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Artigo Técnico

Briquettes production from green coconut shells: technical, financial, and environmental aspects

Produção de briquetes da casca de coco verde: aspectos técnicos, financeiros e ambientais

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ABSTRACT

The United Nations Sustainable Development Goals emphasize the need to better understand and propose solutions for the growing demand for resources and the generation of waste by anthropic systems at any scale and intensity. Although it can be considered as secondary importance problem, hundreds of tons of green coconut shell residues annually generated in the Brazilian coastal cities are transported and dumped in landfills, wasting their energy potential and resulting in economic and environmental problems – this approach is known as take, make, disposal, or "linear" production model. This work proposes a "circular" model by using the biomass from green coconut shells generated by the cities of Baixada Santista region as a raw material for briquettes production. Technical-operational, environmental, and financial aspects are considered to assess the proposed "circular" model in comparison with the existing "linear" model. Results show that technical-operational aspects of the "circular" model are viable due to already existing technologies in the market that can be easily adapted for the purposes in converting green coconut shells into briquettes. The "circular" model proposed allows a reduction in greenhouse gases emission by ~40 thousand tons year^{-1} when compared to the "linear" model, besides avoiding leachate generation. Furthermore, the 66% profitability, 195% rentability, and 6 months of investment payback suggest the financial viability of briquettes production. Together, all these indicators claim for public policies incentives and private investments to make the proposed "circular" model a reality, which is aligned with the objectives of 2030 agenda.

Keywords: Baixada Santista; circular economy; coconut biomass; global warming potential; leachate.

RESUMO

Os objetivos do desenvolvimento sustentável enfatizam a necessidade de melhor entender e propor soluções para a crescente demanda de recursos e geração de resíduos pelos sistemas antrópicos, em qualquer escala e intensidade. Embora em princípio possam ser considerados como um problema de menor importância, os resíduos de casca de coco verde gerados nas cidades litorâneas brasileiras são transportados e despejados em aterros sanitários, desperdiçando-se seu potencial energético e resultando em problemas econômicos e ambientais — conhecidos como modelo "linear" de gerenciamento. Este trabalho propõe um modelo "circular" com o uso das cascas de coco verde geradas pelos municípios da baixada santista como matéria-prima para a fabricação de briquetes. Aspectos técnico-operacionais, ambientais e financeiros são considerados para avaliar a o modelo circular de forma comparativa ao modelo linear existente. Os resultados mostram que os aspectos técnico-operacionais do modelo circular são consistentes, passíveis de serem implementados. Esta proposta possibilita a redução na emissão de gases de efeito estufa em 40 mil toneladas por ano quando comparada ao modelo linear, além de não gerar lixiviado. Adicionalmente, a lucratividade de 66%, a rentabilidade de 195% e o retorno sobre o investimento de seis meses evidenciam a viabilidade financeira deste modelo. Estes resultados sustentam a necessidade de políticas públicas e/ou investimentos privados para tornar o modelo circular proposto uma realidade, em busca de atingir os objetivos da agenda 2030.

Palavras-chave: baixada santista; economia circular; biomassa de coco; potencial de aquecimento global; lixiviado.

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INTRODUCTION

Population growth has been causing an increase pressure on natural capital due to the growing demand for resources and waste generation. As promoted by the United Nations Sustainable Development Goals (SDGs; UN nacoesunidas.org/pos2015/agenda2030), a way to reduce this pressure would be implementing alternative production models to the "linear" take-make-disposal one, as well as changing individuals lifestyles to more sustainable ones. Actions must be carefully planned for the most different production systems considering their different scales, socioeconomic, and environmental relationship. For such a purpose, a systemic approach becomes imperative to better understand the inherent complexities of different alternatives for production systems.

The relationship between humankind and nature can be modeled from different conceptual perspectives within the economics discipline (ERIKSSON, 2005; Venkatachalam, 2007; ILLGE *et al*., 2009; Mäki, 2018). From a neoclassical economic perspective, Callan *et al.* (2013) stated that circular flow model is the basis for modeling the relationship between households and firms, which shows the biophysical and monetary flows in countercurrent directions driven by factor and output markets. Adding the natural capital, this model becomes the so-called materials balance model, which explicit the relationship between economic activity and the natural environment. From a larger schematic, the materials balance model shows the connections between economic decision-making and the natural environment, divided into the natural resources economics (resources from nature to economy) and environmental economics (focusing on residual flows from economy to nature). For Smith (2015), environmental economics assess the effects that nature has on positive prediction and normative recommendations of economic models. According to thermodynamic laws, the materials balance model shows that all resources withdrawn from the natural capital will ultimately be returned in the form of residuals. Consequently, the fundamental process on which economic activity depends is finite, which claims for a better comprehensive perspective of environmental problems within the important connections between economic activity and nature.

Although it can be perceived as a secondary problem, the waste generated after consuming green coconut water along the Brazilian coast beaches gains fundamental importance mainly in cities based on tourism. In 2014, 1.5 billion of Brazilian green coconut fruits were destined to coconut water consumption, which generated approximately 2.2 million tons of waste; approximately 70–80% generated solid waste along Brazilian beaches is green coconut shells (GCSs) (EMBRAPA, 2015; Bitencourt *et al*., 2008). According to Rosa *et al.* (2001), 85% of green coconut weight is due to its shell, which is usually discarded incorrectly on roadsides or disposed in landfills. Esteves *et al.* (2015) also identified similar problems when dealing with GCS generated in the coastal area of Maceió city, Brazil. Since the GCS takes from 8 to 12 years for decomposition (Holanda *et al.*, 2009), its incorrect handling can cause direct environmental pollution near beaches, fairs, bars, and restaurants. Direct environmental pollution occurs due to the decomposition of biomass that feed animals that carry diseases, generation of gases with odor because of organic matter fermentation, and visual pollution. Additionally, even though respecting the current Brazilian legislation related to the management of solid waste (BRASIL, 2010) (Law 12,305/10 that institutes the National Solid Waste Policy [NSWP]), GCSs disposed in landfills release gases contributing to global warming.

