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Evaluation of green banana pulp drying using infrared radiation with temperature control

Avaliação da secagem da polpa de banana verde utilizando radiação infravermelha com controle de temperatura

Evaluación del secado de pulpa de plátano verde utilizando radiación infrarroja con control de temperatura

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Euler Cunha Martins
ORCID: https://orcid.org/0000-0002-5240-5793
Centro Federal de Educação Tecnológica de Minas Gerais, Brazil
E-mail: euler@cefetmg.br
Anderson Arthur Rabello
ORCID: https://orcid.org/0000-0003-3510-0813
Centro Federal de Educação Tecnológica de Minas Gerais, Brazil
E-mail: arthur@cefetmg.br
Fátima de Cássia Oliveira Gomes
ORCID: https://orcid.org/0000-0002-5227-3532
Centro Federal de Educação Tecnológica de Minas Gerais, Brazil
E-mail: fatimaog@cefetmg.br
Cleverson Fernando Garcia
ORCID: https://orcid.org/0000-0001-9354-1401
Centro Federal de Educação Tecnológica de Minas Gerais, Brazil
E-mail: cleverson@cefetmg.br

Abstract

The green banana flour (GBF) is a functional food rich in resistant starch and nutrients, probiotic, and has low glycemic index. The obtaining of the flour is usually done in dryers with high energy consumption, and possible deteriorating processes. These problems can be minimized with an adaptive temperature control system in infrared heat sources. The aim of this research was to quantify the energy savings in the production of green banana flour produced by infrared drying compared to the conventional process of drying in a resistance oven. The production of flour from green banana pulp was evaluated using an infrared radiation dryer with fruit surface temperature control (IR-FSTC). The IR-FSTC was performed by keeping the pulp surface at 50 °C and 60 °C. The results were compared with conventional drying using a resistive source. The energy consumption of drying using IR-FSTC was significantly reduced compared to the drying by resistive source and prevented the formation of hotspots. The drying process was also evaluated by physicochemical and spectroscopic analyses of the GBF. The product maintained the pH, titratable acidity, total soluble solids, and lipid content with values similar to those obtained by conventional heating oven drying. In turn, the spectroscopic analyses confirmed the maintenance of biomolecules inherent in GBF. Thus, it is concluded that the results contribute to the sustainable use of energy resources in the production of GBF.

Keywords: Infrared drying; Green banana flour; Product quality; Energy efficiency.

Resumo

A farinha de banana verde (FBV) é um alimento funcional rico em amido resistente e nutrientes, probióticos e apresenta baixo índice glicêmico. A obtenção da farinha é geralmente realizada em secadores com alto consumo de energia, sendo possíveis processos deteriorantes. Esses problemas podem ser minimizados com um sistema adaptativo de controle de temperatura em fontes de radiação infravermelha. Na presente pesquisa, objetivou-se quantificar a economia de energia na produção de farinha de banana verde produzida por secagem por infravermelho em relação ao processo convencional de secagem em estufa de resistência. A obtenção de farinha a partir da polpa de banana verde foi avaliada utilizando um secador de radiação infravermelha com controle de temperatura da superfície da fruta (IV-CTSF). O IV-CTSF foi realizado mantendo a superfície da polpa a 50 °C e 60 °C. Os resultados foram comparados com a secagem convencional usando uma fonte resistiva. O consumo de energia na secagem com IV-CTSF foi reduzido de forma representativa em comparação com a secagem por fonte resistiva e evitou a formação de pontos quentes. O processo de secagem também foi avaliado por análises físico-químicas e espectroscópicas da FBV. O produto manteve o pH, a acidez titulável, os sólidos solúveis totais e o teor de lipídios com valores semelhantes aos obtidos pela secagem convencional em estufa. Por sua vez, as análises espectroscópicas confirmaram a manutenção de biomoléculas inerentes à FBV. Assim, conclui-se que os resultados contribuem para o uso sustentável dos recursos energéticos na produção de FBV.

Palavras-chave: Secagem por infravermelho; Farinha de banana verde; Qualidade de produtos; Eficiência energética.

