

Thermal Diagnosis of Heat Conduction and Combustion Time of Fruits of the Brazil Nut Tree (*Bertholletia excelsa* Bonpl.)

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Abstract

The objective of this work was to evaluate the spatial and temporal dynamics of the process of combustion of fruits of the Brazil nut tree (*Bertholletia excelsa* Bonpl.) using thermographic images in order to characterize the potential of this biomass as an energy source for use in ceramic kilns. Infrared thermography was used as a diagnostic tool, and the trial was conducted in November 2018, in two blocks with two repetitions in each, with the fruits organized so that the cavity was oriented upward and also downward. The thermograms were analyzed using Flir Tools (6.3 v). The temperatures were the highest in the center of the fruits (>160°C), attaining incandescence in 6 min 30 s. Heat was propagated from the center to the edge, and this process was quicker for fruits with their cavities pointed upward. A second order polynomial model explained combustion time with a maximum duration of 7.2 minutes. The thermographic diagnostic has the potential to be used in management strategies for this biomass as an energy source, thus aggregating value to the residuals that are normally left in the forest during harvest by extractivists.

Keywords

Residual Biomass, Thermographic Patterns, Non-Wood Forest Products

1. Introduction

The biodiversity of the Amazon rain forest possesses great biotechnological and

bioenergetic potential through byproducts and substances from extraction processes, and these are capable of generating expressive economic benefits for the population in the region [1]-[20]. Among these possibilities are native species such as the Brazil nut tree (*Bertholettia excelsa* Bonpl. Lecythidaceae) which has great potential to aggregate value through non-wood forest products [2], its fruits are denominated *ouriços*, and have an average weight of 1.6 kg, contain 12 to 25 seeds, are covered by a very thick and resistant bark, wherein the seed *in natura* is found [17].

The Brazil nut has been gaining in economic importance, principally due to the results from research on its nutritional value [16] [17] [18]. In some places in the Amazon the Brazil nut is the principal extractivist product that is exported, and it also has high potential for energy generation from residual biomass from its harvest [4]. Since it is very abundant in the region, the Brazil nut tree can also be considered a key species for the evaluation of indicators of conservation and development, since its harvest occurs in native forests each year. The harvest of the Brazil nut itself has low environmental impact [21] but the pericarp of the fruit, after having the seeds removed, is rarely used.

Brazilian production of *B. excelsa* in the period between 2012 and 2013 was 38,805 and 38,300 tons, respectively, and concentrated in the North region, which produced in 2013 36,704 tons, totaling 96% of national production, with the greatest production in the states of Acre, Amazonas and Pará. Furthermore, production is greater during the rainy season, and years with greater rainfall cause an increase in the harvest of the following year [19].

Currently, there is an intense demand for Brazil nuts in local, regional, national and world markets, which increases job availability, income, and interest of businesses, and producers to install companies in Brazil nut producing regions. Furthermore, the Brazil nut trade strengthens production chains that are the base of agroextrativist communities [5].

The combustion of biomass is a conversion technology based on the principle of transformation of chemical energy into thermal energy through a series of chemical reactions [7]-[15]. The use of technologies capable of diagnosing the heating process and the response time can help in understanding the process of conversion of energy stored in the biomass (fruit of the Brazil nut) up to the point of combustion. Biomass combustion is mainly used for heat production in small and medium scale units such as wood stoves, log wood boilers, pellet burners, automatic wood chip furnaces, and straw-fired furnaces [18]. The thermal gradient expressed as a gradient of colors indicates that the radiation in the infrared spectrum is proportional to the temperature of what is being measured [9]. It is important to emphasize that thermography allows for the identification of thermal responses from the energy emitted by the surface of the measured object and the transformation of this response into an image showing thermal gradients as captured by a thermographic camera [22].

