BRIQUETTES MADE FROM GREEN COCONUT HUSK FIBER – ENERGY AND SUSTAINABILITY

BRIQUETES DE FIBRA DA CASCA DO COCO VERDE – ENERGIA E SUSTENTABILIDADE

BRIQUETAS DE FIBRA DE CÁSCARA DE COCO VERDE – ENERGÍA Y SOSTENIBILIDAD

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ABSTRACT

The need to readjust energy production methods to reduce environmental impact involves the strategic use of biomass. Through biomass densification, which can be made up of agricultural waste, it is possible, using the briquetting technique, to obtain high-density blocks with a high degree of compaction, defined as briquettes. Briquettes are high-energy materials that can significantly contribute to the energy matrices of various countries. A proposal for the development of studies aimed at guaranteeing and optimizing the production of briquettes using green coconut husk residue mixed with crude glycerol (resulting from the biodiesel production process) could optimize the production of high-quality coated briquettes with a sustainable character. The proposal is based on studies already developed and found in the literature, in which green coconut fiber is collected, used in its natural state or transformed into charcoal by slow pyrolysis, mixed in predefined proportions with glycerol to obtain briquettes. The physicochemical properties of these briquettes are evaluated simultaneously with characterization tests, with the aim of determining an ideal proportion of the mixtures of the components involved that result in briquettes with better energy performance for specific applications. The development of proposals such as this implies a scientific contribution to the current energy transition process and can also solve local and/or regional problems related to the high production and inadequate disposal of green coconut husks. Although the demand for briquettes made from green coconut waste in Brazil and other coconut-producing

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regions is influenced by several factors, its market potential in the industrial, commercial, and residential sectors can be considered. Although it is challenging to precisely quantify the current demand for green coconut waste briquettes in Brazil without access to specific market data, the significant potential for growth in this demand is evident, driven by the need for low-carbon energy sources, sustainability, and the development of public policies that encourage the use of renewable energies, stimulating market prospecting. Thus, briquette production can open new markets and create local value chains, generating income for coconut-producing communities due to its energy efficiency.

Keywords: Energy Recovery. Biomass Briquettes. Green Coconut. Decarbonization of the Economy. Low Carbon.

RESUMO

A necessidade de readequar os meios de produção de energia para reduzir o impacto ambiental envolve o aproveitamento estratégico da biomassa. Por meio do adensamento da biomassa, que pode ser constituída por agro resíduos, é possível, com a técnica de briquetagem, a obtenção de blocos de alta densidade e alto grau de compactação definidos como briquetes. Os briquetes são materiais de alto valor energético que podem contribuir significativamente nas matrizes energéticas de diversos países. Uma proposta de desenvolvimento de estudos que visem garantir e otimizar a produção de briquetes utilizando resíduo de casca de coco verde misturadas ao glicerol bruto (resultante do processo de produção de biodiesel) poderá otimizar a obtenção de briquetes de elevada qualidade revestidos de caráter sustentável. A proposta se baseia em estudos já desenvolvidos e encontrados na literatura, na qual a fibra de coco verde é coletada, utilizada in natura ou transformada em carvão por pirólise lenta, misturadas em proporções pré-definidas com o glicerol, para a obtenção de briquetes com a avaliação de suas propriedades físico-químicas de forma simultânea com ensaios de caracterização, com o intuito de determinar uma proporção ideal das misturas dos componentes envolvidos que resultem em briquetes de melhor desempenho energético para aplicações específicas. O desenvolvimento de propostas como esta implica em contribuição científica no processo de transição energética atual podendo ainda solucionar problemáticas locais e/ou regionais relacionadas à elevada produção e descarte inadequado de cascas de coco verde. Embora a demanda por briquetes de resíduos de coco verde no Brasil e em outras regiões produtoras de coco seja influenciada por vários fatores, é possível considerar o seu potencial de mercado nos setores industrial, comercial e residencial. Ainda que seja um desafio quantificar exatamente a demanda atual por briquetes de resíduos de coco verde no Brasil sem acesso a dados de mercado específicos, é evidente o potencial significativo para o crescimento dessa demanda, impulsionado pela necessidade de fontes de energia de baixo carbono, pela sustentabilidade e pelo desenvolvimento de políticas públicas que incentivem o uso de energias renováveis, estimulando a prospecção mercadológica. Assim, a produção de briquetes pode abrir novos mercados e criar cadeias de valor locais, gerando renda para comunidades produtoras de coco dada a sua eficiência energética.