Resumen

La harina de plátano verde (HPV) es un alimento funcional rico en almidón resistente y nutrientes, probióticos, y tiene un bajo índice glucémico. La obtención de la harina suele realizarse en secadores con un alto consumo de energía y posibles procesos deteriorantes. Estos problemas pueden minimizarse con un sistema de control de temperatura adaptativo en fuentes de calor infrarrojo. El objetivo de esta investigación fue cuantificar el ahorro energético en la producción de harina de plátano verde producida mediante secado por infrarrojos en comparación con el proceso convencional de secado en estufa de resistencia. Se evaluó la producción de harina de pulpa de plátano verde utilizando un secador por radiación infrarroja con control de temperatura de la superficie de la fruta (IR-FSTC). El IR-FSTC se llevó a cabo manteniendo la superficie de la pulpa a 50 °C y 60 °C. Los resultados se compararon con el secado convencional utilizando una fuente resistiva. El consumo de energía durante el secado con IR-FSTC se redujo significativamente en comparación con el secado mediante fuente resistiva y se evitó la formación de puntos calientes. El proceso de secado también fue evaluado mediante análisis fisicoquímicos y espectroscópicos de la HPV. El producto mantuvo el pH, la acidez titulable, los sólidos solubles totales y el contenido de lípidos con valores similares a los obtenidos mediante secado convencional en horno de calor. A su vez, los análisis espectroscópicos confirmaron el mantenimiento de biomoléculas inherentes a la HPV. Así, se concluye que los resultados contribuyen al uso sostenible de los recursos energéticos en la producción de HPV.

Palabras clave: Secado por infrarrojos; Harina de plátano verde; Calidad del producto; Eficiencia energética.

1. Introduction

The banana tree is a plant belonging to the Musaceae Family, including hybrids of the *Musa* genus (Vu et al., 2018). Its fruits are rich in carbohydrates, minerals such as potassium and phosphorus (Zhang et al, 2019) and important bioactive substances such as phenolic compounds, flavonoids, carotenoids, biogenic amines, sterols, and antimicrobial compounds, making this fruit a functional food (Ghag & Ganapathi, 2019).

Banana is classified as a climacteric fruit, highly perishable, that presents high respiration rate and high production of ethylene after harvest (Prill et al., 2012). The quantitative and qualitative losses due to its perishability are significant (Tornizielo et al., 2021). At the green ripening stage, banana is not widely consumed, mainly because of its typical hardness and high astringency, caused by the presence of soluble phenolic compounds, such as tannins (Andrade et al., 2018). This astringency is reduced during the ripening process, when the polymerization of these substances and the degradation of starch occur, leading to an increase in sweetness and tenderness and a reduction in acidity, characteristics of ripe fruit. Consequently, obtaining flours is the main alternative to ensure the use of unripe fruit by the food industry ensuring, including, the reduction of postharvest losses and during transport (Sarawong et al., 2014).

Green banana flour can be obtained by natural or artificial drying (Izli et al., 2017; Aljuhaimi et al., 2016), processes that involve removing water from the raw material, inhibiting microbial growth, and preventing biochemical reactions responsible for its deterioration. In general, drying processes are important methods to extend the shelf life of various products, in addition to reducing transportation, packaging, and storage costs.

The green banana flour shows to be a rich source of minerals such a potassium, phosphorus, magnesium, copper, manganese, and zinc, when compared to other types of flours on the market (Borges et al., 2009). Its soluble and insoluble fibers have several functions in the body, such as the regulation of intestinal function, which acts delaying gastric emptying, besides helping to reduce the levels of cholesterol in the blood and being used as substrate for fermentation by aerobic bacteria in the colon (Waszak & Ferreira, 2011). In this context, resistant starch stands out, resisting hydrolysis in the small intestine, but being fermented in the large intestine by bacterial microbiota (Yue & Waring, 1998).

The flour also contains antioxidants such as flavonoids that act protecting the gastric mucosa (Lewis et al., 1999) and vitamins A and C. Organic acids, such as citric and malic acids also stand out, because they are related to the ripening process of the raw material used in the production of flour (Carvalho et al., 2011).

The efficiency of banana flour production can be increased if forced convection drying is associated with heating by electromagnetic radiation at microwave or infrared frequency. In these processes occurs the phenomenon of direct absorption of radiation by the food components, causing the vibration of molecules and consequently the generation of heat.

In microwave dehydrators the radiation penetrates inside the banana forming hotspots which are points of maximum concentration of electric field and heat. They occur due to the non-linearity of heat absorption by the water contained in the food in response to electromagnetic radiation. Consequently, hotspots impair heating homogeneity and product quality (Thuto & Banjong, 2019).