In light of the extensive variety of technological resources and tools currently available, the objective of this work was to evaluate the spatial and temporal dy-

namics of the process of combustion of fruits of the Brazil nut tree (*Bertholletia excelsa* Bonpl.) using thermographic images in order to characterize the potential of this biomass as an energy source for use in ceramic kilns in the Amazon.

2. Material and Methods

The samples of Brazil nut fruits (*Bertholletia excelsa* Bonpl.) were collected at the beginning of the month of November, 2018, at Fazenda Aruanã (03°00'30.63"S and 58°45'50"W), altitude 150 m, located on the AM-010 highway, municipality of Itacoatiara, Amazonas, Brazil (**Figure 1**).

The material selected for the experiment was transported to the city of Manaus where it was submitted to a drying process to remove excess humidity. After drying, the samples with diameter varying between 10 to 15 cm were transported to a ceramic kiln in nearby Iranduba (03°08'19.8"S and 60°21'39.3"W), in order to conduct tests in kiln ovens at temperatures above 700°C. These tests were conducted in order to quantify the time period that the fruits took to enter into combustion, and the entire process was monitored with an infrared thermographic camera, as shown in the image below.

The fruits were organized in two blocks, with one block having the fruit opening pointing upward and the other block with the opening facing downward. The fruits were placed in the oven, measuring the time needed for installation of the blocks in the front of the oven up to the initiation of combustion of a fruit. Subsequently, the samples were removed in order to conduct thermal imaging, which was also done on the external part of the oven with the objective of describing the process of heat conduction in the fruits.

The ovens are semi-continuous and of the type “paulistinha” (**Figure 2(a)** and **Figure 2(b)**). As a reference, the average temperature at the entry door of the oven was used, as this is the locale where materials to be burned are introduced for the process of brick burning (**Figure 2(c)** and **Figure 2(d)**).

In order to provide broader support to the experimental trials, georeferenced climate data for the area were used from [14] using only data from the state of Amazonas to spatially identify the region of Iranduba. **Figure 3** shows that the Köppen climate type is Am₃, indicating that during the least rainy month average rainfall is below 60 mm, and annual rainfall is between 2000 and 2500 mm. In this way, it is evident that the ceramic industry center of Iranduba has climate conditions that are propitious for growth of native Brazil nut stands in the Amazon.

As Iranduba is near the metropolitan area of Manaus, climatological data provided by the National Meteorological Institute (INMET) were also used, and based on a historical series from 1961 to 1990 it was determined that the study area has a thermal regime with an annual average temperature of 26.7°C, maximum of 31.4°C and a minimum of 23.3°C. With respect to the hydrological regime, annual average rainfall is 2307.4 mm, with the rainiest month of March having 335.4 mm e, and August, the least rainy month, with 47.3 mm, and average annual air relative humidity of 83.1% [6].

