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# Use of biomass from Amazonian agro-industrial waste for the production of energy[1]

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**A B S T R A C T**

This research aims to analyze the physical and mechanical properties of briquettes made by açaí, cupuaçu, and murumuru waste from agro-industrial activity in a region of the Brazilian Amazon. For the production of briquettes, biomass with different granulometry (48, 60, 65, and 80 mesh) was sent to hydraulic pressure at constant pressure (15t) with various pressing times (15, 20 and 30 minutes). This process occurred without the addition of binders. The obtained outcomes were evaluated for storage time, bulk density, energy density, calorific value, impact strength, water absorption, and mechanical durability. The briquettes produced with açaí and cupuaçu presented good mechanical characteristics compared to murumuru. Concerning the calorific value, the latter showed better results. There was no alteration in the physical and mechanical properties determinant for the material to present favorable energy generation and durability. The açaí briquettes demonstrated better physical and mechanical properties, while murumuru briquettes indicated the best energy properties. Thus, the use of biomass from different agro-industrial wastes from the Amazon proved to be relevant for the elaboration of briquettes, being an alternative in the production of sustainable energy and adding to the reduction of the accumulation of improper waste disposed of in the environment.

# Aproveitamento da biomassa de resíduos agroindustriais amazônicos para produção de energia

**R E S U M O**

Esta pesquisa tem por objetivo analisar as propriedades físicas e mecânicas de briquetes de resíduos de açaí, cupuaçu e murumuru oriundos da atividade agroindustrial em uma região da Amazônia brasileira. Para a produção de briquetes, biomassa com diferentes granulometrias (48, 60, 65 e 80 mesh) foi prensada a pressão constante (15t) em vários tempos de prensagem (15, 20 e 30 minutos). Este processo ocorreu sem a adição de ligantes. Os resultados obtidos foram avaliados quanto ao tempo de armazenamento, densidade aparente, densidade de energia, poder calorífico, resistência ao impacto, absorção de água e durabilidade mecânica. Os briquetes produzidos com açaí e cupuaçu apresentaram boas características mecânicas em relação ao murumuru. Em relação ao valor calórico, os briquetes de murumuru apresentam melhores resultados. Não houve alteração nas propriedades físicas e mecânicas determinantes para o material apresentar geração de energia e durabilidade favoráveis. Os briquetes de açaí demonstraram melhores propriedades físicas e mecânicas, enquanto os briquetes de murumuru indicaram as melhores propriedades energéticas. Assim, a utilização de biomassa de diferentes resíduos agroindustriais mostrou-se relevante para a elaboração de briquetes, sendo uma alternativa na

produção de energia sustentável e agregando na redução do acúmulo de resíduos descartados de forma inadequada no meio ambiente.

## Introdução

Energy alternatives, particularly biofuels derived from living organisms, have garnered significant attention due to the depletion of fossil fuel reserves and their environmental consequences. Simultaneously, the utilization of agricultural residues in biofuel production marks a transition towards a circular economy, that is, an economy that seeks to reuse, recycle, and reintegrate waste as resources, valorizing these resources that were previously underestimated. This convergence between the energy and agricultural sectors diversifies the energy matrix and promotes sustainability amidst rapid industrial growth, population increase, and escalating environmental concerns (Rame et al., 2023).

Biofuels hold promises of global energy security due to their renewable nature and reduction of carbon emissions in an energy landscape still reliant on non-renewable and highly polluting sources such as oil, coal, and natural gas. In Brazil, decarbonization efforts significantly benefit from biofuels, especially through the optimization of ethanol production (Glyniadakis & Balestieri, 2023). At their core, biofuels, with features like renewability and carbon neutrality, have the potential to address challenges related to energy demand and mitigate environmental issues associated with fossil fuels (Sheikh et al., 2023).

Biofuels, derived from renewable organic matter such as plants, agricultural, and forestry residues, have an intrinsic relationship with biomass. In other words, biomass plays a fundamental role as a raw material for biofuel production, being converted into usable forms of energy, such as ethanol, biodiesel, biogas, and briquettes (Rame et al., 2023).

Biomass is any organic matter that can be converted into mechanical, thermal, or electrical energy. It can be of plant origin: forestry (wood, mainly), agricultural (such as soybean, rice, corn straw, and sugarcane), and urban and industrial waste (solid or liquid, such as garbage), and of animal origin (Nagarajan & Prakash, 2021). Its exploitation for energy production purposes has become popular in recent years but has also received criticism for such purposes. However, scientific studies have continuously emerged, providing evidence of various types of biomass with considerable energy potential: cupuaçu husks (Alves, Da Silva, Mumbach, Domenico, et al., 2022), açai seed residues (Souto et al., 2021), coconut fiber (Simões et al., 2024), rice husks (Yiga et al., 2023), corn and wheat straws and rice husks (Y. Zhang et al., 2024); cassava rhizomes (Granado et al., 2023); various leaves (Raju et al., 2021); mixture of sawdust, eucalyptus, and corn cake (Drago et al., 2022), residues of *Senna auriculata* and *Ricinus communis* (Velusamy et al., 2022).

Biomass represents the third largest energy source in the whole world, with great potential for growth in Brazil for being a sustainable, renewable, and low-cost energy alternative (Okot et al., 2018). Within international and domestic markets, biomass is considered one of the main options for the diversification of the energy matrix (Bajwa et al., 2018), with powerful expectations for petroleum-derived raw materials replacement (Santos et al., 2020). Forestry, agricultural, and agroindustrial activities are predominant sources of biomass with plant origin in Brazil (Tavares & Tavares, 2015). The forestry sector produced about 52 million tons of waste in 2018 (IBA Brazilian Tree Industry, 2020), while the agricultural and agroindustrial sectors produced 113,180,826 thousand tons (Mt) between 2016 and 2017 (IBA Brazilian Tree Industry, 2020). These wastes have high energy potential utilization, particularly waste from fruit processing in the agroindustrial sector (Nunes et al., 2020; Santos et al., 2020).

