, and found similar residual turbidity and percentage of removal - 2.18 NTU and 97.89%, respectively.

The effects of the air temperature and infrared radiation application time were significant ($p \leq 0.05$) on residual water turbidity, with a negative effect (Table 3), indicating that an increase in these factors leads to a decrease in water turbidity, which is desired in water treatment systems.

The peroxide value of the grains ranged from 0.009 to 0.052 meq kg^{-1} (Table 2). The statistical analysis showed that the linear and quadratic terms of the drying air temperature was significant, with positive effect on the peroxide values (Table 3); an increase in that factor led to an increase in this variable. This indicates that a small lipid oxidation occurred in grains subjected to drying treatment with high air temperature (trial 6, 58 °C).

Silva & Matos (2008) evaluated the turbidity removal from raw water using four different dispersions of *M. oleifera* grains, with or without tegument and with or without oil, and found higher residual turbidity in samples with oil when compared to those without oil. They concluded that the oil extraction allowed a better solid sedimentation after the coagulation-flocculation stages.

Although the oil was not extracted from the *M. oleifera* grains, lipid oxidation was found in the treatments subjected to high drying air temperatures. In addition, the trials with the highest peroxide values (trials 2, 4 and 6) also had low water turbidity values (1.91 NTU, 1.51 NTU, 1.45 NTU, respectively). This indicates that the lipid oxidation favored solid sedimentation and, therefore, generated a lower residual turbidity (Table 2).

According to the analysis of variance (Table 4), residual water turbidity, grain protein concentration, and peroxide value presented significant regression ($F_{calculated} > F_{tabulated}$), denoting the validation of the models and that the coefficients of determination (R^2) of these variables were suitable, since they explained 92, 81, and 85% of the data, respectively.

Considering the significant and predictive parameters of the model, the Eqs. 7, 8 and 9, showed the encoded models for grain protein content, residual water turbidity and peroxide value of grains, respectively; and Figures 2A and B presented the response surfaces for grain protein concentration and residual water turbidity.

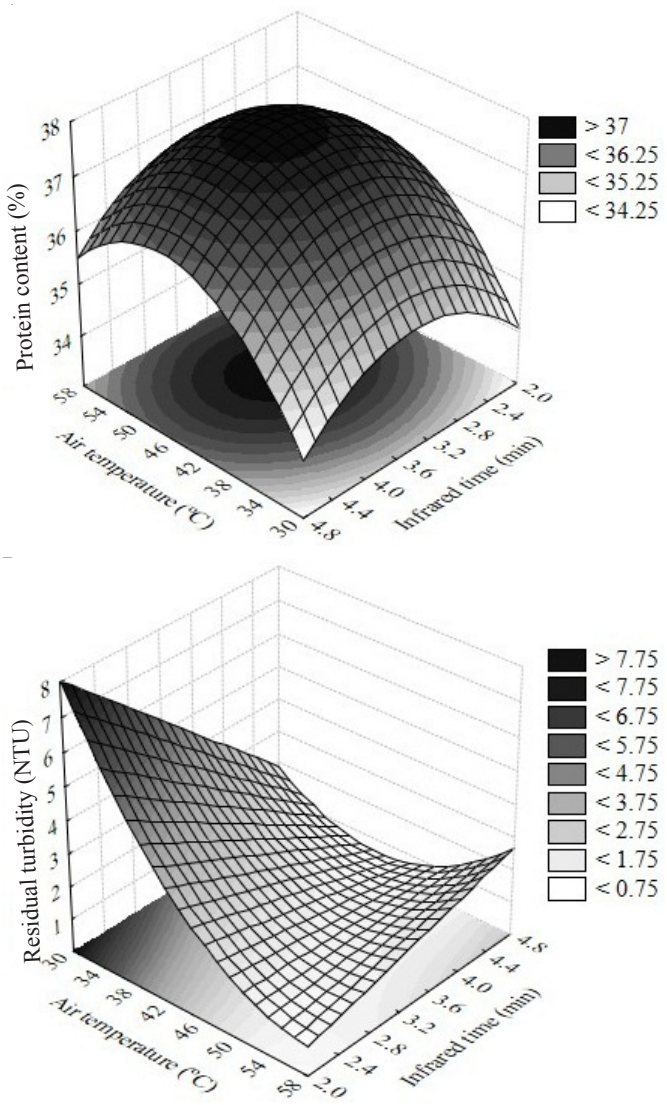

Figure 2. Response surfaces of the grain protein concentration (A, Eq. 7) and residual water turbidity (B, Eq. 8) obtained with dried *Moringa olefeira* grains

$$PC = 37.591 + 0.504^{*}T - 0.801^{*}T^{2} - 0.611^{*}t^{2} \quad R^{2} = 0.81 \quad (7)$$

$$RWT = 1.741 - 1.124^{*}T + 0.824^{*}T^{2} - 0.777^{*}t + 0.999^{*}Tt \quad (8)$$
$$R^{2} = 0.92$$

$$PV = 0.009 + 0.01^{*}T + 0.01^{*}T^{2} \qquad R^{2} = 0.85 \quad (9)$$

where:

PC - protein concentration, %;
RWT - residual water turbidity;
PV - peroxide value, meq kg^{-1};
T - the drying air temperature (°C);
t - the infrared radiation application time (min); and,
* - significant at $p \leq 0.05$ by F test.

Conclusions

1. The application of infrared radiation reduced the total electrical energy consumption of the drying process, and the increase in air temperature led to a proportional increase in energy consumption.

2. The combination of an air temperature of 44 °C and infrared radiation application time of 3.4 min resulted in the highest protein content in grains of *Moringa oleifera*, and provided higher water turbidity removal with use of coagulant solution from dried *M. oleifera* grains.

3. The use of infrared radiation for supplementation of hot-air drying was effective to increase the air and grain temperature, thus, providing lower drying time and energy consumption and higher drying rate.

4. Regarding the quality of *M. oleifera* L. grains, the drying process increases their protein concentration, promoted solid sedimentation due to lipid oxidation and led to a high removal of turbidity from the evaluated synthetic water.

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