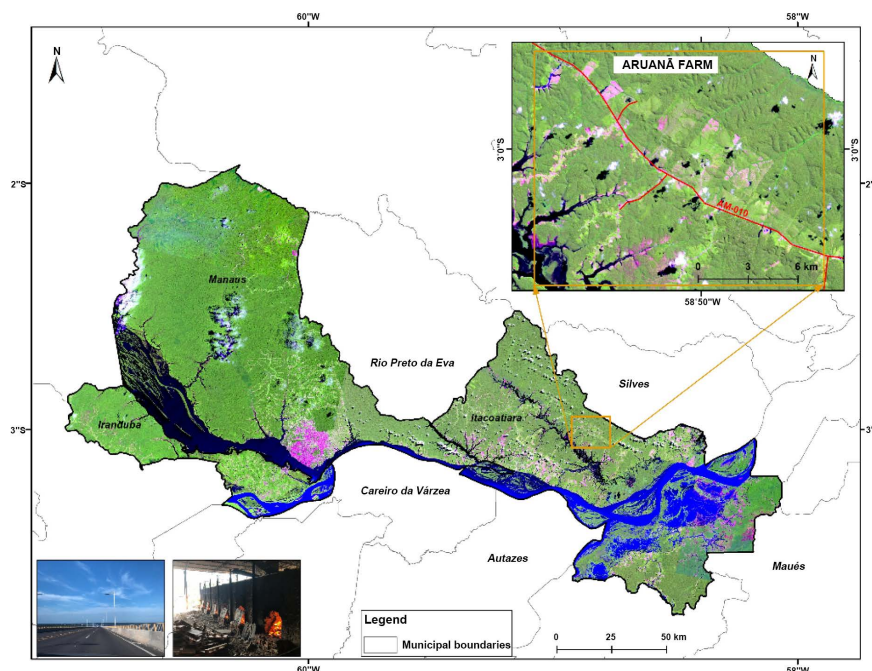


Figure 1. Image of location of Fazenda Aruanã situated on the east side of highway AM-10 (Manaus-Itacoatiara, km 215). Source: Authors.



Figure 2. Chestnut hedgehogs from Brazil.

Climate data were also used from the automatic weather station of INMET at Manaus (latitude $03^{\circ}06'19''\text{S}$ and longitude $60^{\circ}00'49''\text{W}$) to identify climate conditions on the day the experiment was conducted (11/23/2018), which occurred between 15 h:00 min and 16 h:00 min, taking into consideration that the experimental site was under the influence of climate conditions that were prevalent within the range of measurement of the automatic weather station at Manaus.

Data collection was conducted through image capture using a thermographic infrared camera (FLIR T650sc), with a 25 mm fixed lens, and a temperature scale of 40°C to 150°C , and a thermal sensibility of 50 mK ($<0.05^{\circ}\text{C}$ at an ambient temperature of 30°C). The camera's spectral scale ranged from 0.7 to $100\ \mu\text{m}$, but the image targets presented a response between 0.7 and $3.0\ \mu\text{m}$ and an optical resolution of 640×480 pixels with a maximum emissivity index of 0.95.

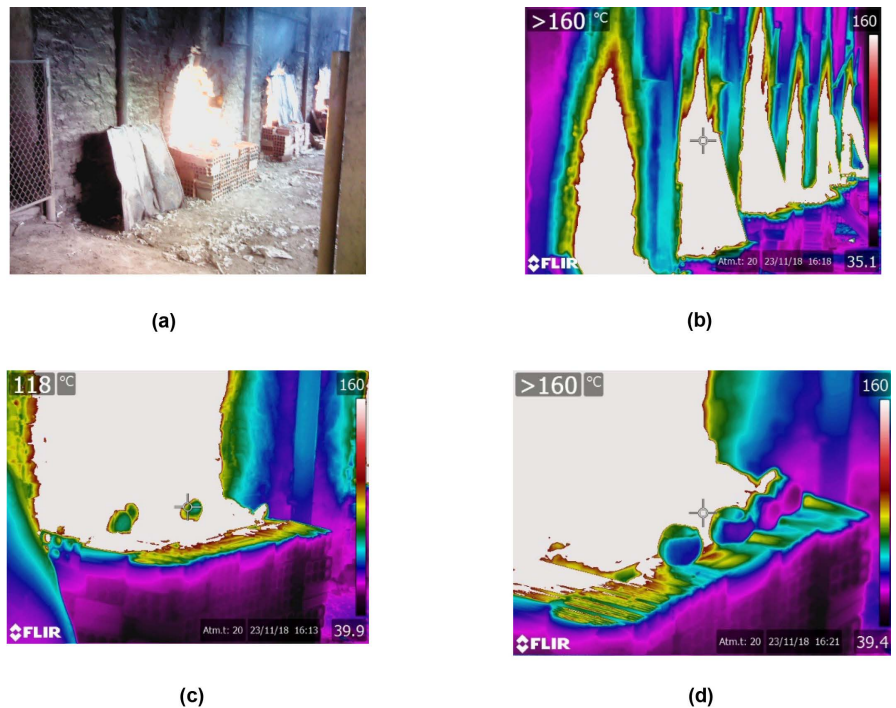


Figure 3. Brick kiln ovens at the ceramic industry center of Iranduba ((a) and (b)) and an example of the organization of the testing surfaces (fruits (c) and (d)).