Palavras-chave: Recuperação Energética. Briquetes de Biomassa. Coco Verde. Descarbonização da Economia. Baixo Carbono.

RESUMEN

La necesidad de reajustar los métodos de producción de energía para reducir el impacto ambiental implica el uso estratégico de la biomasa. Mediante la densificación de la biomasa, que puede estar compuesta por residuos agrícolas, es posible, mediante la técnica de briquetado, obtener bloques de alta densidad y alta compactación, conocidos como briquetas. Las briquetas son materiales de alto valor energético que pueden contribuir significativamente a las matrices energéticas de diversos países. Una propuesta para el desarrollo de estudios destinados a garantizar y optimizar la producción de briquetas utilizando residuos de cáscara de coco verde mezclados con glicerol crudo (resultante del proceso de producción de biodiésel) podría optimizar la producción de briquetas recubiertas de alta calidad y con un carácter sostenible. La propuesta se basa en estudios ya desarrollados y encontrados en la literatura, en los que se recolecta fibra de coco verde, se utiliza en su estado natural o se transforma en carbón vegetal mediante pirólisis lenta, mezclándose en proporciones predefinidas con glicerol para obtener briquetas. Las propiedades fisicoquímicas de estas briquetas se evalúan simultáneamente con pruebas de caracterización, con el objetivo de determinar la proporción ideal de las mezclas de los componentes involucrados que resulten en briquetas con mejor rendimiento energético para aplicaciones específicas. El desarrollo de propuestas como esta supone una contribución científica al proceso actual de transición energética y también puede resolver problemas locales y/o regionales relacionados con la alta producción y la eliminación inadecuada de la cáscara de coco verde. Si bien la demanda de briquetas elaboradas con residuos de coco verde en Brasil y otras regiones productoras de coco está influenciada por diversos factores, se puede considerar su potencial de mercado en los sectores industrial, comercial y residencial. Si bien resulta difícil cuantificar con precisión la demanda actual de briquetas de residuos de coco verde en Brasil sin acceso a datos específicos del mercado, el importante potencial de crecimiento de esta demanda es evidente, impulsado por la necesidad de fuentes de energía bajas en carbono, la sostenibilidad y el desarrollo de políticas públicas que fomenten el uso de energías renovables, estimulando la prospección de mercado. Por lo tanto, la producción de briquetas puede abrir nuevos mercados y crear cadenas de valor locales, generando ingresos para las comunidades productoras de coco gracias a su eficiencia energética.

Palabras clave: Recuperación de Energía. Briquetas de Biomasa. Coco Verde. Descarbonización de la Economía. Bajas Emisiones de Carbono.

1 INTRODUCTION

Biomass is understood as one of the main sources of energy in the world, with the expectation of greater participation in the energy matrices of several countries, especially those with greater potential for agricultural production. While European countries and the USA are making significant progress towards the development of technologies for the use of biomass, Latin American countries, including Brazil, still need to focus more attention on reducing the use of firewood, coal and petroleum products in power generation.

One of the viable alternatives to act directly on the problem related to the use of this type of input is the use of biomass, which is a raw material to supply modern bioenergy production chains, including the use of pellets or briquettes (produced from the compaction of residual biomass such as agro-waste) for the generation of electricity and heat (Silva *et al.,* 2022).

Resulting from agricultural activities, agro-waste consists mainly of organic materials and involves leaves, stems, bark, seeds and bagasse, among other parts of the plants (Moorthy; Bibi, 2023). They can be used in the production of biosorbent materials, agricultural substrates and biodegradable materials, playing an important role in the transition to a circular economy (Singh *et al.*, 2023).

In some countries, the consumption of coconut water and green coconut pulp has increased the generation of coconut shells, which are waste that are difficult to collect and properly dispose of, producing severe social, economic and environmental impacts. The use of the large amount of this permanently generated biomass meets a growing demand for more sustainable energy generation processes that contribute to the reuse of solid waste, mitigation of greenhouse gas emissions and reduction of global warming (Miola *et al.*, 2020).