Infrared radiation (IR), on the other hand, impinges on food surface having small penetration depth, without the need for heat transport through heated air in greenhouses with resistor heating, saving energy (Sakare et al., 2020).

In the present research, it was aimed to quantify the energy savings in the production of green banana flour produced by infrared drying compared to conventional resistor oven drying process. An adaptive system to regulate the power of the heat source to maintain a fixed temperature on the fruit surface was developed to avoid deterioration of the product. Thus, it was possible to obtain drying efficiency compatible with microwave dehydration processes, avoiding the formation of hotspots.

Physicochemical and spectroscopic analyses of the green banana flour produced by infrared drying were performed to verify the quality of the product and its conditions for commercialization.

2. Methodology

Green banana samples

The raw material used was Prata bananas (Pacovan) (*Musa sapientum*), acquired from the local fruit markets in Belo Horizonte (MG) – Brazil, in the green ripening stage, determined by the coloration of the peel, ranging from completely green to green with yellow traces.

The bananas were transported to the Laboratory of Instrumentation and Control of the Department of Electrical Engineering at the CEFET-MG, Belo Horizonte (MG), where they were selected and separated. The fruits underwent a washing process with running water and neutral detergent, the pulp was separated from the peel and sliced using a manual slicer, lengthwise, into slices with a thickness of 3 to 4 mm. The slices were immediately arranged on stainless steel trays and placed in dryers with air circulation for the drying process.

Drying process

For the drying process of green banana, two types of fixed bed dryers with forced air circulation were used. The two dryers have the same dimensions and were built according to the project of Cornejo (2018).

In the first dryer, a heating unit of the resistive type with power of 1.5 kW was placed. In the second dryer, three IR lamps of 250 W were used. The details of the arrangement of the banana dryer using IR lamps are described by Rabello et al. (2021).

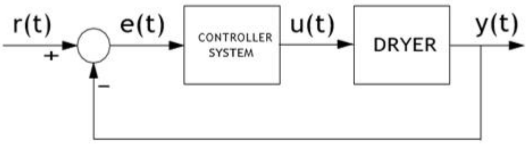
The temperature control system was developed from the modeling of the dryer dimensions and the dynamics of the heat transport process. The dryer was represented by a first order plus dead time model (Seborg et al., 2010; Ljung, 1998), with process gain $K_p = 3.2°C/W\ \%$, time constant $\tau = 170$ s and dead time $\Theta = 13$ s.

From the mathematical model, obtained through tests, PID (proportional, integral, and derivative) type controller was developed, aiming the energy optimization and the stabilization of the drying temperature inside the dryer. For the design of the controller and the tuning of the automatic controller, the Direct Synthesis Method was used which results in an optimal control that considers the desired response profile and the mathematical model of the system (Seborg et al., 2010). Equation 1 shows the obtained controller equation for the PID Controller.

$$u(t) = 1.75 * e(t) + 0.0175 * \int e(t)dt + 0.5 * \frac{de(t)}{dt} \quad (1)$$

Source: authors (2024)

Figure 1 – Block diagram for the closed loop temperature control system in dryers.



Source: Authors (2024).

Figure 1 indicates the block diagram to represent a closed loop control system used. In this system, e(t) is the setpoint temperature signal at the bottom of the food, e(t) represents the deviation between the measured value of the temperature at the bottom of the food (y(t)) and the setpoint value (r(t)), where e(t)=r(t)-y(t) and u(t) represent the percentage of electrical power (P(W)) applied to the heating unit aiming to stabilize the temperature value at each instant.

The electric power consumption EC (kWh) was obtained by integrating the electric power P(W) of the two types of dryer sources over the automatic controller setting times, according to Equation 2.

$$EC = \int_0^t P * dt \quad (2)$$

Source: authors (2024)

Drying procedures were performed with controller setpoint values at 50 °C and 60 °C to avoid product deterioration by overheating the fruit surface (Pekke et al., 2013). At the end, considering better drying efficiency and lower dryer consumption, the dehydrated slices of green banana pulp, were collected and ground, originating a green banana flour.

Physicochemical analyses

After obtaining the green banana flour, the physicochemical analyses were performed in triplicate. The determination of the pH was carried out by reading the samples in a benchtop digital potentiometer, with the samples formed by mixing 10.000 g of green banana flour in 100 mL of distilled water (IAL, 2008).