Subsequently, the images were processed using the software Flir Tools, 6.3v [10], from which minimum, maximum, and amplitude thermal data were extracted.

The samples were distributed into four blocks, with two blocks having the fruit opening pointing upward and the other blocks with the opening facing downward, so that each block had at least one representative from each treatment group. For image treatment, the color palette was defined and categorized into thermal bands of white, red, yellow, green and blue. For evaluation of the thermal bands, five points were extracted from each image corresponding to each block, as shown in **Figure 4**.

The pattern of the thermal responses among the targets were statistically analyzed using the program BioEstat, version 5.3 [3], using Analysis of Variance (ANOVA). Furthermore, the functional relationship between the time necessary for the fruits to enter into combustion (the dependent variable (x)), and the thermal bands as the independent variable (y) was analyzed in order to verify whether the model can explain the process of heat conduction.

3. Results and Discussion

The meteorological variables at the moment of the experimental trials of imaging the targets at the ceramic kiln showed that average air temperature was 24.8°C and air relative humidity was 89.3%, and there was no rainfall during the experiment. The thermographic pattern of the fruits showed that the temperature represented by white was above 160°C, for both treatments of fruits with openings pointed upward and downward. For the red pattern the maximum,

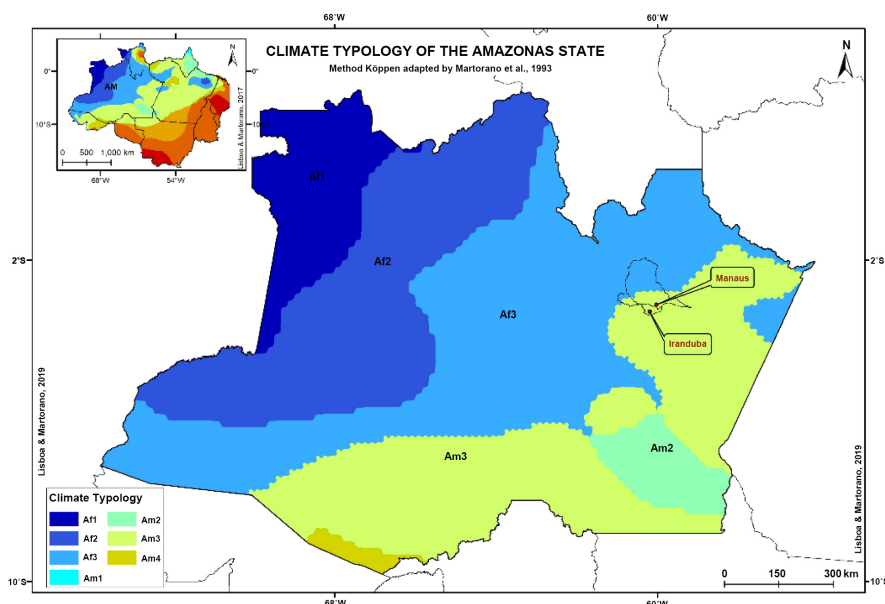


Figure 4. Köppen climate typology of the Legal Amazon adapted by Martorano *et al.* (1993), geodatabase used by Martorano *et al.* (2017).

minimum, and average temperatures were 135.3°C, 122.0°C and 128.5°C, respectively. For the white and red patterns the fruits presented temperatures above 100°C, indicating a greater concentration of heat in the center of the fruits. The samples extracted in the yellow pattern presented maximum values of 91.8°C, a minimum of 84.8°C and an average of 86.9°C.