To follow the current NSWP legislation, the collection, transportation, and disposal of GCSs require financial resources from society, obtained from taxes. Although understanding that managing waste will indirectly avoid public health issues, government should prioritize investments in other areas such as education. Besides investments, another problem is associated with the landfill capacity in receiving waste, limited by its lifetime. Specifically, for the cities of the Baixada Santista region in São Paulo state, the "Sítio das Neves" landfill located in the continental area of Santos city started its activities in 2003 and has 20 years lifetime. This highlights that, in the short term, there will be a need for additional monetary costs to implement other landfill facility a longer distance, which will require more expenses with fuel, labor, and machines, and their respective emissions to transport solid urban waste to landfills in other cities. It is evident the need for alternative managements for urban solid waste, including GCSs, trying to reduce their generation, or reusing shells, and/or recycling them when possible (Senhoras, 2004).

The mostly used production model in Brazil is the "linear" one, with the following steps: raw materials extraction, production, use, and disposal. This model is also known as take-make-disposal. Due to all issues related to Earth's biophysical restrictions to growth, the linear model must be replaced by the so-called "circular economy" model, in which the production system is restorative or regenerative by intention or design (EMF, 2012). Another important concept is that of Zero Emissions (ZERI; zero emissions research initiative), launched by the University of the United Nations (UNU) that supports a business model with constant reuse, respecting the laws of nature in which nothing is lost, everything is transformed (Ferroli *et al.*, 1998). Both approaches or production models become increasingly important in a world where the growing consumption of resources will reach 82 billion tons in 2020 compared to 40 billion tons in 1980 (Ribeiro *et al.*, 2014). According to EMF (2012), the circular economy principles have been successfully put into practice by different leading companies in the manufacturing scenario, such as Michelin, Caterpillar, Renault, Ricoh, and Desso, attesting their efficiency with satisfactory results; examples are also easily found in the technical-scientific literature in relation to zero emissions model. In this context, reusing GCSs become an inexorable condition for the advancement of the green coconut agro-industrial chain, generating jobs, and income opportunities, in addition to causing lower pressure on the natural environment. Hence, GCSs should be viewed as a business opportunity rather than waste, where from a systemic perspective, materials and energy will be circulating and making the production system more efficient, potentially reducing emissions that cause global warming, and ultimately becoming more sustainable.

The supplementary municipal law nº 952 of 30th December 2016, implemented in Santos city, regulates the solid waste management saying that "waste generators are responsible for its environmentally adequate management" by providing "all needed services for waste collection, transportation, and final disposal in an autonomous manner and independent of the public service" (SÃO PAULO, 2016, p.9). Failure in complying with this law, specifically related to inappropriate management of recyclable humid waste – which is the case of GCSs –, may result in economic penalties and civil processes. Additionally, the waste generator must periodically inform the City's Environmental Office about how the waste is being managed. Under this scenario, the businesses that sell green coconuts are legal and economically under pressure to appropriate manage GCSs.

Efforts have been made in an attempt to considering GCSs as raw material for other production systems. For example, Carrijo *et al*. (2002) used the GCS's fiber as an agricultural substrate for tomatoes production in greenhouses, achieving 7.3% higher productivity than using sawdust, considered the second-best substrate. Mukhopadhyay *et al.* (2011) used GCS's fiber to manufacture thermal insulation panels, resulting in a temperature reduction of between 3°C and 4°C. In the automotive industry, biodegradation tests were carried out by comparing GCS's fiber with sisal fiber (Salazar *et al.*, 2011). In the footwear industry, biological maceration, exposure, and microscopy tests were performed, and the results showed that GCS's fiber has potential to be used as reinforcement in the footwear manufacture and other design products (Costa *et al.*, 2013). In the building engineering area, the use of GCSs has high potential in replacing cement in the binary cement matrix (Pereira *et al.*, 2013).

Besides all these alternative uses of GCS as raw material, there is another equally important: the manufacture of compacted and dense blocks of vegetable biomass named "briquettes." The briquette is generally considered a substitute for conventional firewood and/or charcoal due to its high heat value. GCS has characteristics that satisfy its conversion into briquettes and can be used in cement production industries, potteries, or even in small-scale business such as pizzerias and bakeries. The high amount of lignin present in the GCSs makes it appropriate as a heat source. According to Raveendran *et al.* (1996), in the thermal degradation of biomass components, the existence of high lignin concentration leads to the highest charcoal yield (higher heat value), which confers to GCSs the potential in generating charcoal. From an energy perspective, Esteves *et al.* (2015) and Miola *et al.* (2020) also emphasized the importance in using GCSs as raw material for briquettes production. Although there exists high technical potential in converting GCSs into briquettes, there are still a number of social, financial, and environmental variables that must be validated from a systemic perspective, considering the entire life cycle such as collection, transportation, production, and market steps.

Recognizing that the current management of GCS residues must be replaced by a more sustainable alternative, this work aims to assess the technical, environmental, and financial aspects of using the GCSs generated by the Baixada Santista region as raw material for briquettes production.

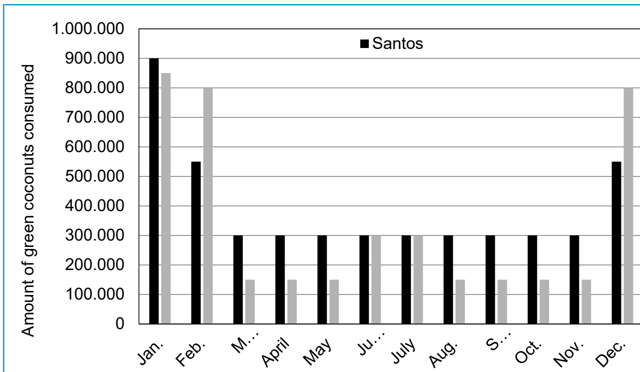
METHODS

Case study and raw data

Due to its regional representativeness in the generation of GCS residues, allied to the availability of data, this work considers the cities of Praia Grande, Santos, and São Vicente, all they belonging to the Baixada Santista region in the coast of São Paulo state. These cities have strong tourist appeal due to their beaches and, consequently, there is high consumption of green coconut water mainly during summer season (Figure 1). Among the evaluated cities, Santos stands out with 17 beachfront places selling green coconut water, which also makes it the largest generator of GCS waste.