From the pressing and densification of small pieces of biomass, such as pruning wood or coconut shells, briquettes can be obtained, which have a density between 650 and 1,200 kilograms per cubic meter, a diameter of approximately 60 mm and a length of 250 to 300 mm (EMBRAPA, 2012). The quality and performance of a briquette depend on several factors, such as the production technique and geometry used, but mainly on moisture, ash content, possible surface modifications of the vegetable fibers and the quality of the binder used, an aspect that requires further development and innovation. The burning of biomass in the form of briquettes with high calorific value represents, in addition to energy production, the reduction of methane gas emissions derived from the decomposition of biomass, especially when the material is improperly disposed of in dumps, buried or not (Zhanga; Suna; Xua, 2018).

The production of good quality briquettes from biomass is highlighted by the important contribution of the implementation of appropriate technologies for energy production and waste management in developing countries, including the application of the energy generated in the combustion of briquettes to feed electrolyzers and green hydrogen production (Zhang *et al.*, 2022).

2 THEORETICAL FOUNDATION

2.1 GENERAL CONSIDERATIONS

The search for alternative energy sources is an emergency and has been a trend around the world (Raju *et al.,* 2021).

Carbon production by biomass is a major industrial source of energy conversion. In countries with large agricultural production, such as African and Asian countries and Brazil, similar scenarios occur: after harvesting, a significant amount of agricultural residues or residues remain, which can be used as biomass energy (Promdee *et al.*, 2017).

It is expected that by 2030, approximately one billion individuals in emerging economies will suffer serious difficulties in using primary energy. A significant part of its primary energy demand is met through firewood. Unsustainable harvesting practices used in the routine harvesting of forest resources for residential and commercial purposes pose serious threats to climate change, environmental degradation, biodiversity loss and risks to human health (Ossei-Brmang *et al.*, 2024). This results in an annual depletion of about 3.9 million hectares and a loss of carbon assets totaling up to 317 Mton within these forest reserves, as reported by FAO (2021).

Biomass valorization can be effected by different paths and technologies, including briquetting, incineration, pyrolysis, gasification and hydrogen production. These are initiatives to reduce the environmental impact associated with the final disposal of waste and greenhouse gas emissions, mainly methane (CH4) and carbon dioxide (CO2) (González; López; Pérez, 2020).

Densification (manufacture of pellets and briquettes) represents a promising strategy for the reuse of biomass. Pelleting and briquetting facilitate the production of solid biofuel with low moisture content, high bulk and particle density, as well as homogeneous shape and size, with high calorific value (González; López; Pérez, 2020).

The low bulk density of agro-waste requires densification via briquetting and/or pelleting (briquettes and pellets are biofuels with high energy content by volume and, in most Latin American countries, densified biofuels are still an emerging market, despite having a great potential for production already explored in European countries and the USA, due to the high calorific value and valued environmental appeal (Silva *et al.*, 2022).

2.2 AGRICULTURAL WASTE

In order to comply with the seventh Sustainable Development Goal (SDG 7), which advocates "Ensure access to affordable, reliable, sustainable and modern energy for all", it can be seen that there is a need to increase efforts to replace firewood with efficient, clean energy sources with less negative environmental impact (Akam *et al.*, 2024).

The use of municipal and solid waste as an alternative source of energy needs further research. Producing fuel briquettes with naturally available and biodegradable waste is an advantage. The use of biomass briquettes has environmental benefits that include reduced tree degradation, better waste management, and reduced emissions (Raju *et al.*, 2021).

Although there are several ways to convert biomass into energy, several studies indicate that making biomass briquettes has several benefits, such as improving calorific value and allowing for easy transport, storage, entry into the furnace, and combustion. Briquetting is a sustainable way to provide alternative energy solutions. In addition, briquettes made from biomass are a renewable and cost-effective resource and do not pollute the environment as they do not contain sulfur (Akam *et al.*, 2024).