The acidity (g malic acid/100 g of sample) was determined by the titrimetric method, using sodium hydroxide 0.1 mol/L, previously standardized, as the titrant and an alcoholic solution of phenolphthalein 1% m/V as indicator. The sample was prepared by adding and mixing 5.000 g of green banana flour to 100 mL of distilled water (AOAC, 2005).

The total soluble solids (% w/w) was obtained after analysis of the green banana flour samples in a refractometer. Samples were prepared from 10.000 g of green banana flour in 100 mL of distilled water, with the mixture then being stirred. The final content was corrected considering the temperature of the mixture and the content of insoluble solids. The ash content

(% w/w) was determined with 5.000 g of the green banana flour samples measured in corresponding porcelain capsules. The set was transferred to a muffle at 550 °C, and the masses obtained were used to determine the ash content (IAL, 2008).

The determination of the lipid content (% w/w) was performed using the Soxhlet extraction method. Green banana flour samples were measured (2.000 g) in filter paper cartridges. Then, the cartridges were transferred to the extractor apparatus. The system was heated for 8 h and the solvent was evaporated to obtain the lipids (IAL, 2008).

Spectroscopic analyzes

Infrared spectra were acquired on a Prestige-21 IR spectrophotometer, Fourier Transform Shimadzu, with Total Attenuated Reflectance (ATR) sampler. The solid samples of green banana flour were analyzed directly in the ATR sampler and the spectra obtained according to the following parameters: 50 scans, range 4000 to 400 cm^{-1} and resolution 1 cm^{-1}.

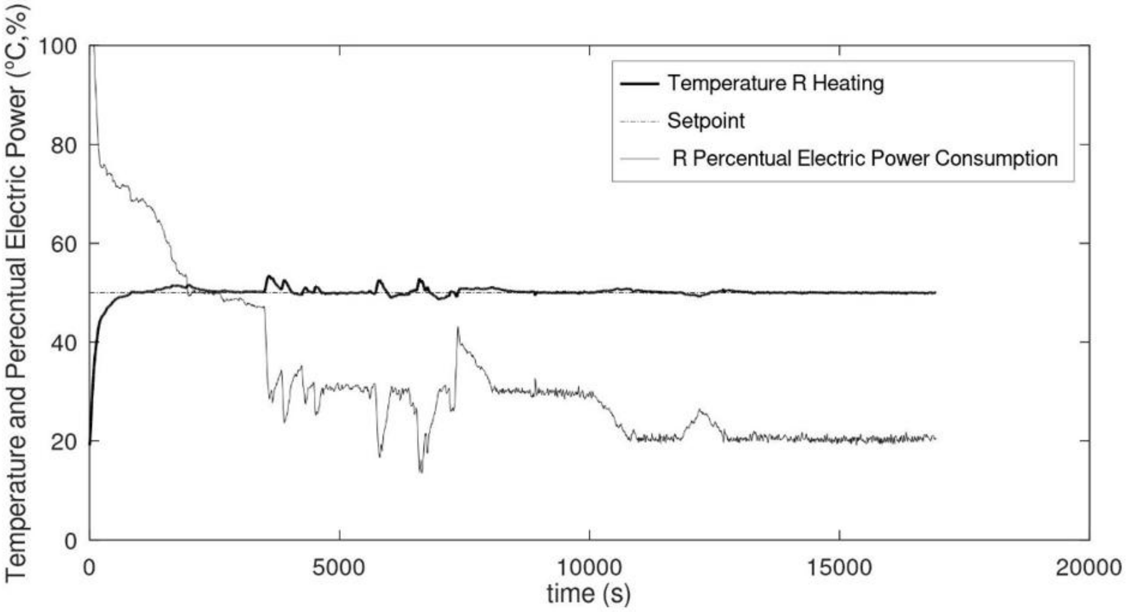
Finally, the ultraviolet spectra were acquired between 200 and 400 nm, in a Varian UV-Vis spectrophotometer, model Cary 50, with quartz cuvettes, distilled water as solvent, adapting the method of Grasel et al. (2016).

3. Results and Discussion

Drying process

Initially, the setpoint of the temperature controller on the surface of the fruit was adjusted at 50 °C. The results obtained are shown in Figures 2 and 3, which demonstrate the temperature at the bottom of the banana and the percentage of electrical power applied to the heating device over time, for the dryers with resistive and infrared sources.

