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Articles

An alternative method to increase the energy potential of briquettes *Anadenanthera macrocarpa* (Benth.) Brenan

Um método alternativo para elevar o potencial energético de briquetes de *Anadenanthera macrocarpa* (Benth.) Brenan

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ABSTRACT

The creation of innovative materials for the reuse of waste generated by the wood industry represents a significant set of energy that can be harnessed. This work aimed to examine an alternative approach to increase the energy capacity of briquettes made from wood species. The biomass used for this test was the angico of the species Anadenanthera macrocarpa. Particles of the angico wood Anadenanthera macrocarpa were compressed without the addition of binders, at pressures that reached 300 MPa. Then, the resulting briquettes were immersed in an aqueous solution containing 63% carbonaceous materials, until their porous microstructures were completely saturated and, finally, they were heat treated in the oven until all moisture from their microstructures was eliminated. The briquettes created were analyzed by measuring the apparent and energy density, in addition to proximate analysis' and evaluation of the upper and lower calorific value. Whole briquettes were produced with energy density values reaching 11970-11969 MJ/m³.

Keywords: Energy density; Briquettes; Carbonaceous solids; Binders

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RESUMO

A criação de materiais inovadores para a reutilização de resíduos gerados pela indústria madeireira representa um significativo conjunto de energia que pode ser aproveitado. Este trabalho teve como objetivo examinar uma abordagem alternativa para aumentar a capacidade energética de briquetes feitos de espécies madeireiras. A biomassa utilizada para esse teste foi a angico da espécie *Anadenanthera macrocarpa*. Partículas da madeira de angico *Anadenanthera macrocarpa* foram comprimidas sem a adição de aglutinantes, em pressões que chegaram a 300 MPa. Em seguida, os briquetes resultantes foram mergulhados em uma solução aquosa que continha 63% de materiais carbonáceos, até que suas microestruturas porosas estivessem completamente saturadas e, finalmente, foram tratados termicamente no forno até que toda a umidade de suas microestruturas fosse eliminada. Os briquetes criados foram analisados através da medição da densidade aparente e energética, além de análise imediata e avaliação do poder calorífico superior e inferior. Briquetes inteiros foram produzidos com valores de densidade energética que atingiram 11970-11969 MJ/m³.

Palavras-chave: Densidade energética; Briquetes; Sólidos carbonáceos; Ligantes

1 INTRODUCTION

According to Genovese (2006), biomass is the organic matter of the earth, and the main representative of this class is plant residues. In terms of energy, biomass is described by all forms of plants and derivatives that can be converted into usable energy, such as wood, urban and forestry waste, grains, vegetable oils and sludge from biological effluent treatment. And this energy provided by biomass is known as bioenergy. Furthermore, among all the forms of biomass that are used as fuels, in our country the ones that have the greatest share of use in terms of quantity are those that come from wood, such as firewood, briquettes, sawdust and chips. And also due to the large Brazilian sugar and alcohol production, we have sugarcane bagasse, which is also widely used.

Several recent studies have demonstrated the high technical and economic potential of using wood waste to generate electricity in Brazil. According to Alves et al. (2023), forest biomass, especially eucalyptus, has an energy density greater than 18 MJ/kg, which makes it competitive with other agricultural sources such as sugarcane bagasse (14 MJ/kg). This characteristic gives eucalyptus a strategic position in the national renewable energy matrix.

According to Moreira (2025), the use of mixtures of Amazonian waste in decentralized systems can achieve conversion efficiencies greater than 25%, with levelized electricity costs ranging between US$ 0.11 and US$ 0.19/kWh. These values fall within the competitiveness range observed in forest biomass projects in Minas Gerais, which vary from US$ 0.10 to US$ 0.24/kWh, according to regional studies.

In addition, national estimates point to an annual availability of over 200 million tons of wood waste from sawmills, furniture industries, and eucalyptus plantations (Alves et al., 2023). This volume corresponds to a potential electricity generation of approximately 20 GW, equivalent to about 10% of Brazil's installed capacity.