In the briquetting of coconut shells, the energy balance shows that the useful energy, consumed mainly during the briquetting process, is mechanical and thermal energy. An economic analysis was carried out over a period of 20 years in Cameroon, Africa. This analysis is mainly composed of the cost of employee labor, which represents about 30% of total expenses, after expenses with diesel fuel (10–16% of total expenses). The net value for coconut shell waste was set at €67,189. The economic viability of briquette production is sensitive to the market price of the briquette, the discount rate and the cost of capital. In conclusion, the production of briquettes from crop residues could be economically benefited by the adoption of appropriate strategies in Cameroon and in any developing country (Bot *et al.*, 2022).

Despite the apparent limitations such as low bulk density, transport and storage logistics, and relatively low energy content in relation to fossil fuels, the use of biomass as the waste generated by the production and consumption of green coconut for energy production has particular properties and advantages, such as renewable nature, availability and geographical diversity, facilitating the deployment of energy systems and ensuring a sustainable supply chain in relation to other energy resources (Miola *et al.*, 2020).

2.3 THE GREEN COCONUT

The coconut originated in Sri Lanka and has been planted in 90 countries, but mostly in Asia and the Pacific. Coconuts are produced today at 60.77 million tons per year on 12.30 million hectares in more than 94 countries worldwide (Bot *et al.*, 2022).

The coconut tree belonging to the Palmae Family is known scientifically as Cocos nucifera L., and is the source of the multipurpose product known as coconut. The tree is native to Southeast Asia, from where it spread to South America, Africa, and the rest of the Asian continent. Coconut palms flourish in tropical and rainforest climates, especially along the coast, where they enjoy abundant sunlight as well as water and high humidity. In addition to the edible interior, coconut shells are known to be valuable raw materials for the production of activated carbon, a vital material that provides high surface area (1,000 m2/g) for adsorption/absorption of different gases, liquids, emulsions, and fine suspensions (Promdee *et al.*, 2017)

Information on the quantities of green coconut shells discarded in the areas where coconuts are consumed is inaccurate, making it difficult to manage this waste and to assess the potential of this material to obtain other products that, in addition to reducing the impact on the environment, contribute to economic development and the health of populations (Akolgo *et al.*, 2021).

On average, the coconut shell represents about 85% of the weight of the fruit and has a presumed composition of 33.30% lignin, 30.58% cellulose, 26.70% hemicellulose, 8.86% water and 0.56% ash. Due to lack of management and investment by the public or private sector, the peels are not used as raw material for wider production in Brazil (Nunes *et al.*, 2020).

The green coconut shell is formed by fiber and powder, represented by the mesocarp and endocarp of the fruit. Through the crushing and pressing of the shells, a liquid called Green Coconut Shell Liquid (LCCV) can be extracted, which can be used in the formulation of phenolic resins, in fermentation processes, for biogas generation and for fertilization of agricultural crops (Nunes *et al.*, 2020).

There is potential for the use of coconut shells, in the form of fiber or powder, for the production of magnetite nanoparticles, biosorbents for the removal of heavy metal ions, thermal insulation boards, production of agglomerates and panels, substrates for planting vegetables and various fruits, blankets for soil protection, organic filter elements, reinforcement in polymeric matrices, in the aggregation of cement or concrete composites for civil construction and briquette production (energy recovery) (Nunes *et al.*, 2020).

Solid waste management and the growing demand for energy are a global concern. Waste can play the role of an alternative fuel, partially reducing the environmental footprint in the waste management sector. Waste briquetting is used as a treatment option to improve the efficiency of waste combustion, as well as its management and handling (Zhang *et al.*, 2022).

Brazil ranks fourth in the world in coconut production, and the state of Bahia leads with an annual production of approximately 550 thousand tons of fruit (IBGE, 2015). This indicates an amount of up to three million tons of unused green coconut per year (Brasil, 2017). However, it is not known how much green coconut shell is thrown away at the place of consumption, which makes it difficult to manage the amount of waste produced in the region (Santos *et al.,* 2019), making it difficult to manage the waste, associated with the pollution of public spaces (up to 10 years for the coconut shell to degrade in the environment), contributing as places for mosquito breeding and disease transmission (Nunes *et al.*, 2020).

The adequate (gravimetric) quantification of green coconut shell waste in each location makes it possible to raise awareness about reuse and recycling, promoting the saving of natural resources, the reduction of environmental pollution and the generation of direct and indirect jobs (Nunes *et al.*, 2020).