In the areas represented by a green pattern the maximum thermal value was 75.0°C, the minimum was 63.0°C and the average was 67.0°C. The hottest areas of the blue pattern were 45.0°C, with a minimum of 41.0°C, for an average of 44.0°C. The isotherms that expressed heat conduction demonstrated that in the center of the fruits the high temperatures surpassed the thermal limit of the thermographic camera, and that there was differentiation in the imaged surfaces, which was shown by the coincidence of the isotherms. The higher thermal amplitudes attained values around 13°C, demonstrating that the fruits have high potential for heat conduction, because the values surpassed 120°C. In areas on the periphery of the fruits the temperatures were above 40°C, thus showing that the temperatures on the edges of the fruits were also very high (Figure 5).

Temperature elevation intensified during the interval between 3 to 5 minutes for both treatments of fruits with the openings upward and downward, and these initiated combustion after 5 min and 40 s and became completely incandescent when the material remained for 6 min and 30 s (Figure 6). The quickness of the combustion process of the fruits could be associated with their chemical composition which possess high lignin and cellulose contents [8] [9] [10] [11]. It is important to emphasize that for the block in which the fruits were with their openings pointed upward incandescence was more quickly reached.

The small variation between the block with their openings pointed downward could be related to a larger concentration of water vapor due to the difficulty of

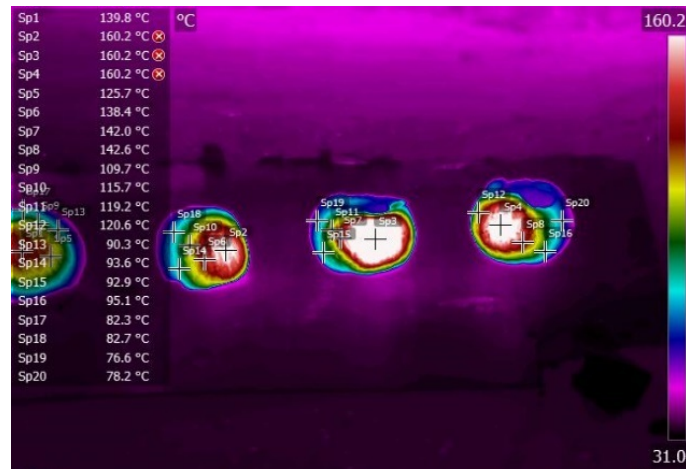


Figure 5. Example of an image indicating the targeted collection points on the fruits using Flir Tools.