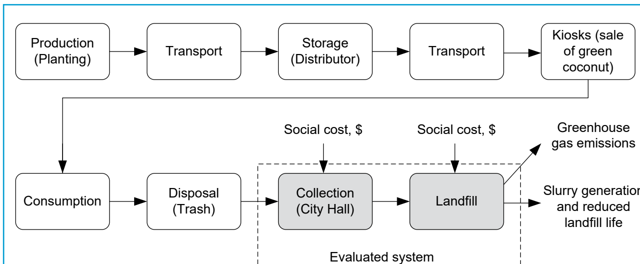
Considering aspects of logistics and costs, the factory proposed in this study to transform GCS into briquettes will be located in Cubatão city, also located in the Baixada Santista region. Since Santos city is the largest GCS residues generator followed by Praia Grande and São Vicente cities (responsible for 70% of green coconut consumption in Baixada Santista region, excluding Santos), these three cities are the focus in this study. Together, all three cities consume 630,833 coconuts month^{-1} in average, generating approximately 946,250 kg month^{-1} (1.5 kg shell^{-1}) of waste with 85% moisture. Mongaguá, Peruíbe, and Itanhaém cities were disregarded from this study because they would require a higher energy and monetary cost for the GCS transportation phase, as they are located farther from the place where the briquette factory will be implemented; additionally, these cities generate lower amount of GCS waste compared to others.

Currently, the management of GCS residues generated by the three evaluated cities follows the processes shown in Figure 2. The "linear" production model generates social problems, economic costs, and environmental pressures, and therefore, it should be replaced by another more sustainable model. An alternative is the "circular" model as presented by Figure 3, proposed and



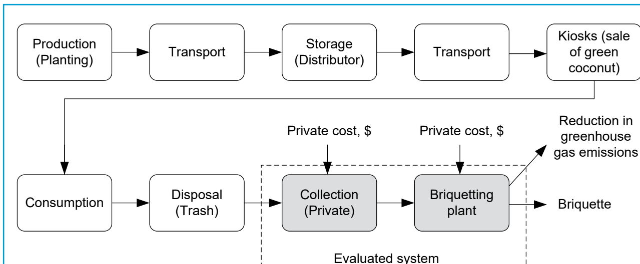
Source: Prepared by the authors.

Figure 1 – Amount of green coconut consumed in the evaluated cities. Source: Interviews held October 2018 with businessman and green coconut distributors in the region.



Source: Prepared by the authors.

Figure 2 – Current "linear" model of management for green coconut shell residues generated in Praia Grande, Santos, and São Vicente cities.



Source: Prepared by the authors.

Figure 3 – Proposed "circular" model to manage the green coconut shell residues generated in Praia Grande, Santos, and São Vicente cities. Circularity is in reusing green coconut shell as an energy source to another production system.

evaluated in this work. It can be noticed in the "circular" model that GCSs are considered as raw material for briquettes production, recycling material, and reducing indirect energy demand, which potentially would reduce the socioeconomic and environmental problems existing in the "linear" model of Figure 2. As all the processes from the production (planting) of the green coconut to the GCS generation are identical for the two models, only the processes after the GCS generation are considered in this work (denoted by dashed rectangle in Figures 2 and 3). While the "linear" model collects and transports the GCS to the landfill, the "circular" model of Figure 3 predicts that management of GCS residues will be under shared responsibility between the generator and the briquette factory.

Technological aspects for the briquette factory

The equipment and machines needed to implement the briquette factory using coconut fiber as raw material were selected in collaboration with a Brazilian company named here as BRIQUEMAX, whose specialty is to design, manufacture, and sell machines for briquetting. Selection is an important step because the type of raw material (GCS) and its availability (~950,000 kg month^{-1}) are different from usual existing briquette factories that considers wood as a raw material and for larger operational quantities.

The equipment needed to produce briquettes from GCS are chipper and picker (crushers), dryer, feeding silos, conveyor belts, and briquetting machine (extruder). Except for the extruder, all other equipment are widely used in the most different industries, so there are many types and capacities available in the market to meet the most different needs. Equipment selection is based on the BRIQUEMAX's equipment catalog, always having in mind the raw material considered in this work and the reduced production capacity due to the amount of raw material available. Mass and energy balances are considered in this stage, as presented in "Results" section.

Environmental indicators and financial viability

To achieve the goals of this work, the current "linear" production model in managing GCS residues is compared with the proposed "circular" model, in which the environmental indicators and financial viability are considered.

Environmental indicators

The global warming potential (GWP) from the perspective of life cycle assessment (LCA) is considered an environmental indicator, providing information on global and local greenhouse gas emissions usually known as direct and indirect emissions. The indirect ones come from the production of materials and energy used in the briquetting processes, generally located far from the system under study but causing environmental burden on larger scales. Local or direct emissions result from diesel/gasoline burning by the truck's combustion engine during the transportation stage, similar to the generation of methane from the decomposition of organic matter in the landfill. To estimate indirect emissions, all material and energy used by the system (that comes from the inventory phase) are converted into GWP measured in $kgCO_{2eq}$.year^{-1} by using the conversion factors obtained from the Ecoinvent Database (ecoinvent.ch, version 3.2., Method CML2001, 20 years for GWP).

Another environmental indicator considered in this work is the liquid percolated by landfills, called leachate. It is a pollutant with high biological oxygen demand (BOD), dark colored and a nauseating odor resulting from anaerobic biological processes of organic waste decomposition. When inappropriately treated, the leachate can seep into the soil and/or reach watercourses and reservoirs (rivers, lakes, and aquifers). To calculate the volume of leachate produced, the mass of GCS (organic matter) deposited in the landfill is multiplied by the 0.44 m^3 ton^{-1} factor (value obtained through personal interview in October 2019 with technical staff and engineers of Caieiras landfill, São Paulo city).