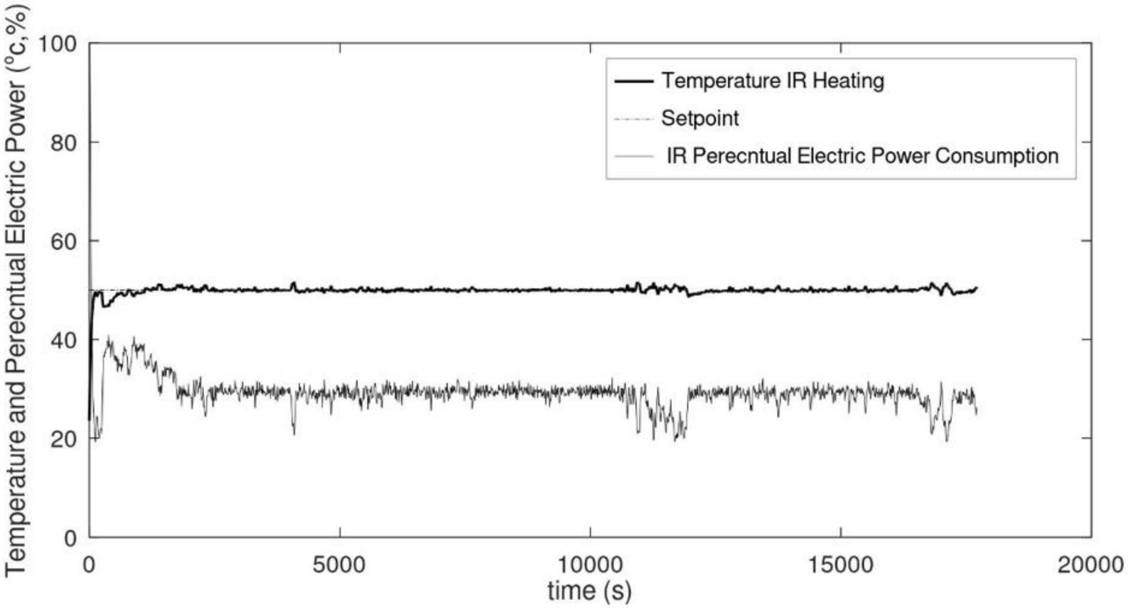
Figure 2 – Temperature (setpoint at 50 ◦C) and Percentual Energy Consumption across drying time with resistive source.



Source: Authors (2024).

The results showed that a long drying time (approximately 4 hours and 40 minutes) was required for a set temperature of 50 °C on the surface of the fruit. In this case the production of the banana flour is inefficient. Under these conditions, the total energy consumption of the resistive heating system was 2.3 kWh, while the infrared consumption was 0.1037 kWh.

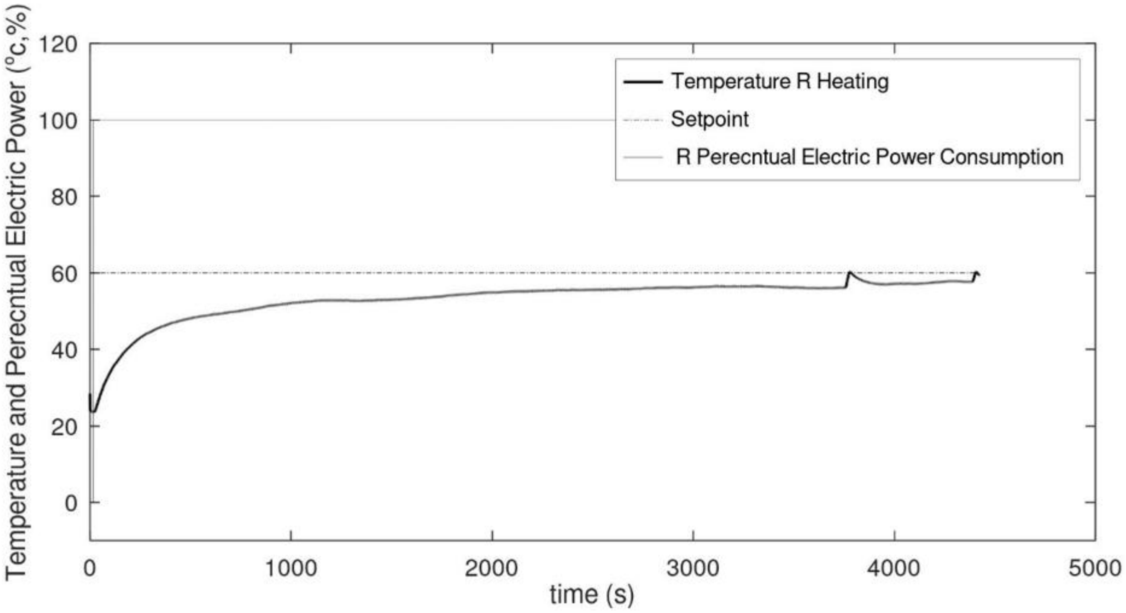
Figure 3 – Temperature (setpoint at 50 ◦C) and Percentual Energy Consumption across drying time with infrared source.