Agricultural residues, enriched in lignocellulosic materials, provide a sustainable raw material for biofuels such as biodiesel, bioethanol, biogas, and briquettes, the latter being a solid biofuel (Koul et al., 2022). Generally, agricultural residues are by-products derived from various agricultural activities and food processing. The sustainable management and utilization of these residues present ecological and economic opportunities. Harnessing the potential of these agro-residues for biofuel production offers a viable solution to the increasing demand for renewable energy sources and the urgent need for waste management (Silveira et al., 2023).

In the Brazilian Amazon, the fruits of açai (*Euterpe Oleracea* Mart.), cupuaçu (*Theobroma grandiflorum* (Willd. ex Spreng.) Schum.), and murumuru (*Astrocaryum murumuru* Mart.) are part of the strengthening of the Amazonian productive chain and contribute to the sustainable, social and economic development of the region (De Oliveira et al., 2022). In particular, the state of Para produced c.a. 1.39 million tons of açaí in 2021, equivalent to 93.4% of Brazil's total (IBGE

Brazilian Institute of Geography and Statistics [Internet], 2023a). To cupuaçu it was estimated 4,965 tons produced in the state of Pará in 2017 (IBGE Brazilian Institute of Geography and Statistics [Internet], 2023b). These products are appreciated in the cooking and cosmetics industry at regional, national and international levels. However, the production cycle of these fruits generates a significant amount of agro-industrial waste, representing an environmental challenge in the region.

An issue faced in small fruit processing agro-industries in the state of Pará, especially in açaí processing units, is the considerable volume of organic waste generated without proper disposal, contributing to a range of environmental and sanitary problems such as emission of unpleasant odors, attraction of pests, inefficient use of space, and soil and water contamination (Ferreira et al., 2021). Furthermore, there is the operation of boilers used in units with higher production volumes, essential to provide energy during the fruit blanching and oilseed extraction stages, which rely on a significant amount of timber for their operation. This necessity not only increases operational costs due to the acquisition of timber from external sources but also contributes to deforestation practices, exacerbating environmental issues.

The conversion of these residues, especially from crops such as açai, cupuaçu, and murumuru, into briquettes emerges as a promising strategy to address the challenges associated with waste management and clean energy production (Granado et al., 2023; Nagarajan & Prakash, 2021). Some authors have revealed good perspectives regarding the energy use of the residual biomass of these products (Bastos et al., 2020), especially for açaí, which 81 to 85% of waste (seed and fiber) after processing the fruit (de Oliveira et al., 2022; Kuhl e Oliveira, 2019; Martins et al., 2020), while cupuaçu presents about 30% of waste, *i.e.* fruit's peel and its seed (Mendonça et al., 2019) and of the murumuru seed, on average, 47% of the mass of the murumuru fruit, with 78% represented by the shell and 22% by the remaining kernel inside the seed (Bastos et al., 2020). According to Alves et al. (2022), cupuaçu husks represent approximately 47% of the fruit (on a dry basis). According to the same author, the assessment of the bioenergetic potential of these husks through pyrolysis is one of the proposed alternatives for reusing this biomass with a high calorific value of approximately 19 MJ/kg, which makes it promising for renewable energy production.

The effectiveness of agro-industrial waste management and the pursuit of more sustainable energy generation methods underscore the need for technological innovations and optimized approaches for biomass-to-energy conversion. Recent research highlights the bioenergetic potential of various agro-industrial residues, emphasizing the importance of understanding their physical, chemical, and energetic properties for the development of briquettes from biomass with energy potential (Alves, Da Silva, Mumbach, Alves, et al., 2022)

The densification technique (briquetting) can transform biomass into energy production by increasing the mass and energy density of this material (Shuma & Madyira, 2017). In this process, biomass or other organic matter is transformed into a regular shaped material that can be used as fuel in boilers or industrial furnaces, i.e., it transforms a low-density waste into a substitute of considerable quality compared to conventional firewood (Ibitoye et al., 2023; Okot et al., 2018).

Despite the recognized energy potential of biomass, the production of briquettes from agro-industrial residues still faces challenges related to energy conversion efficiency, briquette quality, and environmental impacts associated with their production and use. Optimizing production conditions such as temperature and pressure, and understanding the thermal and mechanical properties of the briquettes are crucial to enhance the technical and economic viability of this energy alternative (Velusamy et al., 2022; Yiga et al., 2023).

The composition and quality of briquettes fundamentally depend on factors such as the type and structure of the raw materials used, combustion properties, uniformity, mold type, and operational variables such as moisture, temperature, and particle size (Ibitoye et al., 2023; Okot et al., 2018). The pressure applied during compaction, particle size, moisture content, and in some cases, heating temperature and binder addition are significant parameters for quality and efficiency in the briquetting process (Granado et al., 2023; J. Zhang et al., 2019). In this process, biomass or other organic matter is transformed into a regular-shaped material that can be used as fuel in boilers or industrial furnaces, essentially converting low-density waste into a substitute of considerable quality compared to conventional firewood (Gangil & Bhargav, 2019). According to Kabaş et al., (2022), compared to raw biomass, bio-briquettes, as they are called, are characterized by higher bulk density, uniform shapes (usually cylindrical or rectangular), and sizes (diameter between 25 and 100 mm and lengths between 10 and 400 mm).

Briquetting technologies bring significant benefits to biomass handling, improving transportation, storage, and combustion efficiency of agricultural residues transformed into high-density solid biofuels (Kabaş et al., 2022; Simões et al., 2024).

The pressure applied at compaction, particle size, moisture content, and, in some cases, heating temperature and binder addition are significant parameters for quality and efficiency in the briquetting process (Granado et al., 2023; J. Zhang et al., 2019). Some authors suggest that the optimal moisture value of materials to perform the briquetting process should be between 8 to 12%, as it improves compaction and decreases the angle expansion (Brand et al., 2017; Gendek et al., 2018; Lisowski et al., 2019). However, moisture content between 10 to 20% can also be used to obtain higher densification (Lubwama & Yiga, 2018). Therefore, quality briquettes have high calorific value, high density, low ash content, good mechanical strength, and certain dimensional stability, in addition to particle size homogeneity which ensures higher energy concentration per unit volume and better handling in product storage and transportation (Gangil & Bhargav, 2019; Nagarajan & Prakash, 2021; Nunes et al., 2020; Wu et al., 2018).