Financial viability indicators

Among others, Callan *et al.* (2013) emphasized the importance of environmental economics in modeling the way natural resources goes through the economic system and return to the nature as concentrated by-product (or waste). This way in modeling the humankind–nature interface helps to understand its functioning from a reduced complexity perspective and for the proposal of quantitative performance indicators to support decisions for optimal solutions (VERBURG *et al.*, 2016; SHEMILT *et al.*, 2014). According to the environmental economic theory, the proposed solutions dealing with by-products to achieve most sustainable production chain must be environmentally and economically sensible, by assessing the time and resources needed to implement them. Costs and benefits of the environmental proposed solutions must be assessed for long-term sustained plans. At this point, financial viability appears as a fundamental tool, because it increases the optimism and willingness to invest from investors, while reducing the risk of losing the money invested. At the same time, a detailed financial analysis can result in reduced interests charged by banks on loans. For the purposes of this work, the following indicators of financial viability are used to assess the briquette factory, as suggested by the Brazilian Micro and Small Business Support Service (SEBRAE, 2013), according to Equations 1 and 2:

(a) Break-even point (BEP; Equation 1), which represents how much the briquette factory needs receive (money inflow) to pay all costs in a specified period

$$\text{Break} - \text{even point} = \frac{\text{Total fixed cost (R\$. month}^{-1})}{\text{Marginal contribution rate (dimensionless)},\ \ \text{Equation 2}} \tag{1}$$

$$\text{Marginal contribution rate} = \frac{\text{Total revenue (R\$. month}^{-1}) - \text{Total variable cost (R\$. month}^{-1})}{\text{Total revenue (R\$. month}^{-1})} \tag{2}$$

(b) Profitability (Equation 3). It measures the net income related to sales. It is one of the main financial indicators for factories at any kind because profitability is an indicator of their competitiveness. When a factory has high profitability, it will have greater capacity to compete because it will be able to make more investments in important strategies such as advertising, diversification of products and services, and acquisition of new equipment. The result of this indicator reflects the amount of monthly net income (in %).

$$\text{Profitability (\%)} = \frac{\text{Net income (R\$. month}^{-1}) * 100}{\text{Total revenue (R\$. month}^{-1})} \tag{3}$$

(c) Rentability (Equation 4) indicates the business attractiveness, measuring the payback capital to the investors. It is expressed as a percentage per unit of time (month or year). Rentability should be compared with those indices usually considered by the financial market to assess alternative investments.

$$\text{Rentability (\%)} = \frac{\text{Net income (R\$.month}^{-1}) * 100}{\text{Total investment (R\$)}} \quad (4)$$

(d) The payback (Equation 5), as well as the rentability, it is an indicator of business attractiveness. Payback indicates the time required for the investor to recover the invested money.

$$\text{Payback (month)} = \frac{\text{Total investment (R\$)}}{\text{Net income (R\$.month}^{-1})} \quad (5)$$

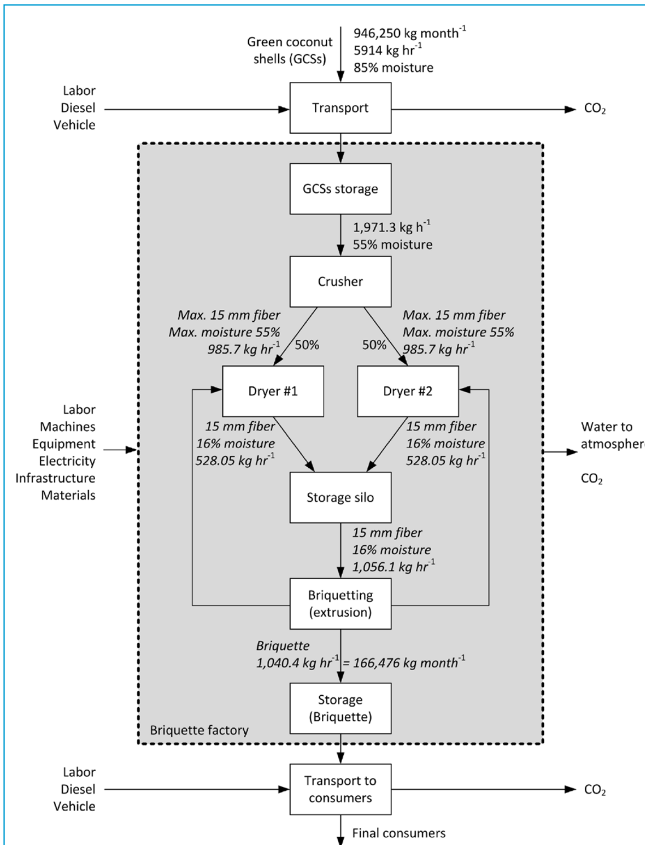
RESULTS AND DISCUSSIONS

Technical aspects

Conversion processes related to briquettes production from the most different raw materials are quite simple. Avoiding to be extensive, Syafrudin *et al.* (2015) analyzed the chemical components of raw materials (e.g., bottom ash coal, teak leaves charcoal, coconut shell charcoal, and rice husk charcoal) used to produce briquettes and have found the need for binding materials to achieve better mixture. Briquettes characteristics showed that increasing the proportion of biomass usage also increases the briquette moisture and its high heat value. This result emphasizes that using biomass for briquette production reduces the need for ashes, besides reducing the energy demanded during the extrusion process. These findings are aligned with Pimenta *et al.* (2015), who identified the technical feasibility of using GCSs as a raw material to produce charcoal and its conversion into charcoal briquettes. Authors have also showed that briquettes produced with carbonized coconut shells have high thermodynamic quality, equivalent to the regular briquettes produced with wood charcoal or sawmill waste existing in the Brazilian and international markets. Similarly, Esteves, *et al.* (2015) and Miola *et al.* (2020) also recognized the potential in using briquette from GCSs as energy sources (reaching values between 11.7 and 19.47 MJ kg^{-1} for high heat power), which would reduce socioeconomic and environmental pressures.