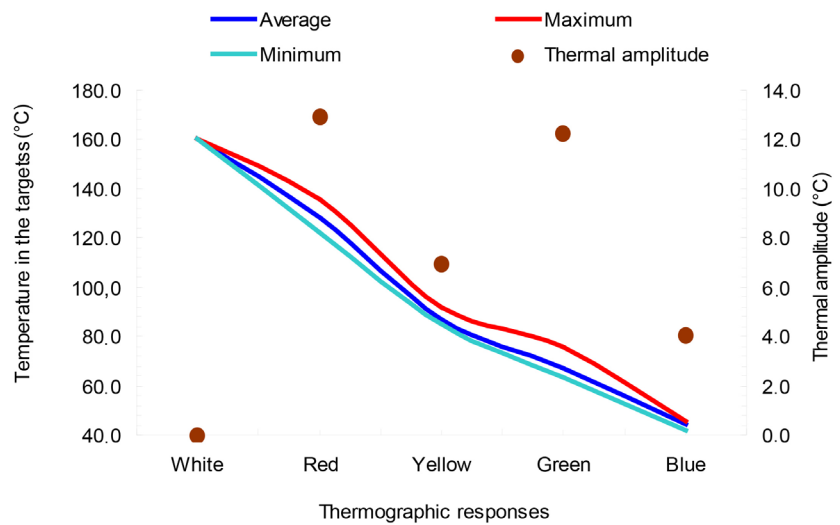
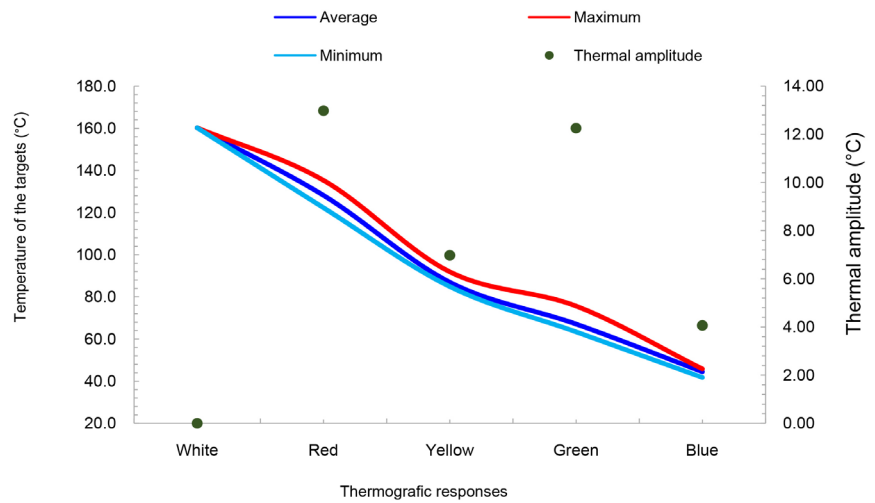


Figure 6. Thermographic diagnosis of heat conduction in fruits of the Brazil nut tree (*Bertholletia excelsa* Bonpl.).

liberation of surrounding air in the process of heating the fruits. At t_1 (1 min 30 s) the fruits reached an average temperature of 73.6°C with a rapid heating, and at t_2 (3 min 00 s) they reached average values of 118.0°C. At t_3 (4 min 00 s) the temperatures had an average of 120.0°C which rapidly at t_4 (5 min 00 s) had an average of 133.0°C. At t_6 (7 min 00 s) the fruits attained temperatures above 160.0°C and entered into combustion (**Figure 5(a)** and **Figure 5(b)**). There was a 97% probability that the temperatures of the fruits could be estimated by a second order polynomial, wherein the inflection point obtained by the first derivative occurs at 7.2 minutes, with this representing the maximum incandescence time of the fruit (**Figure 7**).

It was also observed that the block of fruits that had the fruit openings upward went through a more rapid cooling process than the block that had the fruit openings downward. After 5 min 00 of removal from the oven, the average temperature of the fruits that had their openings downward was reduced to nearly 65.0°C, while that of the block that had the fruit openings upward was 62.0°C. This difference of 3.0°C represents a point where a decision should be made during the process of organization of this biomass for placement in the ovens in order to guarantee a consistent supply of energy to the ovens and to further aggregate value to this material which is normally discarded in the forest by the harvesters. It is important to emphasize that this experiment with infrared thermography was conducted in order to aid with subsequent tests that will be conducted in order to quantify the number of fruits necessary to guarantee uninterrupted functioning of the industrial ceramic plant in Iranduba.

The areas of natural occurrence of *Bertholletia excelsa* in the Amazon are concentrated in the states of Acre, Amazonas, Pará, Amapá, Rondônia, Roraima, Mato Grosso and Maranhão [23]. In the state of Amazonas the municipalities that are most important for Brazil nut production are Beruri, Humaitá and Lábrea [12], and this demonstrates the potential for biomass production for use in kiln ovens in the ceramic industry centers around the Manaus metropolitan