Based on the premise that this study aims to produce simple briquettes from agro-industrial residues of açaí, cupuaçu, and murumuru processing, it is anticipated that the end product will exhibit mechanical strength, increased durability, and energy efficiency. It is speculated that through systematic investigation and the application of advanced processing and compaction techniques, it is possible to develop briquettes that not only overcome the structural integrity challenges faced by similar products in the market but also offer cleaner and more sustainable combustion. This hypothesis is supported by the studies of Costa et al. (2021) and Matheus et al. (2024), which address the evaluation of the potential of agro-industrial residues in the Amazon for activated carbon production and the life cycle assessment of biomass briquettes, respectively. Both studies emphasize the relevance of optimizing the energy utilization of these residues, which aligns with the research proposal of transforming such residues into briquettes as a more efficient and sustainable energy alternative. Thus, the study aims to analyze the physical and mechanical properties of briquettes produced from açaí, cupuaçu, and murumuru residues originating from agro-industrial activity in the Amazon.

**Materials and methods**

*Collection of Residual Biomass*

Agro-industrial waste of açaí, cupuaçu, and murumuru were used in the production of briquettes (Figure 1). The wastes were collected at the Cooperative of Fruit Farmers of Abaetutuba (COFRUTA), located in the city of Abaetetuba, state of Pará, Brazil (1° 44' 52.37" S; 48° 50' 35.36" W), totaling about 400 kg collected for each type of waste. COFRUTA is a cooperative enterprise of family-based farmers, and most of their revenues come from the processing of açaí (*Euterpe Oleracea* Mart.), cupuaçu (*Theobroma grandiflorum* (Willd. ex Spreng. Schum.), and murumuru (*Astrocaryu murumuru* Mart.). After the product processing, the waste is deposited in the cooperative enterprise's facilities, in an inappropriate site, and without adequate infrastructure for its reuse.


Figure 1. Types of biomass from small agro-industries in the Amazon used in the briquetting process: (A) açai, (B) cupuaçu, and (C) murumuru waste.

The cooperative has a boiler which is the source of steam generation for the fruit processing unit, the açaí bleaching, and also as a source of energy for the operation of the oil extraction plant. For people feeding, regular firewood from the surrounding vegetative area is used, bought by the farmers' association, causing more costs for their operation and producing environmental deforestation of the region.

For comparative purposes, it was performed the characterization of conventional firewood in nature used by the cooperative to feed the boiler. It was collected around 4 kg (equivalent to 2 units of firewood) and submitted for preliminary analysis.

*Treatment and physical, chemical, and energetic properties of the residual biomass*

Considering that the optimal moisture content of waste for briquetting is between 8% and 12% w.b. (Brand et al., 2017; Gendek et al., 2018; Lisowski et al., 2019), the waste of açaí and cupuaçu was dried in a solar dryer to meet this requirement. The moisture content of the waste during the drying process was monitored by a digital thermo-hygrometer (Minipar MT-241). Murumuru waste already met the moisture content within the required parameters, so it was not submitted for drying. Subsequently, all waste was ground in a grind (WEG 22 Plus) using sieves with an opening of 3 mm first and then passed through a new grinding using a sieve of 1 mm, successively.

Seven preliminary analyses were performed to characterize the agro-industrial waste as input for the briquettes: (i) moisture content *in nature*, (ii) ash content, (iii) volatile bases, (iv) fixed carbon, (v) bulk density, (vi) higher heating value and (vii) lower heating value. The tests to determine the moisture content, ash content, volatile bases, and fixed carbon followed the Brazilian standard NBR 8112 (ABNT Brazilian Association of Technical Standards, 1986). NBR 6922/1981 (ABNT Brazilian Association of Technical Standards, 1981) was used to determine the bulk density, and NBR 8628 (ABNT Brazilian Association of Technical Standards, 1984), adapted to indicate solid fuel, to determine the higher heating value (HHV - Eq. 1) and low heating value (LHV).

$$HHV = LHV(1 - Ubu) - 600 * Ubu \quad (1)$$

Where:

HHV = higher heating value (J/kg),

LHV = lower heating value (J/kg),

Ubu = moisture of the sample in percent, wet basis (%).

*Briquetting production*

Initially, the three types of waste were sieved in a Granulometric Sieve Electromagnetic Shaker (Model: VP-01 / Brand: Bertel) at 25 Hz vibration, time of 900 s ±1 and sieves with meshes of average diameters equivalent to 48 mesh (0.295 mm), 60 mesh (0.245 mm), 65 mesh (0.208 mm) and 80 mesh (0.175 mm). About 100 g ± 10 of each waste was compacted in a hydraulic press (MARCON-MPH-30) with a capacity of 30 tons in a cast steel cylindrical mold with a removable bottom and folding sides of an internal diameter of 52 mm, a height of 147 mm and thickness of 4 mm (Granado et al., 2023). The waste was compacted at a constant load of 15 tons without the use of a binder or heating. Pressing times varied between 10, 20, and 30 minutes. The briquettes were produced and cured at room temperature (≈ 30 °C) (Okot et al., 2018).

*Chemical, physical and mechanical characterization of briquettes*

Eight chemicals and physical and mechanical parameters were obtained to characterize the briquettes produced. Physical parameters included: (i) moisture content, (ii) longitudinal and diametrical expansion, (iii) bulk density, (iv) energy density, (v) net calorific value, and (vi) water absorption; and, mechanical parameters: (vii) impact resistance and (viii) compressive strength.

The moisture content was obtained by the difference between the initial (after 24 h of production) and the final (after 30 days of storage) moisture content (Gendek et al., 2018).

The longitudinal and diametrical expansion was determined by varying the height and diameter of the briquettes. Records of the height and diameter of the briquettes were obtained at intervals of 0 h, 24 h, and 48 h, then every 7 days until the final time of storage (30 days), with the aid of electronic caliper (MARBERG) and semi-analytical balance (Shimadzu - BL 3200 H), method adapted from Nakashima et al. (2017).