The scale of woody waste generation and inefficient disposal result in substantial costs for municipal management and landfills in Brazil and have environmental implications. A significant amount of solid waste is generated annually, from urban and agricultural environments, and is often not disposed of properly (Marreiro *et al.*, 2024).

The use of green coconut shells as a raw material leads to a reduction in greenhouse gas emissions, considering that the decomposition of this material produces methane (CH4) especially under anaerobic conditions that occur in dumps (3). Considering the recommendation of the Intergovernmental Panel on Climate Change (IPCC, 2000), the potential for generating methane gas is between 6.0 and 12.3 kg/ton of the shells discarded in the environment (Nunes *et al.*, 2020).

2.4 BRIQUETTES

Briquettes replace firewood and can be produced directly from crushed biomass or in a form of charcoal. Briquetting is a process that transforms biomass or other organic matter into a regular-shaped material that can be used as fuel in boilers or industrial furnaces. To produce a high-quality fuel, it is necessary that the briquettes achieve high calorific value, high density, low ash content, good mechanical resistance and a certain dimensional stability (Nunes *et al.*, 2020).

Briquettes derived from organic waste offer a sustainable energy solution. Factors such as biomass proportion, briquetting pressure, and binder ratio are fundamental to achieve adequate caloric value and mechanical properties (Ossei-Brmang *et al.*, 2024).

An estimate of the average daily amount of green coconut shells needed to supply an industrial briquetting machine corresponds to a volume of 56 m3. When such an amount is used for the production of new goods, the useful life of the discarded bark is extended and there is less waste added to landfills and dumps. The equivalent amount of fiber (in kilograms per month) that these wasted shells could generate is approximately 25% of the fiber per unit of coconut (Nunes *et al.*, 2020).

It is important to consider that most Brazilian cities that produce or consume green coconut do not have landfills or other forms of waste management, such as reverse logistics, recycling, reuse or energy recovery (Nunes *et al.*, 2020).

Waste briquetting is an option that facilitates transport, handling and storage and improves the quality of material combustion. The waste becomes effective to be used to replace firewood, kerosene, charcoal, charcoal, among other fossil fuels and biomass-based (Zhang *et al.*, 2022).

The production of briquettes from green coconut shells is still under development and is currently under investigation. Studies indicate that the production of briquettes with green coconut shells is feasible and can be carried out by compacting the fiber in blocks, without the use of carbonization and with appropriate binders (Nunes *et al.*, 2020).

Sant'anna *et al.* (2012) studied the feasibility of producing briquettes with green coconut shell and 20% glycerol, and showed that a plant with productivity equal to 1 t/h is economically viable, producing 8 h/d, more than 260 days per year, thus obtaining a Net Present Value (NPV) of R$ 141,711.54, with an Internal Rate of Return (IRR) of 11.30% and 5.5 years of return.

The quality of densified biomass depends on the type of biomass, moisture content, particle size, temperature, binder used, and densification pressure, which affect its energy potential and its performance in thermochemical processes (González; López; Pérez, 2020).

There are few cases of briquetting mechanisms without the addition of ligands. About briquetting mechanisms from the point of view of the interaction between ligands and the biomass used, pertinent to this proposed research, there are three theories: the solid bridge connection (the pores and the surface of the briquette particles are covered with ligand, a solid bridge is formed at the point of contact of the particles), the electrostatic attraction (a chemical bond or hydrogen bond is formed when ligand molecules interact with active groups or pairs of electrons available in the biomass matrix) and that of the liquid bridge connection (the adhesion energy and the degree of wetting of the briquette increase) (Zhang; Sun; Xu, 2018).

2.5 BINDERS

The briquette binder plays a key role in the production process and the quality of briquettes. Clarification of the briquette binder briquetting mechanism can not only provide a theoretical basis for the development of the binder, but can also provide a ballast for the industrial production of briquettes (Zhang; Sun; Xu, 2018).

Binder materials are used to improve the mechanical and thermal properties of briquettes. Lignocellulose, lignin or cellulose binders increase the calorific value of waste-based briquettes. Briquette binders can be divided into three groups: organic, inorganic, and compound binders. In particular, a composite binder can reduce the need for inorganic binder materials, lowering the cost of briquette production and reducing ash content (Ferronato *et al.*, 2022).