From an environmental point of view, Moreira (2025) demonstrates that replacing coal with woody biomass can reduce CO_2 emissions in industrial processes by up to 90%, reinforcing the role of bioenergy as a vector for climate mitigation.

According to Mojtahezadeh (2025), investigates in his study sustainable pruning and wood waste management strategies in Tehran through a comprehensive economic, environmental, and operational assessment. The authors employ quantitative analyses to compare conventional disposal practices with optimized sustainable approaches, focusing on cost efficiency, resource utilization, and emission reduction. The research highlights the potential of integrated waste management systems to enhance operational performance while minimizing environmental burdens. Results demonstrate that sustainable strategies not only reduce greenhouse gas emissions but also improve energy recovery potential and overall system resilience. The findings underscore the necessity of aligning technical solutions with policy frameworks to achieve long-term sustainability in urban waste management.

Dovichi Filhoet al. (2025) proposes an integrated methodology to evaluate the technical and economic potential of electricity generation from biomass waste, with an emphasis on thermochemical conversion technologies. The application was carried out in the state of Minas Gerais, Brazil, considering waste from the corn, soy, coffee, eucalyptus, and sugarcane production chains. The results indicate that

eucalyptus stands out as the most appropriate biomass, due to its high energy density, while sugarcane waste has greater availability in terms of volume. Economic analysis revealed levelized electricity costs ranging from US$0.10 to US$0.24 per kWh, with the conventional Rankine cycle being the most cost-effective alternative for projects with a capacity greater than 5 MWe.

Dinesha et al. (2019), Saccol (2020) , Franco (2022) and Bays (2024), as reported by the authors, a significant increase in the briquette market in Europe is expected by 2030, driven by the RED III targets and the search for renewable alternatives to coal and natural gas. The global market is expected to grow from approximately USD 0.96 billion in 2025 to USD 1.44 billion in 2030, at a compound annual growth rate (CAGR) of approximately 8.39%, with Europe emerging as one of the main consumers. RED III is the third version of the European Union's Renewable Energy Directive, approved in october 2023, which establishes more ambitious targets for increasing the share of renewable energy in the European energy mix, setting a binding target of 42.5% by 2030, with the possibility of reaching 45% inform us that a significant increase in the briquette market is expected in Europe. Although it currently leads the global market for this biomass, Brazil, as the second country in the world with the largest forest area, presents itself as a potential producer of these materials. Therefore, a strong competitor for the supply of briquettes to the Brazilian and global markets.

According to Alves et al. (2023), between 2021 and 2022, approximately 779.6 million tons of agricultural waste were generated in Brazil. If converted into energy, this would correspond to approximately 12.1 million PJ (1015 Joules). Currently, there is already a considerable market, but it still does not fully meet the needs of Brazilian industry (Saccol, 2020). The increase in the energy properties of wood and briquettes can be significantly increased by subjecting these materials to processing techniques such as carbonization and torrefaction. These are widely used to increase the energy yield from these biomasses (Imaniraguha et al., 2025) in his study, observed the potential of using cassava peel and guinea grass as viable raw materials for briquette

production, offering an environmentally friendly alternative for energy generation. Immediate analysis showed promising fuel characteristics, corroborating the suitability of these biomass sources for briquetting. Future research should focus on emissions testing, which was not performed in this study, as this test allows for an assessment of the environmental impact during combustion. Furthermore, including a boiling test in water would be beneficial to evaluate the actual cooking efficiency of the briquettes in real-world situations. Addressing these aspects will provide a more comprehensive assessment of the briquettes' performance and sustainability Obi et al. (2022).

Furthermore, according to Almeida et al. (2015), Sena et al. (2021) and Marreiros et al. (2021), briquetting through combinations of temperature and compaction pressure is a well-known process that reuses solid waste to produce fuels with high energy density. However, to our knowledge, there are no published studies that address the production of intact briquettes without the use of binder and temperature, which present an increase in their energy density of more than 50%. In the present study, angico wood waste (*Anadenanthera macrocarpa*) was compacted at pressures of up to 300 MPa. Then half of it was immersed in a solution enriched with carbonaceous solids until saturated. The other half was not immersed. Comparing the results with each other, it was possible to identify a percentage increase in energy density of up to 62.33% in the saturated briquettes.