Source: Authors (2024).

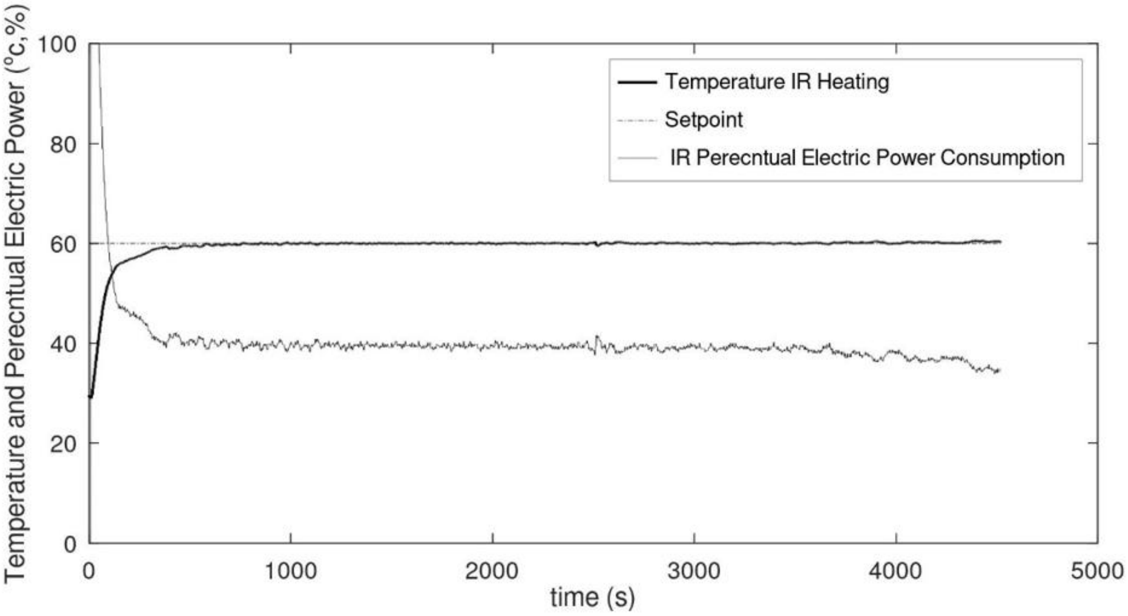
To increase the efficiency of the drying process the setpoint of the temperature controller was changed to 60 °C. Figures 4 and 5 shows the results obtained by resistive and infrared drying for 1 hour.

Figure 4 – Temperature (setpoint at 60 ◦C) and Percentual Energy Consumption across drying time with resistive source.



Source: Authors (2024).

Figure 5 – Temperature (setpoint at 60 ◦C) and Percentual Energy Consumption across drying time with infrared source.



Source: Authors (2024).

The resistive drying process operated outside the control zone when the fruit surface temperature was increased by only 10 °C. Thus, the power supplied by the resistive heat source was maximum during the experiment. On the other hand, the efficiency of the IR drying increased significantly by using only 40% of the power supplied by the lamps for the temperature of 60 °C. The total energy consumption of the resistive heating system was 1.4999 kWh, while the consumption of the IR dryer was 0.3 kWh.