The briquetting and pelleting of agricultural residues using binders such as starch and wood powder were investigated. Cassava starch and corn starch were used as binders for the manufacture of biomass-based briquettes with good results in densification and lower cost. Sawdust, charcoal, and molasses binder increase the fixed carbon content, with increased compressive strength. Cassava starch increases the compaction rate in the production of briquettes. Therefore, it is suggested that binding materials are an additional component to improve the quality of biomass-based briquettes (Ferronato *et al.*, 2022).

The glycerol generated as a by-product of biodiesel production can be used as a binder in the manufacture of briquettes. During the transesterification step, approximately 10% of the total biodiesel production is crude glycerol, which is considered a by-product of the process. Thus, new strategies to take advantage of glycerol, especially in combustion processes, have been investigated, including the combination of glycerol with solid fuels (González; López; Pérez, 2020).

Crude glycerol is an important by-product of biodiesel commonly produced by a transesterification process, which uses raw materials such as vegetable oils or animal fats to react with short-chain alcohols with the aid of catalysts. Crude glycerol has received considerable attention due to its huge amount associated with the high global biodiesel production rate, considering a biodiesel production of 46.7 million cubic meters globally in 2019, with an increasing trend in the future (Rath; Mahapatro; Pattanayak, 2023).

The use of glycerol for the production of pellets and briquettes has been pointed out as a simple and low-cost solution to add value to this by-product. Glycerol improves the durability and energy performance of dense biomass. The addition of glycerol as a binder can lead to lower ash content, higher densities and increases in calorific value. Energy density can increase when glycerol is added as a binder, including due to its combustible characteristic. In addition, glycerol contributes to facilitate the formation of briquettes due to the favored bonding between biomass particles, also acting as a lubricant between the biomass feedstock and the matrix (González; López; Pérez, 2020).

Over the years, Indonesia has taken the world lead in biodiesel production (17% of the total share), followed by the USA (14%), Brazil (12%), Germany (8%), France (6.3%) and Argentina (5.3%). This geographical distribution is a clear indication that production, as well as the challenges associated with it, have a global impact (Sandid; Spallina; Esteban, 2024).

Crude glycerol is considered a low-value residual raw material and whose disposal is restricted due to its dangerous nature, including the possibility of fire and oxygen depletion in the water that suffocates the fish. As a result, exploring the value-added use of crude glycerol and its main component, glycerol, is critical for the biodiesel industry to maximize its economic and environmental benefits (Rath; Mahapatro; Pattanayak, 2023).

The dizzying growth of the biodiesel industry has led to an oversupply of glycerol by-product as a direct consequence, which has been detrimental to its market value. The chemical reactivity that this compound possesses makes it an excellent building block from which many synthetic routes can originate. In the last two decades, as a way to update glycerol, there have been major developments in experimental approaches to obtain different products with applications such as fuel additives, green solvents or precursors of other materials (Sandid; Spallina; Esteban, 2024).

During the preparation of pellets and briquettes, crude glycerol serves as a binder to increase yield yield, production rate, and durability (Rath; Mahapatro; Pattanayak, 2023). The addition of glycerin increased the overall thermal efficiency of briquettes produced with sawdust, dry corrugated paper, and rice and coffee husks (Jamradloedluk; Lertsatitthanakorn, 2015).

Glycerol also works efficiently in reducing soot by being highly oxygenated, changing the oxygen concentration profile during fuel/air mixing. The high oxygen content of glycerol can withstand early-stage reactions even at a relatively low air concentration, raising the local temperature above the soot-forming threshold and making it difficult for soot to form. In addition, glycerol has three OH groups that can prevent the growth of the aromatic ring and suppress the formation of acetylene, which is the main precursor to soot generation. Glycerol as an oxygenated fuel could produce a particular type of soot, the surface of which contains different oxygen groups that are highly reactive and are able to promote secondary oxidation of soot before it is emitted. It is important to consider that, in addition to the binding capacity for agro-waste due to the hydrogen bonds promoted by glycerol, the burning of this material generates small portions of nitrogen and sulfur gases, with the possibility of minimizing these gaseous emissions using appropriate treatments (Rath; Mahapatro; Pattanayak, 2023).