From an energy perspective, the possibility of enriching the microstructure of different wood species with carbon, through the incorporation of carbonaceous solids, is a promising alternative. This approach is not limited exclusively to wood, but can be extended to other forms of solid biomass, including those described by Rendeiros and Nogueira (2008), which also have the potential to benefit from this enrichment process. The main objective of this work was to associate in an exploratory way the combined action of pressure and the presence of carbonaceous solids in the microstructure of the briquettes with the behavior of their energy properties. The quantitative data presented by Alves et al. (2023) and Moreira (2025) confirm that the treatment and

utilization of wood waste in Brazil is technically feasible, economically competitive, and environmentally strategic. Forest biomass, especially eucalyptus, emerges as one of the main alternatives for diversifying the energy matrix, reducing emissions, and promoting sustainability in the electricity sector.

2 MATERIALS AND METHODS

Particulate waste from angico wood of the *Anadenanthera macrocarpa* type with a particle size equal to or less than 0.85 mm (20 mesh) was used in the present study. Samples weighing 14.5 g were compacted without binders prior to drying. Compaction was performed at five pressure levels: 100, 150, 200, 250, and 300 Mpa (23.1, LG23.2). For quantitative analysis, a total of 100 briquettes were compacted, with 20 produced at each pressure level (24.1 LG24.2 25.1). Subsequently, 10 briquettes were immersed until saturation in a liquid solution enriched with 63% carbonaceous solids. The remaining briquettes were left in their compacted state only..The process of saturating the briquettes with carbonaceous solids required the complete removal of the initial moisture from the biomass. For this, the samples were subjected to drying in an oven at 105°C ± 5°C, being weighed at regular intervals until the difference between two consecutive measurements did not exceed 0.5%, as established by NBR 14929 (ABNT, 2003). This criterion ensures the obtaining of constant mass, a necessary condition for the adequate characterization of the biomass (63% carbonaceous solids). Then, all manufactured specimens were characterized via immediate analysis, calorific value, apparent density, and energy density. The proximate analysis was performed based on the standard (ASTM D 1762-84, 2021). It consisted of determining the moisture, volatile material, ash, and fixed carbon contents on a dry basis. The fixed carbon content was calculated according to standard NBR 8112 (ABNT, 1986).

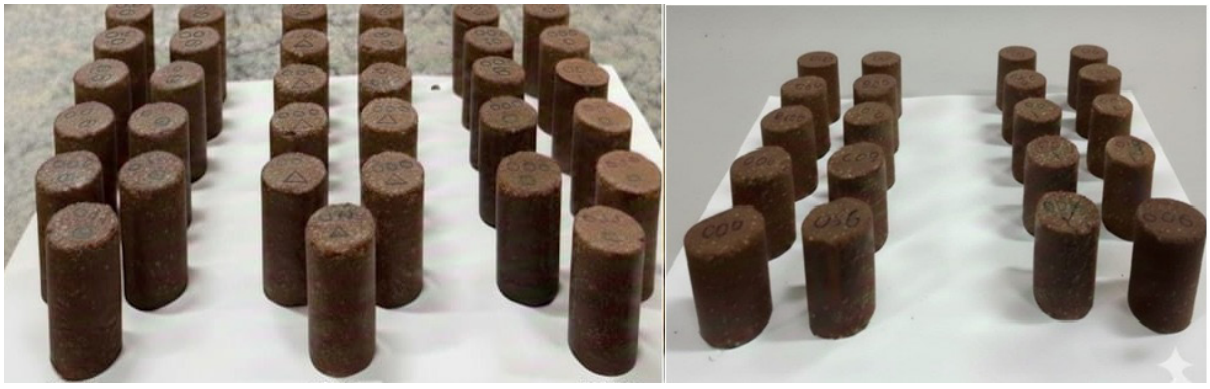
All analyses were performed in triplicate. The calorific value was estimated according to the equation of Parikh et al. (2005) and the apparent density was measured according to standard NBR 6922 (ABNT, 1981), in a container with a volume equivalent to a box with internal dimensions of 22.90 x 22.90 x 22.90 mm.