The technical aspects evaluated in this study involve all the processes necessary to obtain the briquettes, starting with the GCS collection and ending with the briquette produced, as detailed in Figure 4. The main sources of energy and material that support the well-functioning of system are also presented, such as labor, diesel, vehicle, equipment, electricity, infrastructure, and other materials. The larger dashed rectangle represents the factory production area, responsible for the proper processes of GCS to obtain the briquette. As outputs of the proposed "circular" model, besides the briquettes, there is water vapor from the drying process and CO_2 emitted by burning diesel during the transport steps.

The briquette machine acts as a limiting factor within briquette factory and, therefore, this equipment is the first one to be selected. The capacity of extrusion machine as presented by BRIQUEMAX is designed to receive raw materials with 180 kg m^{-3} (wood waste) of specific weight and 16% of moisture to achieve efficient extrusion capacity. As the raw material considered in this work is GCS, the nominal productive capacity of extrusion machine must be chosen as the minimum suggested by BRIQUEMAX, since GCS is a fibrous waste with higher density than wood. This is important to guarantee that extrusion process using GCS will be well succeed. Thus, according to the available



Source: Prepared by the authors.

Figure 4 – The proposed "circular" model for briquettes factory. White rectangles indicate all the analyzed involved processes.

extrusion capacities in the BRIQUEMAX machines catalog, it was chosen the capacity ranging from 0.5 to 1.0 ton h^{-1}, which is the minimum option available when using raw materials with specific weight between 90 and 100 kg m^{-3} and 16% of moisture.

After choosing the extrusion machine, all other equipment can be now selected. Before the size reduction process, the GCS moisture must be reduced from 85% to 55%, to ensure maximum efficiency in the size reduction process. This initial drying process is simple, by exposing the GCS to the natural solar radiation in protected place from rainfall. According to the mass balance and initial availability of 946,250 kg$_{GCS}$ month^{-1}, Figure 4 shows 5,914 kg$_{GCS}$ h^{-1} (wet basis; operating 160 h month^{-1}) at 85% moisture going into the process, which is equivalent to 5,026.9 kgH_2O h^{-1} + 887.1 kg$_{GCS}$ h^{-1} (dry basis), and as output we have 3,941.97 kgH_2O h^{-1} + 1,971.3 kg$_{GCS}$ h^{-1} (wet basis) at 55% moisture. After dried, the crusher reduces the GCS size in fibers with maximum size of 15 mm, which is required before going into the next process of drying. César *et al.* (2009) found that in order to keep a briquette plant running 6 h a day, an average of 25,000 tons of coconut shells are needed to feed equipment with a production capacity of 600 kg h^{-1}.

The dryer machine reduces the moisture of fibers (crushed GCS) before extrusion process. Due to its capacity, two dryers are needed, each one equally receiving half (985.7 kg$_{fibers}$ h^{-1} at 55% moisture) of the total crushed GCS. At the end of drying process, the fibers have 16% of moisture, as demanded by the extrusion machine. According to the mass balance, Figure 4 shows that 985.7 kg$_{fibers}$ h^{-1}

(wet basis) at 55% of moisture go into the processes, which is equivalent to 542.1 $kgH_2O\ h^{-1}$ + 443.5 $kg_{fibers}\ h^{-1}$ (dry basis). The outputs are 457.6 $kgH_2O\ h^{-1}$ + 528.05 $kg_{fibers}\ h^{-1}$ (wet basis) at 16% of moisture for each dryer machine, achieving a total of 1,056.1 $kg_{fibers}\ h^{-1}$ (wet basis) at 16% moisture. This amount is the same as the briquettes produced, since the extrusion process is responsible to simply compress the fibers. To reduce costs, the amount of 2,500 kg $month^{-1}$ of briquette production is used as energy source in the dryer machines, which results in a monthly briquette production capacity of 166,476 kg $month^{-1}$. The amount of 2,500 kg $month^{-1}$ is estimated based on the briquettes high heat value (4,000 kcal kg^{-1}, LIPPEL 2017), the operating power of dryer machines (39 kW $dryer^{-1}$, total of 78 kW; obtained from BRIQUEMAX), and the operation time of 160 h $month^{-1}$.

Environmental aspects: global warming potential and leachate generation

The "linear" production model obtained an amount of 4.02E+05 $kgCO_{2eq}$. $year^{-1}$ (Table 1) for GWP indicator due to indirect emissions, while for direct emissions, Table 2 shows an amount of 4.00E+07 $kgCO_{2eq}$. $year^{-1}$. Thus, from the GCS collection in kiosks to their disposal in landfills, the "linear" model releases 4.04E+07 $kgCO_{2eq}$. $year^{-1}$ or 5.34 $kgCO_{2eq}$. GCS^{-1}.

The GWP for the "circular" production model considers the indirect and direct emissions (Table 3), including the GCS transport from kiosks to briquette factory and those emissions caused by processes within factory, achieving an amount of 6.45E+05 $kgCO_{2eq}$. $year^{-1}$. For this model, there is no emission in the landfill, as the GCSs are transformed into briquettes. Comparatively, these numbers show that proposed "circular" model releases ~40 thousand tons lower CO_2 equivalent per year than the "linear" model.

Regarding the volume of leachate generated, the "linear" model disposal about 946,250 kg $month^{-1}$ of GCS in landfills, which results in 4,996 m^3 $year^{-1}$ of leachate generated. For the "circular" model, leachate generation is zero, as the GCSs are transformed into briquettes instead of being dumped in landfills.

Financial viability

Before calculating the financial indicators, it is necessary to perform the inventory of costs (Table 4). The inventory includes the rental for briquette factory structure and all the needed equipment and machines, besides including labor demand as other fixed and variable costs. Table 4 shows that variable cost (including governmental and employees taxes) is the most costly item among all, followed by expenses with salary and equipment.

Santos city established the Law 952 on 30th Dec. 2016, in which the waste generators are legally and economically responsible for their appropriated management. Currently, there is a cost of 0.60 R$ GCS^{-1} to collect and disposal GCSs in the landfills, and this cost is paid by the kiosk owners to the hired companies. Considering the generation of 630,833 GCSs $month^{-1}$ by Santos, São Vicente, and Praia Grande cities, the total cost of collection and transportation of GCSs reaches 378,499 R$ $month^{-1}$. Strategically, the briquette factory proposed in this study could be responsible in managing the GCSs generated by owners, transporting them to the briquette factory. For such a work, the factory is willing to charge the kiosks owners in 0.40 R$ GCS^{-1}, a value ~33% lower than the current practice of 0.60 R$ GCS^{-1}. This additional revenue for the briquette factory would reach 252,333 R$ $month^{-1}$, a value that would have important influence on final financial indicators.