2.6 PROPERTIES OF BRIQUETTES

Some of the fundamental properties that impact the quality of the briquette are moisture content, ash content, amount of volatile matter, fixed carbon, sulfur content, calorific value, and water resistance (Raju *et al.*, 2021).

The amount of carbon and hydrogen in the briquette is an equally important factor, as it is an indication of how much these components contribute to the briquette's combustibility. The composition of biomass also affects its combustion characteristics as the total mass of the fuel decreases during the volatile combustion phase and changes the relationship between the constituent elements of the material (Fernandez *et al.,* 2017*;* Zhang; Sun; Xu, 2018; Raju *et al.*, 2021).

Moisture content: The total energy required to bring a briquette to its pyrolytic temperature depends on its moisture content, which affects the internal temperature of the briquette due to endothermic evaporation. The lower moisture content of briquettes implies a higher calorific value (Fernandez *et al.,* 2017*;* Zhang; Sun; Xu, 2018; Raju *et al.*, 2021).

Ash content: ashes can give rise to the formation of clinker in furnaces, impacting the yield of chemical reactions. These samples, when burned, will give rise to significant environmental pollution (Fernandez *et al.,* 2017*;* Zhang; Sun; Xu, 2018).

Fixed carbon: this is the percentage of carbon (solid fuel) available for the combustion of coal after the distillation of a volatile matter. Fixed carbon provides a rough estimate of the calorific value of the fuel and acts as the main heat generator during burning (Raju *et al.*, 2021).

Volatile matter: Briquettes with a high volatile matter content ignite easily and are highly reactive in combustion applications. With the increase in the volatile matter content of the briquette, there is a decrease in the calorific value of the briquette (Fernandez *et al.,* 2017*;* Zhang; Sun; Xu, 2018; Raju *et al.*, 2021). The combustion of volatiles reduces smoke and contributes to the total heat released by the fuel (Promdee *et al.*, 2017).

Caloric value: it is one of the most influential factors in the burning of briquettes. The higher the calorific value, the easier and better they will be burned (Fernandez *et al.,* 2017*;* Zhang; Sun; Xu, 2018).

Porosity: Low porosity makes mass transfer difficult during combustion due to fewer spaces for mass diffusion. The higher the porosity, the higher the oxidant infiltration rate and the outflow of the combustion/pyrolysis products during combustion and the higher the briquette burning rate (Fernandez *et al.,* 2017*;* Zhang; Sun; Xu, 2018; Raju *et al.*, 2021).

Water absorption: lower water absorption will imply greater density and, consequently, easier burning (Fernandez *et al.,* 2017*;* Zhang; Sun; Xu, 2018; Raju *et al.*, 2021).

Breakage rate: important to ensure that storage, transportation, and handling are easier (Raju *et al.*, 2021).

Compressive strength: the compressive strength of briquettes is one of the indices used to evaluate their ability to be handled, packaged and transported without breaking (Promdee *et al.*, 2017).

Degree of densification: is defined as the percentage increase in biomass density due to briquetting. The degree of densification represents the material's ability to bond (Fernandez *et al.,* 2017*;* Zhang; Sun; Xu, 2018; Raju *et al.*, 2021).

Power estimation and power calculation: to produce 1 kWh of electrical energy, 10,285.71 KJ of steam energy is required (electric energy generation = steam energy ÷ 10,285.71 kJ/kWh). The power estimate can be calculated by the ratio: mass of the material x calorific value / burning time (Raju *et al.*, 2021).

2.7 MARKET PROSPECTING

Under the context of a growing increase in the consumption of coconut water accompanied by a relevant increase in the generation of waste, basically consisting of the fibrous shells of the green coconut, associated with its sometimes inadequate disposal, bringing risks to public health, in addition to representing significant costs to urban cleaning. The possibility of obtaining new products and circular inputs with added value from the adoption of conversion processes, such as briquetting and pyrolysis, considered environmentally and economically viable for the use of available waste, can stimulate the implementation of new business models, with the generation of values, employment and income, increasing the competitiveness of the important green coconut production chain (EMBRAPA, 2020).