Physicochemical analyses

The results of the physicochemical analyses can be seen in Table 1. The pH of banana pulp is a measure related to the presence of substances such as malic acid and citric acid, and, according to Carvalho et al. (2011), ripening is related to an increase in the content of organic acids and a reduction in pH. In addition, when green bananas are subjected to drying processes, the loss of moisture raises the content of organic acids. Borges et al. (2009) obtained pH equal to 5.30 ± 0.08 for green silver banana flour using oven drying (70 °C for 12 h), and Ferreira et al. (2018) obtained pH 5.88 ± 0.08 with oven drying at 40 °C for 48 h. In the present work it was observed that the infrared irradiation drying process was responsible for an intermediate pH to those previously cited, showing a similar behavior to the use of oven drying and not indicating adverse patterns related to possible chemical degradations. According to Franca et al. (2020), by presenting pH higher than 4.5, the green banana flour is also classified as low acid.

When evaluating the titratable acidity of the green banana flour, obtained by drying process in Pardal dehydrator, Santos et al. (2010) obtained 0.48 ± 0.08 g of malic acid/100 g. In turn, Carneiro et al. (2020) observed the following range of values: 2.02 to 2.5 g of malic acid/100 g, depending on the previous treatment performed on green bananas. When comparing with the average obtained in the present work (0.50 ± 0.04 g of malic acid/100 g), it was observed great similarity with the results of Santos et al. (2010) and lower acidity compared to the results of Carneiro et al. (2020). When considering the tendency of increasing acidity with the advancement of the drying process, it is estimated that the irradiation drying method was less aggressive to the green banana samples than the mentioned oven drying. Green bananas have low total soluble solids because they are rich in resistant starch. During the ripening process, the starch is converted into soluble sugars, increasing the total soluble solids. In a study on postharvest conservation of ‘silver’ and ‘nanicão’ cultivates, the total soluble solids of green bananas (ripening stage 2) were determined, obtaining 11.70% w/w (silver cultivate), regardless of the form of conservation (Rinaldi, 2010).

Table 1 – Mean and standard deviation of physicochemical analyses of samples of green banana flour.

Experiments*	pH	Acidity (g malic acid/100 g (% w/w)	Total soluble solids (% w/w)	Ash (% w/w)	Lipids (% w/w)
Results (av ± sd)**	5.65 ± 0.00	0.50 ± 0.04	1.2 ± 0.0	3.24 ± 0.18	1.36 ± 0.08

*n = 3; **av: average; sd: standard deviation. Source: authors (2024).

In the present work, the content was equal to 1.2% m/m, similar to that obtained by Carneiro et al. (2020) (2.1 to 2.3% m/m), indicating that the samples were in the initial stage of maturation and that the irradiation process was not responsible for representative chemical transformations, such as hydrolysis reactions, in the resistant starch.

On the other hand, the ash content of the samples in this work (3.24 ± 0.18% m/m) was similar to Franca et al. (2020) (3.63 ± 0.96% m/m) and slightly lower than the range determined by Carneiro et al. (2020) (3.84 to 4.04% m/m).

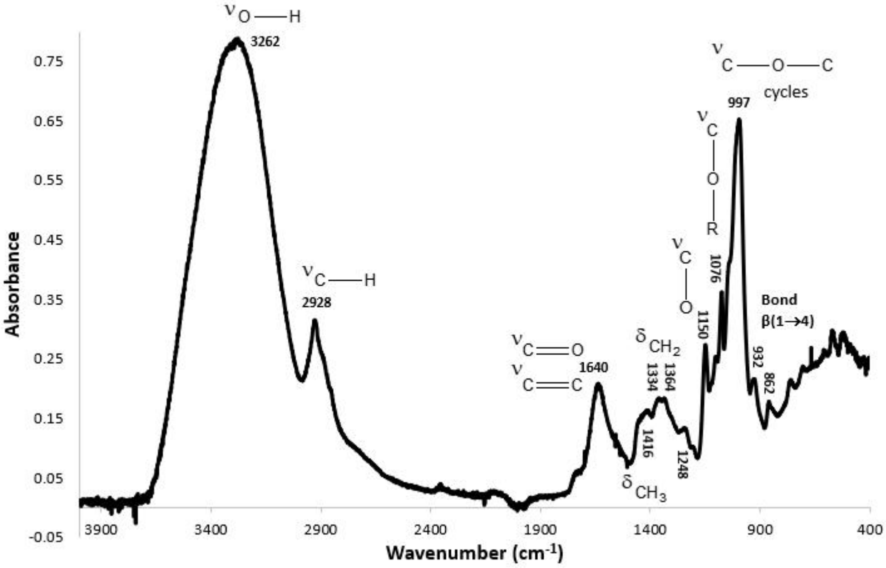
The lipid content in banana pulps is generally low at the early ripening stage. Sena et al. (2022), for example, analyzed fruits from the ‘Terra Maranhão plantain’, and found 0.52% w/w. In the present work, after the drying process by infrared irradiation, the green banana samples showed an average content equal to 1.36 ± 0.08% w/w, close to that obtained by SÁ et al. (2021) (0.97 ± 0.03% w/w), indicating a slight increase in the proportion of lipids, given the water loss.