3 RESULTS AND DISCUSSION

The typical configuration of the compacts produced is shown in Figures 1, 2, and 3. It can be seen that, under all conditions evaluated—moist, dry, or saturated with carbonaceous solids—the briquettes preserve their original shape. This uniformity demonstrates the physical stability of the material in the face of different processing stages, confirming its structural strength and the reliability of the method employed Saturated.

When comparing the briquettes without moisture with the dry and saturated ones, produced at the same pressure, a significant change in their dimensions and, probably, an increase in their mass can be seen. The addition of the aqueous solution enriched with carbonaceous solids was the determining factor for the emergence of these changes.

Figure 1 – Image of dry briquettes (a) and (b)



200 mPa 250 mPa 300 mPa 100 mPa 150 mPa

(a) (b)

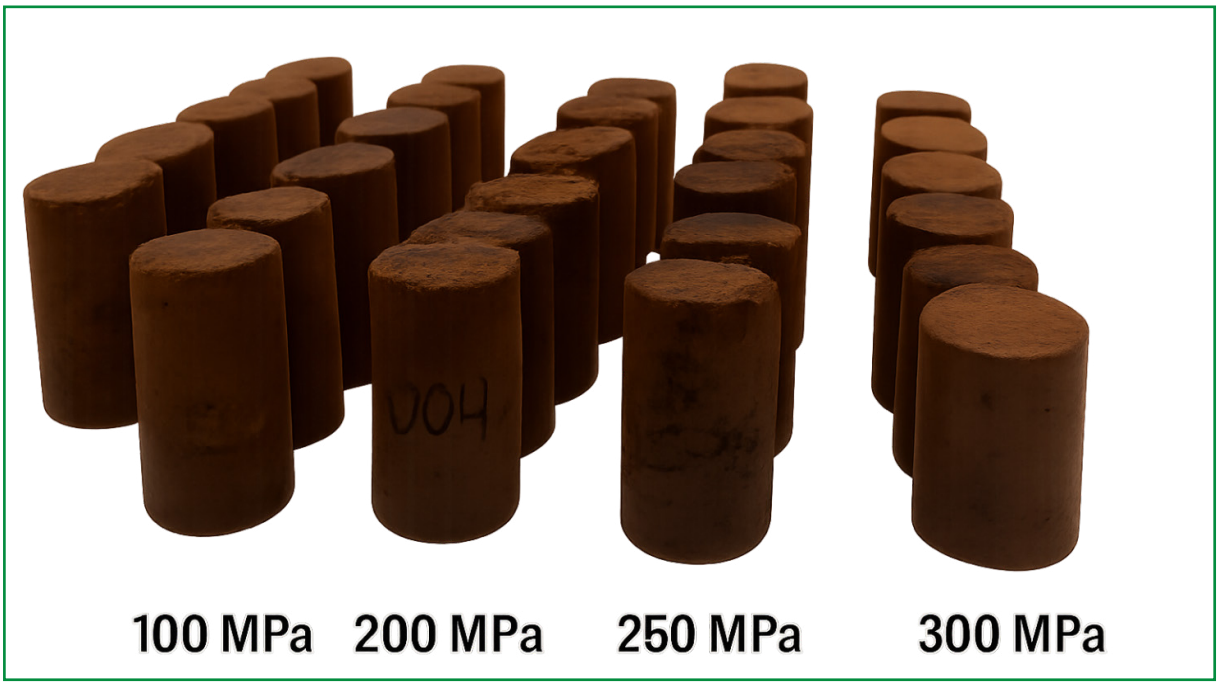
Source: Authors (2025)

Figure 2 – Image of wet briquettes (a) and (b)



Source: Authors (2025)

Figure 3 – Image of briquettes: (a) saturated and dry



Source: Authors (2025)

Table 1 shows the masses of the dry unsaturated briquettes and the dry briquettes saturated with carbonaceous solids. The confirmation of the mass change mentioned previously in Figure 3 is confirmed by the results presented. When comparing the briquettes compacted at the same pressure, a clear increase in mass is noted in all those that were saturated. This occurs due to the incorporation of carbonaceous particles into the structure of these materials, being more evident in those that were compacted under a pressure of 100 MPa. In this scenario, the mass of the briquettes increased by approximately 55%.