Total briquettes production is 166,476 kg $month^{-1}$, with a market value of 400 R$ ton^{-1}, resulting a total revenue of 66,590 R$ $month^{-1}$. Considering the results

Table 1 – Global warming potential due to indirect emissions of "linear" model.

Note	1		2
Item	Pickup truck		Fuel
Amount	4.50E+04 kg		1,05E+06 MJ year–[1b]
Material	Steel (40%)	Cast iron (60%)	Diesel
Lifetime	20 years	20 years	-
Emission factor[a]	0.06155 $kgCO_{2eq}$ kg^{-1}	1.8604 $kgCO_{2eq}$ kg^{-1}	0.37971 $kgCO_{2eq}$ MJ^{-1}
Global warming potential	55.4 $kgCO_{2eq}$ $year^{-1}$	2,511.5 $kgCO_{2eq}$ $year^{-1}$	399,151.15 $kgCO_{2eq}$ $year^{-1}$

[a]Emission factors obtained from Ecoinvent database; Appendix B; [b]Five trucks covering a total of 146,000 km $year^{-1}$; Conversion=146,000 km $year^{-1}$ (1/5 L km^{-1}) 36 MJ L^{-1}=1.05E+06 MJ $year^{-1}$

Table 2 – Global Warming Potential due to direct emissions of "linear" model.

Note	1		2
Item	Disposal in landfills		Transport to landfill
Amount	1.14E+04 ton $year^{-1}$		1.46E+05 km $year^{-1}$
Material	Green coconut shells		Truck (diesel)
Lifetime	8 year generating and realizing biogas		-
Emission factor	270 Nm^3_{biogas}.ton^{-1}[a]		1.21 $kgCO_{2eq}$ km^{-1}[b]
Conversion (%)	50 CO_2	50 CH_4	-
Total emissions[c]	-	1.53E+06 $kgCH_{4eq}$.$year^{-1}$	-
Global warming potential	1.53E+06 $kgCO_{2eq}$ $year^{-1}$	3.83E+07 $kgCO_{2eq}$ $year^{-1}$	1.77E+05 $kgCO_{2eq}$ $year^{-1}$

[a]Estimated emission factor from USEPA (1991); [b]Emission factor obtained from Ecoinvent database, Appendix B; [c]CH_4 has global warming potential 25 times higher than CO_2.

presented in Table 5 for the "circular" model of management without the collection revenue, the total revenue from the briquette factory will be 1,868,000 R$ $year^{-1}$ (BEP). Profitability shows −62%, indicating that all costs will not be covered by profits, resulting in an annual deficit of −38% for rentability over the total invested. Both indicators reflect in a negative payback, which means that investment would never return. All these indicators show the financial infeasibility in implementing the briquette factory as suggested here by the "circular" model. On the other hand, when considering the additional revenue of 0.40 R$ GCS^{-1} from collecting the GCS from kiosks, Table 5 shows a BEP of 972,000 R$ $year^{-1}$, profitability of 66%, rentability of 196% and payback of approximately 6 months. In this scenario, the financial indicators support the implementation of briquette factory as proposed.

Table 3 – Global warming potential due to direct and indirect emissions of "circular" model.

Item	Description	GWP ($kgCO_{2eq.}$ $year^{-1}$)
1	TMF 3280 crusher	3.84E+04
2	B-12000 dryer	2.85E+05
3	Storage silo	4.27E+04
4	Briquette machine B85/210	1.17E+05
5	Wheel loader	1.32E+03
6	Compactor pickup truck	5.13E+02
7	Trunk truck	5.43E+02
8	Electricity	9.16E+04
9	Diesel	5.25E+04
10	Briquette burnt in the dryer machine	1.59E+04
Total		6.45E+05

GWP: Global warming potential. Calculations details available at Appendix A.

Table 4 – Inventory of briquette factory costs.

Item/description		Value (R$ $year^{-1}$)
1. Structure rental	Subtotal	180,000.00
2. Equipment	Subtotal	167,633.33
2.1. Briquette factory: machinery and transport stage		164,800.00
2.2. Office supplies (materials)		2,833.33
3. Employees (salary)	Subtotal	402,000.00
4. Costs	Subtotal	543,412.80
4.1. Fixed (electricity, water, diesel, etc.)		113,620.80
4.2. Variable (maintenance, taxes, etc.)		429,792.00
	Total	1,293,046.13

Detailed calculations are presented in Appendix C.

Integrated and comparative environmental-financial analysis for both studied models

Table 6 shows the results for environmental an*d financial performance for the three studied scenarios*, including

(i) "Linear" model with GCS disposal in the landfill

(ii) "Circular" model with implementation of briquette factory

(iii) "Circular" model with implementation of briquette factory and considering the additional revenue from GCS collecting at kiosks. None financial indicators exists for the "linear" model since no briquette factory will be installed; however, the kiosks owners will have a cost of 0.60 R$ GCS^{-1} to appropriately manage their wastes according to the city's law; this generates a cost of 378,499 R$ $month^{-1}$.

For the "circular" model without additional revenue in collecting the GCSs, there is a financial infeasibility to support the implementation of briquette factory; but in this scenario, the kiosks owners will have no costs for waste management, since the briquette factory will collect the GCSs free-of-charge. Considering now the scenario where there is an additional revenue in collecting the GCSs, the financial indicators strongly support the implementation of briquette factory, achieving a money payback in approximately 6 months after its implementation. In this scenario, the kiosks owners will have a cost of 0.40 R$ GCS^{-1} instead of the current 0.60 R$ GCS^{-1} and will be in accordance with current environmental legislation. These results are in accordance with César *et al.* (2009), which have found the financial feasibility in producing briquettes from GCSs generated in Salvador city, Brazil, instead of disposing them in landfills. Cost-effectiveness and suitability for the commercial application are also discussed by Islam *et al.* (2014), which suggested as optimized solution the briquettes production from coir dust and rice husk in a 50:50 mixture ratio.