The bulk density (g/cm³) was determined by the ratio between the mass and volume of the briquettes, according to methodologies described by Okot *et al.* (2018), with adaptations.

The higher heating value (HHV) and lower heating value (LHV) also were evaluated for the briquettes produced following the standards NBR

8628 (ABNT Brazilian Association of Technical Standards, 1984).

The energy density is one of the main properties to define the quality of the briquette because it summarizes the chemical characteristics, the moisture conditions, and the amount of heat of the product in a single variable (Souza & Vale, 2017), it was calculated by multiplying the higher heating value by the bulk density. And the energy density is obtained by Eq. 2:

$$ED = HHV * BD \quad (2)$$

Where:

ED = Energy Density (KJ),
HHV = higher heating value (J/kg),
BD = bulk density (g/cm$^3$).

To determine the water absorption, the briquettes were weighed and subsequently immersed in water with a solid/liquid ratio of 1:10 for 20 minutes, removed from the water with a sieve, and weighed to gauge the absorbed mass, method adapted from Silva et al. (2019) and Yang et al. (2019), with adaptations.

The impact strength test was performed according to Silva et al. (2019) and Okot et al. (2018), with adaptations. The resistance of the briquettes was evaluated by free-fall throwing at heights of 30, 60, 90, and 120 cm, simulating what might occur during transportation, handling, and storage. The initial mass of each briquette was recorded, according to its granulometry and pressing time. After each launch, the remaining mass was recorded and the percentage calculation was performed, by the difference between the final mass and the initial mass. For each drop height, a new briquette was used according to its characteristics, aiming to accurately obtain the mass loss in relation to the different drop heights.

The mechanical behavior of the briquettes was evaluated by means of the test of resistance to diametrical compression of the specimens, adapted from the standard NBR 7222 (ABNT Brazilian Association of Technical Standards, 1994) (Figure 2). The equipment used was a universal testing machine MC (model WDW-100E), with a load cell of 500 kg applied perpendicular to the compaction force and speed of 3 mm/s. This test was performed in triplicate with the briquettes stored after 28 days.

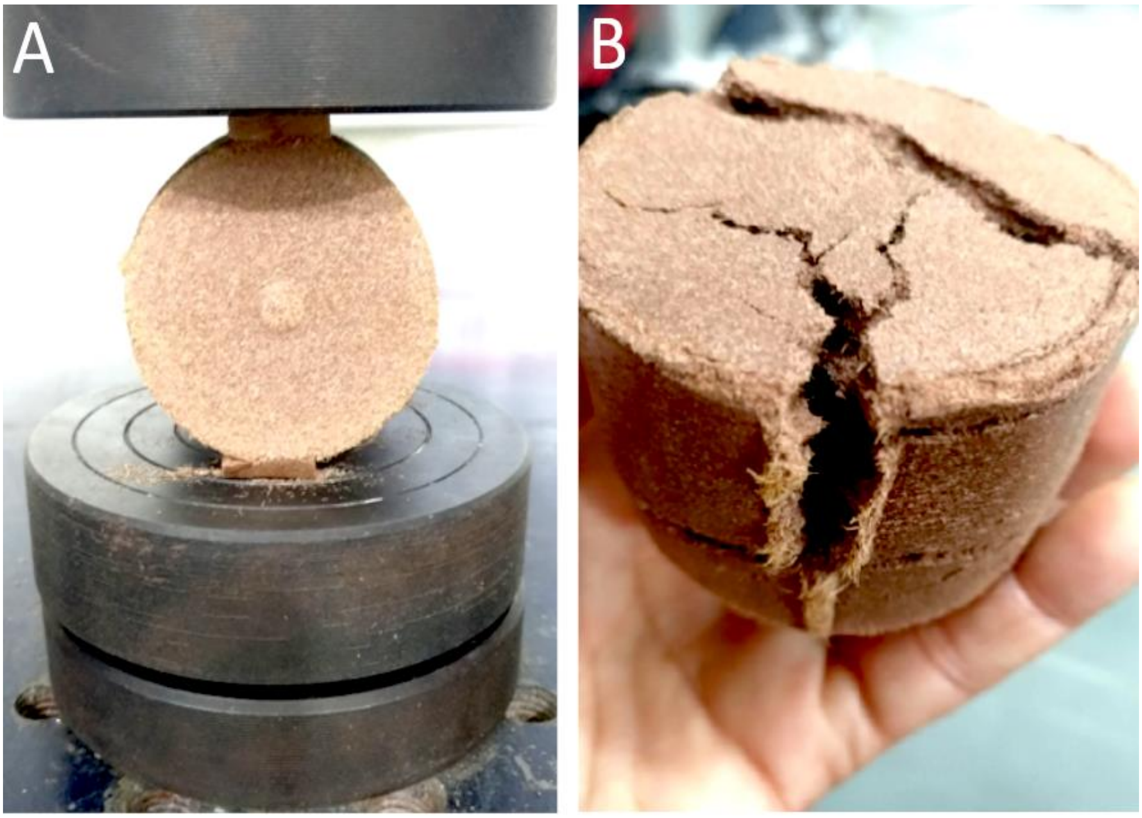


Figure 2. Compression test with hydraulic press on açai briquettes with 80 mesh particle size showing the (A) initial stage and (B) final stage of the testing process

The compressive strength of briquettes was determined to verify their mechanical behavior when subjected to a given load or stress since it is a significant parameter in the evaluation regarding their storage and transport. This analysis also evaluates the quality of compaction done in the energy densification stage, since briquettes with good compaction showed good strength (Brand et al., 2017).

The maximum number of stacked samples that a treatment supports was calculated for the number of vertically stacked briquettes (Nemp) (Silva et al., 2019). The calculation is performed by evaluating the maximum breaking force (FMrup), the factor of safety (fs), and the average mass of the samples (100 g) (Eq. 3). FMrup was determined from the compression test, and the fs was considered as 300%, i.e., it decreases FMrup by three times.

$$Nemp = \left(\frac{FMrup}{fs*0.1}\right) \quad (3)$$

Where:

Nemp = number of vertically stacked briquettes,

FMrup = maximum breaking strength,

fs = factor of safety.