It is essential, at this point, to also discuss the results in terms of the relationship between the filling of the pores, their quantity and size distributed in the structure of these materials. The quantity and size of the pores or voids present in the briquettes are reduced during their compaction under different pressures. According to Soares (2022), the dynamics of particle deformation is associated with the reduction in their size and consequently with their rearrangement during their compaction. The filling of the pores in these materials will depend fundamentally on this dynamic particle rearrangement. Therefore, briquettes of different types of wood produced under the same pressure and those of the same type of wood produced under different pressures will present different sizes and quantities of pores distributed in their microstructure.

In the present study, the increase in mass in briquettes saturated or unsaturated with carbonaceous substances is associated with the filling of their pores with wood residue dust and/or carbonaceous solids, respectively. The voids previously occupied by moisture are now occupied by solid particles. The pores not filled with wood dust in the briquettes compacted at each pressure were filled with carbonaceous solids until their size was smaller than the pore. Therefore, the total mass of the saturated briquettes will be the sum of the masses of wood dust and carbonaceous substances versus their respective percentages distributed in the microstructure of these materials.

Table 1 – Mass results of briquettes obtained at different pressures, saturated or not with carbonaceous materials

Pressure (MPa)	Mass (g)		
	Unsaturated Dry briquette (M_s)	Saturated drought	$\Delta M = M_{ss} - M_s$
100	13,0918±0,0486	20,2745±0,9667	7,1827± 0,9679
150	13,1271±0,0234	19,8593±0,8191	6,7322± 0,8194
200	13,1499±0,0115	18,2171±0,5750	5,0671± 0,5711
250	13,1358±0,0169	19,0259±0,8807	5,8901± 0,8809
300	13,1146±0,0392	14,9216±0,3070	1,807± 0,3095

Source: Authors (2025)

Table 2 presents the results of the i proximate analysis of briquettes with and without the inclusion of the carbonaceous solution. When comparing the results, a significant decrease in moisture content is noted in those that received saturation with carbonaceous substances. According to Foelkel (2016), this circumstance contributes significantly to improving the energy efficiency of briquettes and is highly relevant for energy production in boilers. According to Moreira, Lima and Goulart (2012), biomass with lower moisture content has higher calorific value, resulting in an increase in the amount of energy supplied by the fuel, improving boiler performance and reducing the cost to produce the same amount of energy.

Another relevant point is the reduced ash content, observed mainly in briquettes saturated with the carbonaceous solution. All concentration levels are below 2.5%. In comparison, the most significant reduction in ash content (30.3%) occurred in those compacted at 150 MPa. According to Carvalho et al. (2021), a content below 4% is recommended for energy production in boilers. Under these conditions, corrosion, wear or scale formation in the equipment are reduced, thus reducing boiler maintenance costs.

The increase in the mass of the briquettes, as discussed in the results shown in Table 1, together with the decrease in their moisture content and the reduced ash content, suggest the possibility of significantly increasing their energy density.

Table 2 – Results of the statistical analysis of briquettes saturated or not with carbonaceous solids

Briquettes	% Moisture	% Volatiles	% Fixed carbon
AB10CC	2,5033	74,5473	24,7092
AB15CC	1,9750	79,7024	19,6414
AB20CC	2,5033	73,7376	24,8424
AB25CC	1,8367	73,3414	25,1273
AB30CC	2,1467	73,6677	25,2021
AB10SC	5,3633	74,8214	24,3678
AB15SC	6,5217	74,7998	23,9377
AB20SC	6,0133	74,2160	23,9740
AB25SC	5,9412	74,5226	24,4231
AB30SC	5,8850	74,7078	24,0578

Source: Authors (2025)

Note: In the briquette nomenclature, the number corresponds to the compaction pressure, CC and SC to briquettes saturated and unsaturated with carbonaceous solids, respectively.