Focusing now on the environmental performance based on the life cycle analysis, Table 6 shows a reduction of ~63 times in its potential to cause global

Table 5 – Financial indicators for the "circular" model of coconut shell management, with and without the additional collection revenue.

Indicators[a]	"Circular" model without collection revenue	"Circular" model with collection revenue of 0.40 R$ GCS^{-1}
Total fixed cost (R$ $year^{-1}$), Table 4	863,254.13	863,254.13
Total variable cost (R$ $year^{-1}$), Table 4	429,792.00	429,792.00
Total revenue (R$ $year^{-1}$)[a]	799,084.80	3,827,083.20
Net income (R$ $year^{-1}$)[b]	-493,961.33	2,534,037.07
Total investment (R$ $year^{-1}$), Table 4	1,293,046.13	1,293,046.13
Break-even point (R$ $year^{-1}$), Eq. 1	1,867,930.42	972,464.59
Profitability (%), Eq. 3	-61.82	66.21
Rentability (%), Eq. 4	-38.20	195.97
Payback (year), Eq. 5	-	0.51

[a]Circular model without revenue=166,476 kg $month^{-1}$ of briquette at 400 R$ ton^{-1}; Circular model with collection revenue=166,476 kg $month^{-1}$ of briquette at 400 R$ ton^{-1}+630,833 GCS $month^{-1}$ collected at 0.40 R$ GCS^{-1}. [b]Net income=Total revenue − Total investment.

Table 6 – Comparison of environmental and financial indicators between the "linear" (landfill) and "circular" (briquette factory) management models for green coconut shell waste.

Indicators	"Linear" model	"Circular" model without collection revenue	"Circular" model with collection revenue of 0.40 R$ GCS^{-1} shell collected	Unit
Break-even point	-	1,867,930.42	972,464.59	R$.$year^{-1}$
Profitability	-	−61.82	66.21	%
Rentability	-	−38.20	195.97	%
Payback	-	-	0.51	year
Global warming potential	4.04E+07	6.45E+05	6.45E+05	$kgCO_{2eq.}$ $year^{-1}$
Leachate generation	4,996	0	0	m^3 $year^{-1}$

warming (~40 thousand tons lesser of CO_2eq released annually) after implementing the factory. Besides reducing the amount of greenhouse gas emissions, the "circular" model will reduce the generation of leachate volume from ~5,000 m^3 $year^{-1}$ to zero, resulting in lower social and environmental pressures caused by the high organic load of this pollutant. Both environmental indicators support the implementation of the alternative production system ("circular" model) proposed in this work, as promoted by the concepts of circular economy and zero emissions.

CONCLUSIONS

The implementation of proposed "circular" model of briquette production from green coconut shells (GCSs) is supported under technical-operational aspects. The need for equipment and machines and their selecting stage to transform GCSs into briquettes is facilitated by the existence and experience of mature specialized companies in the Brazilian market, requiring simple modifications in the production line to achieve the highest efficiency by combining the equipment nominal capacities with the needs of briquette factory.

While the "linear" model produces annually ~5,000 m^3 of leachate, the proposed "circular" model does not produce this pollutant harmful to the environment and people. Additionally, the "circular" model reduces ~40 thousand tons of CO_{2eq}. annually released to the atmosphere compared to "linear" model. Both indicators support the replacement of "linear" model by the implementation of the briquette factory as proposed by the "circular" model.

Financial indicators show the viability of implementing the "circular" model in producing briquettes; however, this happens when there is an additional revenue of 0.40 R$ GCS^{-1} in collecting the GCSs from kiosks. For this scenario, the performance of financial indicators shows a 66% profitability, 195% rentability, and 6 months for investment payback.

Producing briquettes from GCSs as proposed by the "circular" model is consistent from a technical-operational perspective, besides being environmental and financially supported. Replacing the "linear" by the "circular" model should be promoted by public policies, in search of municipal managements more aligned with the sustainable development goals of the United Nations Agenda 2030.

AUTHORS' CONTRIBUTIONS

Clasen, A.P.: Conceptualization, data curation, formal analysis, methodology, writing – original draft. Bonadio, J.C.: Investigation, software, validation, and visualization. Agostinho, F.: Conceptualization, formal analysis, funding acquisition, project administration, methodology, resources, supervision, writing – review & editing.

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Appendix A – Primary data to calculate the global warming potential of the proposed "circular" model.

Note	Item	Amount	Unit	Material (%)	Lifetime (year)	Emission factor [a] ($kgCO_{2eq.}$ $Unit^{-1}$)
1	TMF 3280 crusher	1.80E+03	kg	Stainless steel	10	213.65
2	B-12000 drum dryer (input redler, dryer chupim, pneumatic transport)	2.20E+04	kg	Stainless steel (60)	10	213.65
				Bronze (20)		4.7592
				Cast iron (20)		1.8604
3	Storage silo	2.00E+03	kg	Stainless steel	10	213.65
4	Briquette machine B85/210	9.00E+03	kg	Stainless steel (60)	10	213.65
				Bronze (20)		4.7592
				Cast iron (20)		1.8604
5	Wheel loader	2.32E+04	kg	Steel (40)	20	0.06155
				Cast iron (60)		1.8604
6	Compactor pickup truck	9.00E+03	kg	Steel (40)	20	0.06155
				Cast iron (60)		1.8604
7	Trunk Truck	1.10E+04	kg	Aluminium (30)	20	0.74714
				Steel (30)		0.06155
				Cast iron (40)		1.8604
8	Electricity[b]	1.21E+05	kW $year^{-1}$	-	-	0.7575
9	Diesel[c]	1.38E+05	MJ $year^{-1}$	Diesel	-	0.37971
10	Briquette burnt in the dryer machine	5.02E+05	MJ $year^{-1}$	Briquette	-	0.03159

[a]Emission factors in Appendix B; [b]Electricity=63 kWh 160 h $month^{-1}$=10,080 kW $month^{-1}$ or 120,960 kW $year^{-1}$; [c]Fuel=320 L $month^{-1}$=3,840 L $year^{-1}$ 36 MJ L^{-1}=138,240 MJ $year^{-1}$.