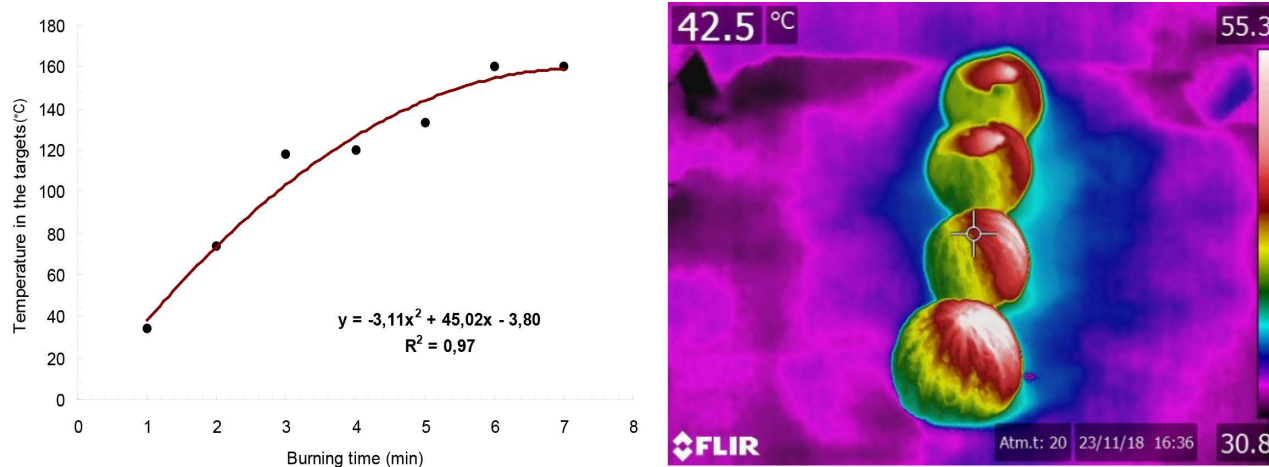


Figure 7. Second order polynomial model to estimate the average time of heat conduction in fruits of the Brazil nut tree (*Bertholletia excelsa* Bonpl.) as a strategy for use in kiln ovens in the ceramic industry center of Iranduba, Amazonas.

region. Considering that a Brazil nut tree produces, on average, 236 fruits [13]-[24], and that each fruit possesses about on average 20 seeds [25], it is estimated that there is an annual production potential of 4720 seeds per tree. Also considering that the average weight of a seed is 6.0 g then the total weight of seeds produced per tree is 28.3 kg per harvest year. If average annual production is 40 thousand tons coming from 1,716,738 trees then potential biomass production would be 7 tons annually which could be used in the combustion process in the kiln ovens in the ceramic industry center of Iranduba near Manaus. Besides that, the Brazil nut can be considered a key species for combining conservation with development, as it is abundant in the Amazon region, harvested almost exclusively in natural forests, and due to the robust market demand, exploited by various communities in the short term and at low cost, in addition to the low environmental impact of the harvest [9]-[28].

The high lignin and cellulose content of the fruits cause them to begin combustion in 7 minutes, and this result indicates that the use of this biomass represents a strategy to provide an alternative fuel source for the ceramic kilns in the region, and further work and planning should be conducted to refine the estimates of the biomass volume needed on an annual basis.

4. Conclusion

Brazil nut fruits (*Bertholletia excelsa* Bonpl.) have a high potential for combustion, with a maximum time of 7.5 minutes. Using a second degree polynomial, combustion time was estimated for Brazil nut fruits as a strategy to aggregate value to this residual biomass that is normally discarded in harvests by agroextrativist communities. Thermal diagnosis allowed for quantification of the combustion time and identification of the bands of heat conduction in fruits, and these results can be used to aid in planning for the use of this residual biomass from non-wood forest products that is abundant in the Amazon. The advantage of using Brazil nut hedgehogs is very clear, as the combustion time is extremely fast compared to other Brazilian biomass. The biggest advantage of using chestnut hedgehogs as a fuel is to allocate an appropriate end without causing natural and environmental effects, in which they would be used for the production of coal, activated carbon, renewable fuels, among others, in addition to collaborating with the farming industry.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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