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International overview of the use of spent coffee ground as solid fuel. A review of worldwide studies

Panorama internacional del uso de la borra de café como biocombustible sólido. Revisión de estudios en el mundo

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ABSTRACT

This article is a review of the state of research (2010-2020) on studies and projects for the elaboration, characterization and commercialization of briquettes and pellets, whose base material in the world is coffee grounds. The reviews showed that these solid fuels use as a base material this coffee waste with residues such as sawdust, kitchen grease, branches, and dry leaves; or inputs such as glycerin, xanthara gum, yucca starch, or biodiesel. The manufacture of the briquettes or pellets involves a process of mixing the base coffee ground with the agglomerating substance and then pressing it manually in most cases. The results of physical-chemical characterization, mainly its calorific value, are compared with charcoal and firewood, which seek to be replaced with the implementation of this type of biomasses. The results of this review showed very similar values for briquettes in terms of energy potential and the generation of combustion gases, but in all cases, they were lower than those of the mineral coal used as a reference. Despite this, briquettes are presented as a sustainable solution to the problem of deforestation and lung diseases due to exposure to wood smoke.

KEY WORDS: briquettes, solid biomass, charcoal, alternative solid fuels.

RESUMEN

El presente artículo es una revisión del estado de la investigación (2010 – 2020) sobre estudios y proyectos de elaboración, caracterización y comercialización de briquetas y pellets, cuya materia base es la borra del café, a nivel mundial. Las revisiones evidenciaron que estos combustibles sólidos utilizan como materia base este desecho del café con residuos como aserrín, grasa de cocina, ramas, y hojas secas, o insumos como la glicerina, la goma xantara, el almidón de yuca, o el biodiesel. La fabricación de las briquetas o pellets tiene un proceso de mezclado de borra base con la sustancia aglomerante para luego ser prensado de forma manual en la mayoría de los casos. Los resultados de caracterización físico-química principalmente su poder calorífico, es comparado su desempeño con respecto al carbón y la leña, los cuales se buscan sustituir con la implementación de este tipo de biomasas. Los resultados de esta revisión arrojaron valores muy similares para briquetas en cuanto al potencial energético y la generación de gases de combustión, pero en todos los casos fueron inferiores al del carbón mineral utilizado como referente. A pesar de esto, estas briquetas se presentan como una solución sustentable al problema de la deforestación y las enfermedades pulmonares por exposición al humo de leña.

PALABRAS CLAVE: briquetas, biomasa sólida, borra, combustibles sólidos alternativos.

Introduction

One of the problems facing the world population is the availability of accessible, sustainable, and affordable energy sources (Shukla & Vyas, 2015). Approximately 3 billion people in the world use wood biomass in fuelwood or charcoal as their only energy alternative (Nijhuis, 2017), (Kurmi et al., 2012). It is obtained by cutting down trees, which reduces a significant number of hectares that could produce oxygen, serve as a carbon sink, and other

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ecosystem services (Armenteras et al., 2018). The World Health Organization (Organización Mundial de la Salud, 2020) and González-García et al. (2013) indicate that exposure to smoke from wood combustion is one of the risk factors causing chronic obstructive pulmonary disease (COPD), which, according to estimates, is suffered by about 64 million people, mainly in developing countries. A study conducted in Colombia showed that exposure to wood smoke also appears as a risk factor for this disease development (Ministerio de Salud, 2016).

Given the risks associated with obtaining and exposing to wood smoke, an opportunity arises for solid biofuels using a large amount of biomass waste as a source of energy in stoves and other traditional processes (Goche et al., 2015). The use of these biofuels has brought socio-economic benefits such as that generated in the local economy of East Africa with the production of briquettes, where traditional fossil fuels such as charcoal and kerosene for domestic use have been replaced (Asamoah et al., 2016). Its implementation has provided advantages such as decreased dependence on firewood, good burning efficiency, reduced deforestation, along with job creation and price affordability compared to charcoal and firewood (Maninder et al., 2014). In another study, the Swiss Energy Office (Itten et al., 2011) analyzed the life cycle of different biomass fuels, highlighting that greenhouse gas emissions are lower than those of fossil fuels, although higher than those of wood. Though their energy potential does not exceed that of conventional fuels, coffee grounds briquettes emerge as a solution to both energy and health problems, together with circular economy business opportunities, in addition to serving as an input for future studies where other ways of improving their energy performance are studied in detail.

Methodology

This review is exploratory with a mixed quantitative-qualitative perspective by consulting research articles, mainly since 2010 and obtained from Springer, Science Direct, Scopus, Google Scholar databases, and papers from different repositories. This document was prepared by geographical locations in Africa, Europe, Asia, and America, underlining the most relevant contribution of each of the studies in aspects such as those mentioned by Shukla and Vyas (2015) in terms of binder substance, mixture proportions, calorific value, emissions produced or applications. The document allowed establishing the feasibility of manufacturing this solid biofuel and its implementation to replace firewood charcoal and avoid cutting trees for its use.

Coffee harvest residues

Regarding the use of coffee residues, the research activity on the potential of its products such as pulp, husk, and mucilage as raw material for enzymes and bioactive compounds, antioxidants, and food additives stands out (Figueroa et al., 2016). According to the type, they can be used as an absorbent in heavy metal removal, colorant for aqueous solutions, pellet and briquette production, alcoholic beverages, natural phenolic antioxidants, reusable cups, biogas substrate, biogas, alcohol, and biodiesel production, among other utilities (Blinová et al., 2017). For their part, Rodríguez and Zambrano (2010) describe the opportunities and potential uses of coffee constituents. The pulp allows it to be used as a direct fuel, with a calorific value of 15.88 MJ but low energy efficiency. Mixed with water, carbon dioxide gas, and other compounds, it can produce biogas. The mucilage is obtained in the milling process and used in biogas and bioethanol production. If not correctly disposed of, its open-air decomposition generates methane production and soil and water contamination.