Subsequently, it was possible to calculate the stacking height (Hemp), considering the average diameter of the briquettes as 5.4 cm (Eq. 4).

$$Hemp = \left(\frac{Nemp*5.4}{100}\right) \quad (4)$$

Where:

Hemp = number of vertically stacked briquettes,

Nemp = number of vertically stacked briquettes.

*Data analysis*

Statistical analysis was performed using Statistica software version 7.0 (Stat Software - USA). Initially, the sample data were treated based on descriptive statistics, considering the general range of data, measures of central tendency (arithmetic means), and variability (standard deviations), for ash content, bulk densities, energy densities, higher calorific value, lower calorific value, and useful calorific value.

The effects of the input variables of the briquetting process were also quantified for each biomass used in this work, through the analysis of variance (ANOVA), considering as a source of variation the particle size of the materials (wastes) and the pressing time. The differences between the means of the response variables due to the treatments and blocks were analyzed by hypothesis and Tukey tests, considering a 95% confidence level, *i.e.,* significance level $\alpha = 0.05$, in accordance with the precepts of parametric statistics, *i.e.,* independence and normality of residuals, absence of extreme points (outliers), and homoscedasticity.

For the impact strength test, the data were analyzed by the mean test of variance by Tukey's test with 95% reliability using the R-Studio program.

## Results and discussion

Characterization of the agro-industrial waste

To produce a high-quality fuel, the briquettes must have high values of calorific value and density, but a low percentage of ash, good mechanical strength, and some dimensional stability as well (Alves, Da Silva, Mumbach, Domenico, et al., 2022; Nair et al., 2022; Nakashima et al., 2017; Nunes et al., 2020). The Table 1 presents the results of the comparative analyses between the three types of waste and the conventional firewood used in the cooperative's boiler. The moisture content of waste varied on average from 8 to 12%, according to the moisture content range (8 to 12%) that provides better compaction during the briquetting process (Brand et al., 2017; De Oliveira et al., 2022; Gendek et al., 2018; Lisowski et al., 2019).

**Table 1.** Physicochemical and energetic properties of açaí, cupuaçu, and murumuru waste and briquettes. Where: MC - moisture content; VM - volatile material; FC - fixed carbon; BD - bulk density; HHV - higher heating value; LHV - lower heating value.

| Biomass | Form | MC (%) | VM (%) | Ashes (%) | FC (%) | BD ($g/cm^3$) | HHV (MJ/Kg) | LHV (MJ/Kg) |
|---|---|---|---|---|---|---|---|---|
| Açaí | waste | 12.00 ± 0.25 | 79.30 ±0.01 | 1.00 ±0.01 | 20.00 ±0.32 | 0.58 ±0.02 | 11.64 ±0.84 | 11.12 |
| | briquette | 0.97 ±0.48 | - | - | - | 0.98 ±0.09 | 14.95 ±0.11 | 14.56 ±0.09 |
| Cupuaçu | waste | 11.00 ± 0.32 | 75.90 ±0.01 | 1.20 ±0.06 | 23.80 ±0.78 | 0.35 ±0.01 | 12.82 ±0.31 | 12.34 |
| | briquette | 0.6 ±0.22 | - | - | - | 0.77 ±0.05 | 14.57 ±0.18 | 14.30 ±0.13 |
| Murumuru | waste | 8.00 ±0.05 | 74.03 ±0.81 | 3.40 ±0.03 | 22.60 ±0.63 | 0.66 ±0.01 | 13.39 ±0.03 | 13.07 |
| | briquette | 1.28 ±0.22 | - | - | - | 1.08 ±0.08 | 15.83 ±0,25 | 14.24 ±0.16 |
| Ordinary firewood | - | 24.97 ±0.06 | 71.50 ±1.32 | 4.67 ± 0.80 | 18.01 ±0.04 | 0.59 ±0.60 | 11.06 ±2.34 | 10.98 |

The ash contents of the three biomasses analyzed were low (1 to 3.4% - Table 1) when compared to corn cob meal biomass (6.54%) (Zhang et al., 2019), rice husk (14.23%) (Brand et al., 2017) and cassava biomass (14.45%) (Granado et al., 2021). However, the results of this study are similar to those found by Nunes *et al.* (2020) when analyzing coconut husk biomass (2.9%) and those found by Alves, Da Silva, Mumbach, Alves, et al., (2022) when evaluating macaúba endocarp (1.79%). The ash content is also undesirable for the operation of boilers, where the biomass can be burned for converting it into energy (Cherney e Verma, 2013; Sommersacher et al., 2012), since ash is responsible for generating incrustations, corrosion, unscheduled stops for maintenance, for example. Thus, the biomasses in this study can be considered good sources for energy purposes regarding the ash content.

The content of volatile material and fixed carbon for açaí waste (79.30% and 20%, respectively) were similar to the results found in other studies that analyzed chemical properties of *in natura* açaí seed in the Amazon, which ranged from 67 to 74% for volatile material content and, 25 to 30% for fixed carbon (Sato et al., 2019). The volatile material content for cupuaçu and murumuru waste was also similar to those found by other studies that analyzed this parameter in woody biomasses with an average ranging from 76% to 86% (Alves, Da Silva, Mumbach, Alves, et al., 2022; Okot et al., 2018). In general, high values of the volatile materials facilitate the ignition of the fuel at low temperatures and favor the pyrolysis process. On the other hand, fixed carbon represents the part of the fuel free of moisture, volatile materials, and ash. Studies conducted with different biomasses reveal that the higher volatile material content and lower ash content, usually, will provide high calorific value (Barskov et al., 2019). For Alves, Da Silva, Mumbach, Alves, et al. (2022), the potential of macaúba endocarp, with fixed carbon (22.02% by weight), high volatile matter content (76.19% by weight), and low ash content as previously mentioned (1.79% by weight), makes it an excellent candidate for energy production. These characteristics favor a high yield of volatile products, similar to the biomass analyzed in this study, and thus, they can be considered easily combustible biomass, given the volatile matter and fixed carbon values found.