Table 3 presents the values of calorific value, bulk density and energy density of the manufactured briquettes. As observed, the saturated briquettes have a higher bulk density than the unsaturated ones, even when manufactured under the same pressure. Since the size of the particles used to measure the bulk density varied from 60 to 100 mesh, it is likely that the carbonaceous particles played a significant role in the increase in the number of particles smaller than 100 mesh. Therefore, the bulk density values in the saturated briquettes increased.

Table 3 also shows the values of the energy properties obtained for the compacted samples, both without and with the inclusion of carbonaceous solids. It can be observed that the mass growth had a considerable impact on the increase in the energy density of these materials. Although the amount of wood and/or carbonaceous particulates added to the microstructure of the briquettes may vary, the total sum of

these components was mainly responsible for the increase in the energy density of these materials. The research indicates that the highest energy densities were 10.343 MJ/m^3 to 11,969 MJ/m^3 for briquettes with compaction between 100 MPa and 200 MPa.

In relation to the results of Soares (2023) for angico wood (*Anadenanthera macrocarpa*), a significant growth is observed.

Table 3 – Results of the energetic properties of the briquettes

Samples	PCS (MJ/Kg)	PCI (MJ/Kg)	Bulk density	Energy density (MJ/m^3) PCS	PCI
AB10CC	20,5844	17,3498	502,4556	10342,746	8717,5031
AB15CC	19,6128	16,3782	592,7766	11625,994	9708,5985
AB20CC	20,4975	17,2629	583,9550	11969,596	10080,735
AB25CC	20,5344	17,2998	573,2314	11770,938	9916,7640
AB30CC	20,4480	17,2133	438,2353	8961,0363	7543,4765
AB10SC	20,5067	17,2721	438,2353	8986,7825	7569,2664
AB15SC	20,3477	17,1131	463,7019	9435,2617	7935,3714
AB20SC	20,2634	17,0288	368,1953	7460,8966	6269,9319
AB25SC	20,3044	17,0700	410,6514	8338,0306	7009,8197
AB30SC	20,2019	16,9673	403,3367	8148,1670	6843,5342

Source: Authors (2025)

Note: The number corresponds to the compaction pressure of the briquettes, AB to briquette CC and SC to briquettes saturated and unsaturated respectively with carbonaceous solids

4 CONCLUSIONS

The interaction between compaction pressure and carbonaceous solids saturation in the briquette structure resulted in a significant increase in energy density, especially under a pressure of 200 MPa. Under this condition, when comparing unsaturated briquettes with saturated briquettes, a 62.33% increase in energy density was observed. The incorporation of carbonaceous solids increased the fixed carbon content, responsible for greater energy release during combustion.

The compaction process associated with saturation decreased water retention, favoring energy efficiency. Briquettes produced under pressures of 100 and 150 MPa

presented energy densities of 10.343 MJ/m³ and 11.625 MJ/m³, respectively. These values are particularly relevant because they fall within the typical operating range of industrial briquetting machines, demonstrating the practical viability of application on an industrial scale. We can cite several reasons for the observed increase in energy density, which are: greater structural compaction, application of high pressures, reduction of internal pore spaces, and increase in the volumetric density of the material.

There was also an improvement in internal cohesion, as the pressure promoted greater bonding between particles, resulting in more resistant briquettes with less mass loss during handling and combustion. The increase in apparent density reduced internal voids and the higher concentration of solid material per unit volume, which explains the observed energy gain.

If we examine the results obtained, those referring to those compacted at the aforementioned pressures are the most intriguing, mainly because industrial briquette machines can produce them in this pressure range. In terms of energy, the results achieved paved the way for briquettes of any wood, produced as in the present study, without the use of heat and full of carbonaceous materials, to have a considerable increase in their energy density.

In addition, it may result in: a) the availability of an alternative method for the manufacture of wood briquettes with high energy potential; b) the possibility of their use in the generation of energy in boilers; c) aggregation of value to solid biomass residues; d) reduction of the large amount of disposal of these materials as garbage in the areas where they are produced; e) the creation of an alternative for the reduction of deforestation in several areas of the country.

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