Appendix B – Emission factor for global warming potential obtained from the ECOINVENT® database (https://www.ecoinvent.org/), version 3.2, method CML2001, 20 years for global warming potential.

Item	Unit	$kgCO_{2eq.}.Unit^{-1}$	Especification	Note
Steel	kg	0.06155	Market for steel in car crusher residue, global values	Steel is a widely studied item and the Ecoinvent database has 359 entries for this item. It was considered only global values due to the lack of data related to Brazil; this reduced the number of items to 114. Of this group, we believe that 1 item had a definition similar to the steel used for vehicles.
Stainless steel	kg	213.65	Market for outside air intake, stainless steel, DN 370, global values	Few results are found for the item, among the 359 items for steel only 3 of them were associated with stainless steel, and we believe that one of them was the closest we needed.
Aluminium	kg	0.74714	Market for sheet rolling, aluminum, global values	Aluminum is another widely studied and vast item in the database, with 329 entries. When considered only global values reduced to 81 entries. Four of them were related to aluminum plates; however, only one approached the definition sought.
Bronze	kg	4.7592	Market for bronze, bronze, global values	There are not many results in the Ecoinvent database for the Bronze item, only 10. As there were no data for Brazil, only global data were considered, filtering for only 3 entries. We think that one of them was the most appropriate.
Cast iron	kg	1.8604	Market for cast iron, global values	For cast iron, there are 39 input items and were filtered for 13 when considering only global data; however, 1 was considered.
Diesel	MJ	0.37971	Market for transport, passenger car, large size, diesel, EURO 5, global values	Diesel has 122 entries, it was considered only global items and diesel for transporting large vehicles, reducing the search to 3 entries. One of them was selected as suitable for our study.
Electricity	kW	0.7575	Market group for electricity, medium voltage, global values	For electricity, medium voltage supply and global values were considered. It resulted in 2 items, one of them was considered ideal for use in the briquette factory.
Briquette	MJ	0.03159	Market for hard coal briquettes, RER	The briquette has 18 entries in the Ecoinvent database. It was considered that only one of them was compatible with this work.

Appendix C – Complete financial inventory for implementation and operation of the briquette factory from green coconut shells.

1	Structure rental	Amount	Unit		Unit value (R$ month⁻¹)	Total (R$ year⁻¹)
1.1	Land area	4,000	m²		15,000.00	180,000.00
1.2	Covered area (within 4,000 m²)	2,000	m²			
1.2.1	Reception and raw material storage area					
1.2.2	Production shed					
	Warehouse and Analysis Laboratory					
	Finished products storage area					
	Area for the Administration and Sales sectors					
	Total Structure					180,000.00
2	Equipment	Amount	Unit	Life cycle (years)	Unit value (R$ month⁻¹)	Total (R$ year⁻¹)
2.1	Briquette factory					
	Factory assembly machinery					
	TMF 3280 Waste Crusher	1	Unit	10	80,000.00	8,000.00
	Input Redler	2	Unit	10	36,000.00	7,200.00
	Chupim dryer	2	Unit	10	28,000.00	5,600.00
	Drum dryer B-12000	2	Unit	10	267,000.00	53,400.00
	Pneumatic transport system	1	Unit	10	69,000.00	6,900.00
	Air dosing silo	1	Unit	10	26,000.00	2,600.00
	Briquette machine B 85/210	1	Unit	10	192,500.00	19,250.00
	Engine of briquetting machine (60 hp)	1	Unit	10	14,500.00	1,450.00
	Briquetting control panel	1	Unit	10	15,000.00	1,500.00
	Wheel loader	1	Unit	5	19,500.00	3,900.00
	Compactor collection truck (own)	1	Unit	5	200,000.00	40,000.00
	Chest truck (small)	1	Unit	5	75,000.00	15,000.00
	Total machinery and transportation					164,800.00
2.2	Office supplies (materials)					
	Table	5	Unit	5	310.00	310.00
	Chairs	15	Unit	5	140.00	420.00
	Computers	3	Unit	3	1,633.33	1,633.33
	Laser printer	2	Unit	5	600.00	240.00
	Fax	2	Unit	5	450.00	180.00
	Phone	4	Unit	5	62.50	50.00
	Total office supplies		Unit			2,833.33
	Total equipment		Unit			167,633.33
3	Employees	Amount	Unit		Unit value (R$ month⁻¹)	Total (R$ year⁻¹)
	Reception	1	People		2,000.00	24,000.00
	Sales	1	People		3,500.00	42,000.00
	Driver	2	People		3,500.00	84,000.00
	Performing administrative activities	1	People		3,500.00	42,000.00
	Production area (4-7 employees)	5	People		3,500.00	210,000.00
	Total employees					402,000.00

Continue...

Appendix C – Continuation.

4	Costs	Amount	Unit		Monthly value (R$ Unit^{-1})	Total (R$ year^{-1})
4.1	Fixed					
	Water, electricity, phone, and Internet	1	Unit		1,450.00	17,400.00
	Electricity at the factory=63 kWh	160	Hours		30.24	58,060.80
	Accounting advice	1	Unit		1,100.00	13,200.00
	Office material (office)	1	Unit		800.00	9,600.00
	Fuel	320	L		4.00	15,360.00
	Total Fixed Costs					113,620.80
4.2	Variable					
	Equipment maintenance	1	Unit		3,500.00	42,000.00
	Packaging	1	Unit		6,800.00	81,600.00
	Govermental tax	1	Unit		2,736.00	32,832.00
	Other taxes, contributions, and fees [a]	1	Unit		22,780.00	273,360.00
	Total variable costs					429,792.00
	Total fixed and variable costs					543,412.80
Total						1,293,046.13

Source: BRIQUEMAX Company and market values obtained from other companies.
[a]68% of total costs with employees.