The apparent density varied on average from 0.35 g/cm³ for the cupuaçu waste to 0.66 g/cm³ for the murumuru waste, results superior to those found by Granado *et al.* (2021) for cassava waste which showed an apparent density equivalent to 0.119 g/cm³. In addition, the waste presented a calorific value varying on average from 14.14 MJ/Kg to 30.2 MJ/Kg, values in the expected range for agricultural waste (15 MJ/Kg to 21 MJ/Kg) according to Bajwa *et al.* (2018).

The three types of agro-industrial waste showed better chemical and physical parameters for energy use than the firewood used as an energy source by the cooperative. Once conventional firewood presented high moisture and ash content that directly influences the combustion process and generation of inorganic residues, respectively (Granado et al., 2021).

*Briquettes and different types of agroindustrial waste*

The briquettes produced had a diameter varying on average from 51.59 mm for murumuru to 53.54 mm for cupuaçu and, height from 42.69 mm for cupuaçu to 63.15 mm for murumuru (Figure 3).


Figure 3. Briquettes made from açai (A), cupuaçu (B), and murumuru (C) with a grain size of 60 mesh (0.245 mm) subjected to a pressing time of 15 minutes. This image showcases the compacted biomass products after the briquetting process..

The moisture content for the three types of briquettes produced is in accordance with the literature for the production of briquettes and there was no change after the pressing process (Alves, Da Silva, Mumbach, Alves, et al., 2022; Lisowski et al., 2019)

The murumuru briquettes had the lowest average diametral expansion and the highest average longitudinal expansion than other types of briquettes (Figure 4).

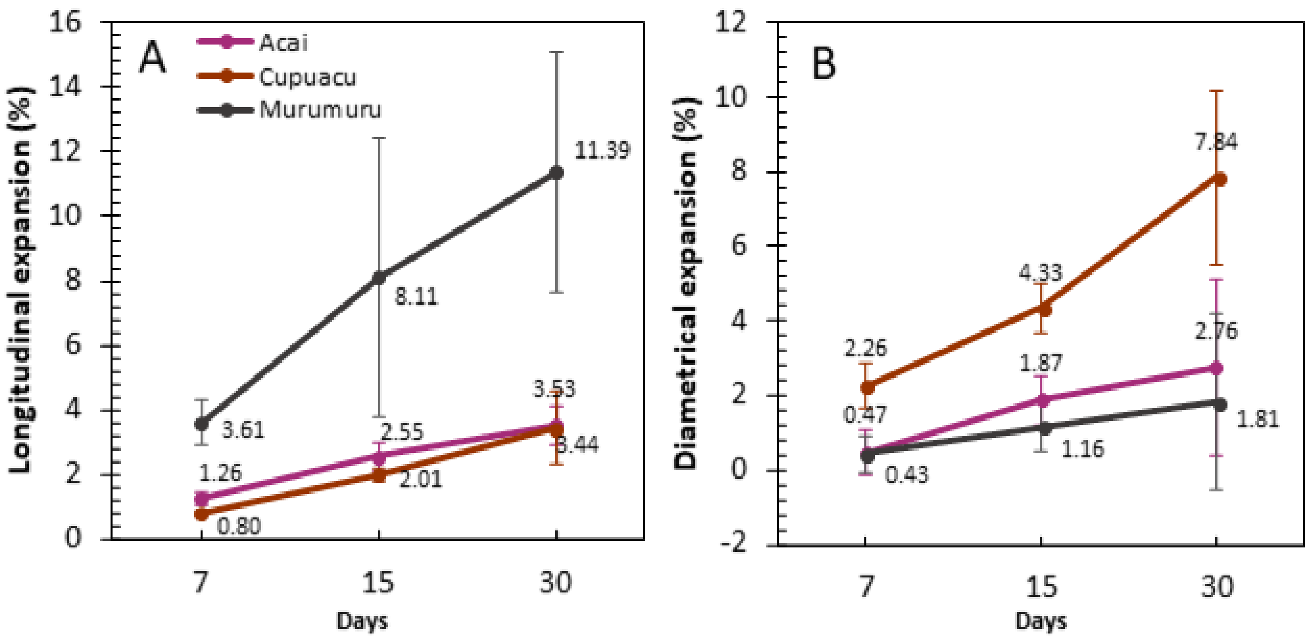


Figure 4. (A) Longitudinal expansion and (B) diametrical expansion measurements for the briquettes produced after 15 minutes of pressing of the biomasses under investigation. This data illustrates the dimensional changes experienced by the briquettes during the production process.

For Alves, Da Silva, Mumbach, Alves, et al. (2022), the potential of macaúba endocarp, with fixed carbon (22.02% by weight), high volatile matter content (76.19% by weight), and low ash content as previously mentioned (1.79% by weight), makes it an excellent candidate for energy production. These characteristics favor a high yield of volatile products, similar to the biomass analyzed in this study, and thus, they can be considered easily combustible biomass, given the volatile matter and fixed carbon values found. Also, for the purpose of comparison, the energy density of the murumuru briquettes is higher than briquettes produced with macauba waste (Acrocomia aculeata (Jacq.) Lodd. Mart.), a palm tree of the same family (Aracaceae) of murumuru (Evaristo et al., 2016).

Regarding the calorific value, the murumuru briquettes presented a higher percentage than the açaí and cupuaçu power (Table 1). After compression, the calorific value of the briquettes increased between 1.13 and 1.28 times in relation to the waste.

All the briquettes produced in this study did not resist the water absorption test, because they completely absorbed the water in the first 5 minutes of contact with it. Tests performed with pellets made with corn straw in the previous carbonization showed the same behavior (Yang et al., 2019).