Therefore, it can be seen from the physicochemical analyses that there are no discrepant results related to inadequate drying processes. And, in parallel, the results proved the initial ripening condition of the fruits.

Spectroscopic analyses

The mid-infrared spectrum of the green banana flour (Figure 6), in turn, was performed to evaluate whether the sample presented the following expected metabolites: starch, cellulose, pectin, lignin, and hemicellulose (Castro et al., 2019; Silva et al., 2020).

Figure 6 – Mid-infrared spectrum of green banana flour.

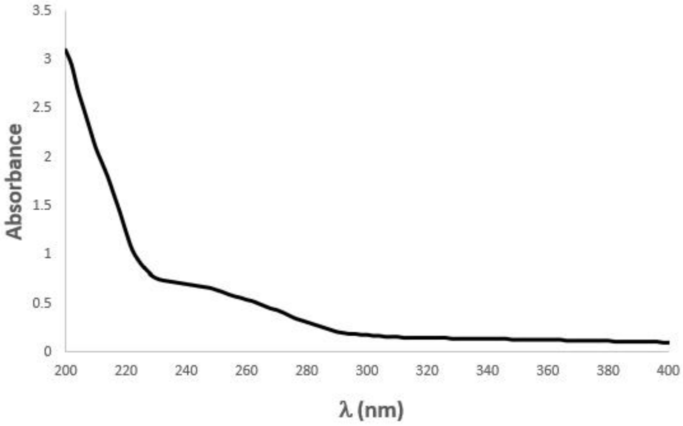


Source: Authors (2024).

When analyzing the spectrum, the signal at 3262 cm^{-1} was assigned to the axial stretching of O−H bonds present in remnant molecules of water, cellulose and/or starch (Alonso et al., 2019; Lima et al., 2012). The signal at 2928 cm^{-1} was attributed to axial stretching of C−H bonds of cellulose and hemicellulose, and between 1334 cm^{-1} and 1248 cm^{-1} was attributed to the angular deformations of CH_2 groups, of the mentioned carbohydrates. The signals at 997 cm^{-1} and 932 cm^{-1} were related, respectively, to the axial stretching of C−O−C bonds in porphyrin cycles and to glycosidic bonds $\beta(1 \rightarrow 4)$ of cellulose and hemicellulose. At 1640 cm^{-1}, the band was related to the overlap between the signals of the axial C=O stretching of pectin and the axial C=C stretching of aromatic chains of lignin. The signal at 1076 cm−1 was assigned to the axial stretching of the C−OR bond in lignins (Silva et al., 2020; Oliveira et al., 2016). Therefore, the mid-infrared spectrum indicated that the drying process was not overly intense, preventing the loss of the said metabolites in the flour.

The analysis of the green banana flour using ultraviolet spectroscopy (Figure 7) showed only bands attributed to starch (Fiedorowicz et al., 2010), the constituent with the highest water solubility among the majority polymeric metabolites.

Figure 7 – Ultraviolet spectrum of green banana flour.



Source: Authors (2024).

It stands out that, as the flour was produced from fruits at the early stage of maturation, the band referring to glucose molecules, near 260 nm (Kaijanen et al., 2015), did not stand out.

4. Conclusion

The total energy consumed by the drying process using infrared radiation was representatively lower than the energy consumed by the resistive heating process. The use of the temperature control system caused an increase in the efficiency of the IR drying process when the surface temperature of the fruit pulp was increased. In turn, the physicochemical and spectroscopic analyses of the green banana flour obtained by drying using infrared radiation indicated the preservation of the studied metabolites and the similarity of properties related to the flours obtained by conventional drying methods, in oven. Therefore, the results contribute to the sustainable use of energy resources in the production of green banana flour.

In future research, it is intended to carry out sensory analyses to verify the acceptance of the product by consumers.

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