Brazil is the fifth largest producer of coconuts in the world, but participates with only 3.7% of the total, which corresponded to 62.9 million tons in 2019 (BNB, 2021). The world's two main exporters of coconut derivatives (mostly water, oils and desiccats) are also the largest producers, Indonesia and the Philippines, with respective shares of 32.1% and 24.2% in total exported volumes. The top 10 exporters account for 86.4% of total revenues; Brazil is in the 47th position with a share of only 0.03% in this market. The coconut tree is cultivated in almost all of Brazil, whose current area is 187.5 thousand hectares, with production of 1.6 billion fruits with an average skin weight of 0.9 kg (giant coconut tree) and an average yield of approximately 30% of fiber and 70% of powder in the industrial process. It is estimated that 80% of the Brazilian coconut production is destined to the purchasing industry, with the shell as a by-product, Brazil has a production potential of 804,218 t of shell that, after industrialization, would result in 241,265 t of fiber and 562,953 t of powder. In the Northeast region, the main national producer, 80.9% of the harvested area of coconut in the country and 73.5% of its production are concentrated. The value of national coconut production was R$ 1.15 billion, with a share of 62.6% from the Northeast (IBGE, 2020).

Clasen *et al.* (2022) proposed a "circular" model with the use of green coconut shells generated by the municipalities of the Baixada Santista as raw material for the manufacture of briquettes. The results showed that the technical-operational aspects of the circular model are consistent, and can be implemented. This proposal made it possible to reduce greenhouse gas emissions by 40 thousand tons per year when compared to the linear model. Additionally, it presented a profitability of 66%, a profitability of 195% and, with the return on investment in six months, it was evident that there is financial viability in this model.

The demand for green coconut waste briquettes in Brazil and other coconut-producing regions is influenced by several factors, including environmental awareness, the cost of fossil fuels, and policies to encourage renewable energy. In Brazil, coconut production is significant, especially in the Northeast and North regions, providing an abundant raw material for the production of briquettes. However, the utilization of this biomass is still growing, with the majority of the briquettes market focused on wood waste.

The main initial challenges would be regarding its availability and logistics chain regarding the collection and processing of green coconut waste, which may represent logistical and cost challenges, affecting the availability and price of briquettes, in addition to competition with other biomasses such as wood and agricultural waste, which may influence demand.

While it is difficult to quantify the current demand for green coconut waste briquettes in Brazil without access to specific market data, it is evident that there is significant potential for growth in this demand. This growth will be driven by the need for cleaner and more sustainable energy sources, the abundance of green coconut waste in producing regions, and the development of public policies that encourage the use of renewable energy. The expansion of this market will also depend on the ability to overcome logistical and cost challenges and the effectiveness in communicating the environmental and economic benefits of green coconut briquettes to potential consumers.

On the environmental side, the production of briquettes from green coconut shells contributes significantly to waste management, turning an abundant and often discarded agricultural by-product into a valuable resource. Additionally, green coconut shell briquettes have a lower carbon footprint compared to fossil fuels, contributing to climate change mitigation. By replacing wood and charcoal with coconut shell briquettes, there is a reduction in pressure on forests, promoting the conservation of ecosystems and biodiversity.

From an economic point of view, the production of briquettes can open new markets and create local value chains, generating income for coconut-producing communities, in addition to recognizing their energy efficiency because they are considered very efficient as fuel, offering a cost-competitive alternative for industries and homes.

3 FINAL THOUGHTS

Brazil stands out worldwide for the mostly renewable composition of its energy matrix, although it still depends on the exploration and use of fossil fuels. There is, however, a paradox regarding sustainability, which is the substantial waste of biomass with potential for energy recovery.

Despite the consolidated use of sugarcane bagasse and forest residues for energy cogeneration, a vast amount of biomass from other agro-industrial activities, urban waste and effluents is neglected or disposed of inappropriately, not to mention the inappropriate use of wood from illegal deforestation.

Such organic material represents an untapped energy potential that could contribute to national energy security, reduce water dependence, and mitigate environmental problems associated with waste management.

Therefore, there is the challenge of transforming this environmental liability into an energy asset, optimizing the use of its natural resources and consolidating a truly circular development model.

Energy recovery from the burning of briquettes produced with green coconut shells, a vast waste usually disposed of inappropriately, and the use of glycerol, a by-product of biodiesel manufacturing, as a binder, represents one of the important alternatives that should be better explored for the mitigation of environmental impacts, with an important socioeconomic contribution.

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