Açaí and cupuaçu briquettes presented excellent impact resistance with preservation of above 80% of the initial weight after free-falling at 30, 60, 90, and 120 cm (Table 4). However, murumuru briquettes preserved only 44% of the starting material on average. Impact strength is a measure that evaluates the durability of briquettes and defines their tendency to produce dust or break when subjected to a destructive force (Okot et al., 2018).

In most cases, açaí briquettes presented the highest values of deformation (around 3.9 mm) and load (around 1.2 KN) in relation to cupuaçu (3.2 mm; 0.6 KN) and murumuru (3.3 mm; 0.2 KN) briquettes. Thus, when analyzing the highest load and lowest deformation the best waste with raw material for the production of briquettes are açaí for presenting better load capacity and deformation.

Açaí briquette had the highest stacking height (2.12 m) with 48 stacked briquettes, while the murumuru briquette had the lowest stacking height (0.47 m) and number of stacked briquettes (9 units) (Figure 5). The lowest performance of murumuru briquettes, not reaching even 1 m of stacking, can be justified because the structure of the material is very woody and under these conditions occurs only a rearrangement of particles and filling of empty spaces without the occurrence of deformation of the particles, facilitating its breakdown. Such behavior was also observed for briquettes produced with walnut shells (Lisowski et al., 2019).

*Effect of particle size and pressing time on briquettes*

The particle size of the briquettes significantly influenced the bulk density of briquette, while the pressing time did not show a significant difference (Table 2). However, for the 65 and 80 mesh sizes, the densities are considered statistically equal. And, the cupuaçu waste briquettes were not influenced by particle size or pressing time (Table 3).

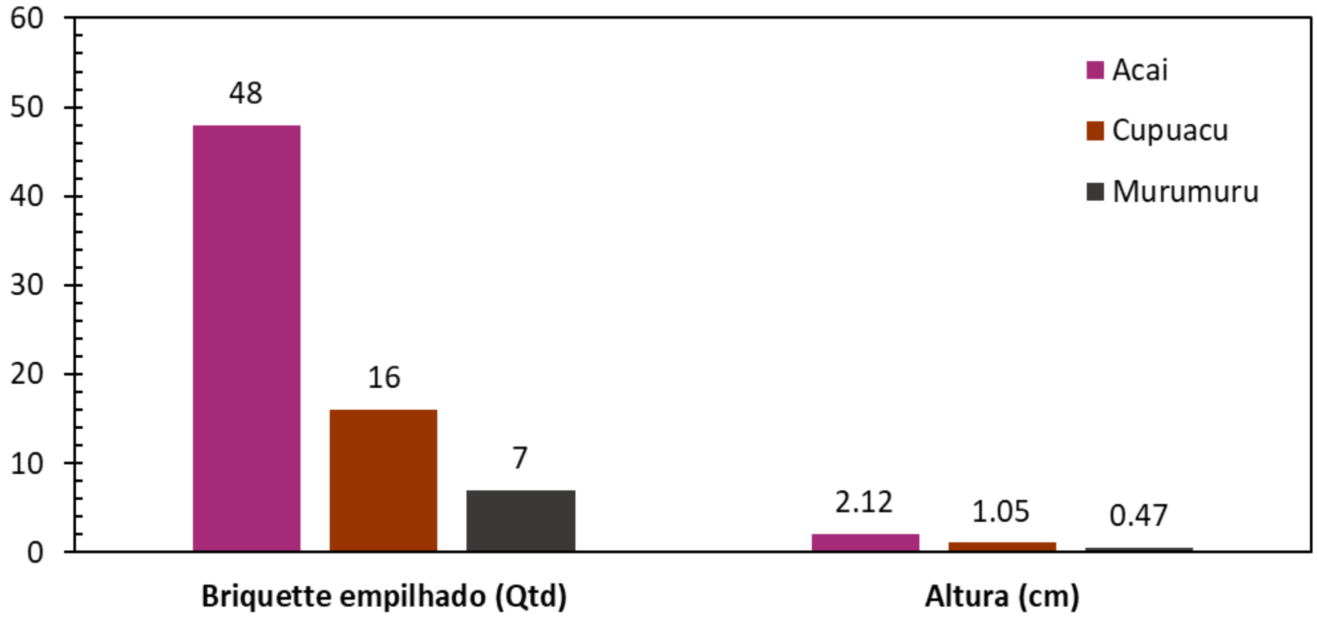


Figure 5. Number of stacked briquettes (Qty) and stack height (cm) formed by briquettes from agro-industrial waste of small agro-industries in the Amazon, using biomass from the fruits acai, cupuaçu, and murumuru.

**Table 2.** Analysis of variance of bulk density (g/cm$^3$) of briquettes obtained with the waste, as a function of treatments (granulometry - G) and blocks (pressing time -TP).

| Biomass | Variation source | GL | SQ | MQ | F | p-value |
|---|---|---|---|---|---|---|
| Açaí | TP | 2 | 0.0018 | 0.0009 | 0.98 | 0.4294 |
| | G | 3 | 0.071 | 0.0237 | 24.97 | 0.0009 |
| | Error | 6 | 0.0057 | 0.0009 | | |
| | Total | 11 | 0.0785 | | | |
| Cupuaçu | TP | 2 | 0.0055 | 0.0027 | 1.38 | 0.3222 |
| | G | 3 | 0.0181 | 0.006 | 3.05 | 0.1141 |
| | Error | 6 | 0.0119 | 0.001 | | |
| | Total | 11 | 0.0354 | | | |
| Murumuru | TP | 2 | 0.0133 | 0.0066 | 4.18 | 0.0731 |
| | G | 3 | 0.0517 | 0.0172 | 10.84 | 0.0078 |
| | Error | 6 | 0.0095 | 0.0016 | | |
| | Total | 11 | 0.0745 | | | |

**GL:** degrees of freedom, **SQ:** sum squared, **MQ:** mean squared, **F:** Fisher-Snedecor statistic, **p:** probability of significance.

**Table 3.** It shows that the particle size positively influences the bulk density of açaí and murumuru briquettes.

| Biomass | TP (min.) | Granulometry - G (mesh) | | | |
|---|---|---|---|---|---|
| | | 48 | 60 | 65 | 80 |
| Açaí | 10 | 0.83 a | 0.94 b | 1.08 c | 1.06 c |
| | 20 | 0.90 a | 0.99 b | 1.08 c | 1.04 c |
| | 30 | 0.88 a | 0.95 b | 1.01 c | 1.06 c |
| Cupuaçu | 10 | 0.82 d | 0.67 d | 0.78 d | 0.82 d |
| | 20 | 0.88 d | 0.80 d | 0.77 d | 0.83 d |
| | 30 | 0.89 d | 0.81 d | 0.79 d | 0.77 d |
| Murumuru | 10 | 0.99 e | 1.00 e | 1.16 f | 1.15 f |
| | 20 | 0.97 e | 0.96 e | 1.01 f | 1.10 f |
| | 30 | 0.98 e | 1.05 e | 1.18 f | 1.13 f |

Averages followed by different letters for the same biomass indicate that there was a statistical difference in Tukey's test at a 5% significance level ($\alpha = 0.05$).

The average bulk densities for the briquettes made from açaí and murumuru are equal in 65 and 80 mesh (Table 3). In the case of briquettes formed by cupuaçu, no differences were observed in the average densities as a function of particle size.

Thus, it is observed that the briquettes made with açaí are the most resistant for the 80 mesh particle size. For the results of impact strength, the authors Okot et al. (2018) establish that it is a measure that evaluates the durability of briquettes and defines their tendency to produce dust or break when subjected to a destructive force. It is an indicator of the mechanical strength of briquettes, so its value should be as high as possible. Considering the comparative effect of the briquettes in relation to particle size and pressing time (Table 4), the experiment in general indicates that the açaí and cupuaçu briquettes were not influenced by these parameters, presenting satisfactory results above 80% of remaining mass. Thus, the results found are consistent with studies for briquettes produced with corn cobs and coffee husk, with a moisture content range of 8 and 12%, respectively, according to Okot et al. (2018) and Brand et al. (2017).

Adeleke et al. (2021) evaluated the properties of composite briquettes made from wood torrefaction and coal fines. They found that the briquettes exhibited densities ranging from 0.92 to 1.31 g/cm³ after curing, with significant compressive and impact strength. This study highlights the importance of briquette composition and curing process in enhancing mechanical strength, providing a parallel to the briquettes produced in this study.

Niño et al. (2020) studied the influence of different mixed biomass, such as rice husk and pine sawdust, on the mechanical properties of briquettes. They found that the mechanical durability of the briquettes was over 97.5%, meeting existing standards. This result suggests that the choice of biomass and the mixing process can have a significant impact on the mechanical properties of the briquettes.

Therefore, the smaller the particle size the greater the power of densification and resistance present. Briquettes that contain high impact strength are considered to be of high quality because they minimize the possibility of breakage and dust formation during transportation. So far there are no certified standards for biomass briquettes, but some researchers report that this test needs to show a response between 80 and 90% or more than 90% for better handling and transportation. These results are in agreement with those found by Lubwama and Yiga (2018), who worked with non-carbonized coffee husk briquettes at 10-ton pressure.

**Table 4.** Percentage (%) of mass remaining in the impact strength test in relation to the free fall launch height (cm) of briquettes produced in particle sizes of 48, 60, 65, and 80 mesh from the biomass of different agro-industrial residues of açaí stone (A), cupuaçu shell (C) and murumuru seed husk (M).

| **Briquettes** | **Height of falling briquettes (cm)** | | | |
|---|---|---|---|---|
| | **30** | **60** | **90** | **120** |
| A48 | 97,90 $^{bc}$ | 96,62 $^{b}$ | 81,79$^{c}$ | 75,41$^{e}$ |
| A60 | 99,58 $^{a}$ | 98,72 $^{a}$ | 96,53$^{ab}$ | 94,89$^{b}$ |
| A65 | 98,42 $^{abcs}$ | 96,55 $^{b}$ | 98,07$^{a}$ | 98,44$^{a}$ |
| A80 | 97,65 $^{c}$ | 97,93 $^{ab}$ | 97,92$^{a}$ | 97,68$^{a}$ |
| C48 | 99,.01$^{abc}$ | 66,22 $^{d}$ | 66,12$^{d}$ | 65,44$^{f}$ |
| C60 | 99,32$^{ab}$ | 94,08 $^{c}$ | 94,8$^{ab}$ | 85,4$^{c}$ |
| C65 | 99,41 $^{ab}$ | 93,55 $^{c}$ | 92,61$^{b}$ | 85,14$^{c}$ |
| C80 | 99,08 $^{abc}$ | 99,6 $^{a}$ | 82,48$^{c}$ | 80,1$^{d}$ |
| M48 | 27,62 $^{e}$ | 0 $^{g}$ | 0$^{f}$ | 0$^{h}$ |
| M60 | 68,99 $^{d}$ | 55,75 $^{f}$ | 0f | 0$^{h}$ |
| M65 | 69,26 $^{d}$ | 60,91 $^{e}$ | 60,58$^{e}$ | 0$^{h}$ |
| M80 | 99,62 $^{a}$ | 99,48 $^{a}$ | 98,40$^{a}$ | 60,63$^{g}$ |
| **p-Value:** | **0,1186** | **0,0442** | **<0,01** | **<0,01** |

$^{a,b,c,d,f,g,h}$ Means, followed by different lowercase letters in the row differ from each other by the Tukey test at 5% significance level.

## Conclusion

It is considered that the evaluated biomasses can be good sources of energy, because they present low ash contents and the energy density is higher than others found in the literature, highlighting the high energy potential of biomass.

The briquettes produced from açaí showed greater strength and quality than the others, followed by those produced with cupuaçu. However, in terms of energy efficiency, the briquettes obtained from murumuru waste are superior to the others, based on the experimental values of energy density.

The pressing time was not a statistically influential variable in the production of briquettes, so in the shortest time (10 minutes) briquettes were obtained with quality and durability. Therefore, the production and use of briquettes from the reuse of agroindustrial waste are relevant to the sustainability and preservation of the environment.

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