Zerbinatti et al. (2014) worked on briquettes made from husks mixed with crop residues such as branches and leaves in different compositions. The applied tests yielded a sulfide content lower than 0.1 % possibly with no SOx in combustion. The calorific value reached 14.04 and 16.83 MJ kg^{-1} with an ash percentage lower than 6 %, very similar to what was obtained by Suryaningsih et al. (2017), who selected biomasses such as coffee husks, rice, coconut, and sawdust to produce briquettes. Coconut husk presented the highest calorific value (18.60 MJ kg^{-1}).

The work done by Mhilu (2014) compared the energy power provided by rice and coffee husks; the values obtained were 18.34 MJ kg^{-1} for coffee and

13.24 MJ/kg for rice. However, the ash contents were high, affecting combustion efficiency. For their part, Pallavi et al. (2013) compared the characteristics of briquettes made with sugarcane bagasse and coffee husks as raw materials to obtain them in the form of biochar. The results showed that a 3:1 bagasse-coffee husk combination has a calorific value of 11.126 MJ kg^{-1}, much higher than those of each biomass with 8.54 and 9.49 MJ kg^{-1}, respectively.

Vera (2014) developed a study with agricultural waste briquettes of coffee husk, sugarcane bagasse, and rice hulls in different proportions. The highest calorific value was obtained by coffee husk with 60 %, followed by rice husk and sugarcane bagasse with 20 % each. Celis (2017) describes the elaboration of briquettes with coffee harvesting and processing residues. As a raw material, he used mucilage, cisco, and wheat flour, molded and dried for five days, providing a product exported to China, where it achieved considerable acceptance.

Experiences in the elaboration and characterization of coffee grounds briquettes worldwide

The following is a brief description of the experiences regarding using coffee grounds as solid fuel, underlining the main contributions of each investigation.

Africa

Pilusa (2010) conducted a study with briquettes whose composition ranged from 32 % coffee grounds, 23 % charcoal fines, 11 % wood sawdust, 18 % corn husks, 10 % recycled paper, and 6 % paper pulp. This study's purpose addresses the economic feasibility of producing environmentally friendly briquettes in rural and urban areas of South Africa. Among the results, the combustion of briquettes produces gases within the accepted levels according to OSHA (Occupational Safety and Health Organization) standards. Pilusa et al. (2013) conducted a study on the characterization of briquette, whose composition of coffee grounds was 32 %; fine coal dust, 23 %; wood sawdust, 11 %; cornhusk, 18 %; recycled paper, 10 %, and 6 % paper pulp with water. They compacted it with a pressure of 0.87 MPa, obtaining dimensions of 100 mm outside diameter, 35 mm inside diameter, and 50 mm long. Among the most outstanding results of this characterization as a potential solid fuel, it yielded a calorific value of 18.9 MJ kg^{-1} compared to coal with 25.92 MJ kg^{-1}. As in the previous work, the low values obtained in emissions produced from its combustion below the exposure limit established by OSHA for 8 hours stand out.

Pilusa et al. (2012) studied the theoretical relationship between pressure and density of hollow cylindrical briquettes made from different biomass such as coffee grounds, cornhusks, charcoal fines, and wood sawdust, without using any binder. They applied pressures through a manual screw press between 1.5 and 3.0 MPa for briquettes of 100 mm external diameter, 35 mm internal diameter, and 50 mm length, reaching densities of 989 kg m^{-3} and a moisture content of 28.87 %. Their analysis contained 26.30 % fixed carbon, 39.34 % volatile material, 10.9 % moisture, and 10.46 % ash. The calorific value obtained 18.9 MJ kg^{-1}.

Eshetu (2019) conducted a study in Ethiopia where obtained methyl ester, bioethanol, and briquettes as products from coffee ground. The briquettes were manufactured using glycerol as a binder in proportions of coffee ground: glycerol of 15:85, 25:75, and 40:60. The results of calorific value did not show substantial variations to the compositions produced. This value was around 13.64 MJ kg^{-1}, while the study conducted in Ethiopia by Shiferaw et al. (2018) characterized briquettes with coffee grounds and eucalyptus leaf extract, using different materials as binders. Within these, wheat flour, three types of local clay named Mehal meda, Sela dengay, and Zemaro, as well as soil and paper were used. The study concluded that the mixture with eucalyptus and wheat flour provided the best-estimated calorific value (26.66 MJ kg^{-1}), very close to those of conventional charcoal.

Limousy et al. (2013), in Tunisia, performed the characterization of coffee ground pellets and combustion fumes released in their use in a domestic boiler. They used pellets made 100 % with coffee ground and agglomerated with 20 % pine sawdust. The physical-chemical description of their properties and combustion fumes was carried out. A 12 kW boiler was used for the combustion test with combustion and boiler efficiency results, together with flue gas particulates. The study concludes that pure coffee ground is a good substitute fuel but does not provide high combustion and boiler efficiency. The best alternative would be agglomeration with wood sawdust, which significantly improves these deficiencies and provides a combustion efficiency of 91.9 %.

Table 1 summarizes the most relevant contributions of each of the investigations conducted in Africa.

Europe

Fröling (2015) conducted a comparative study in Sweden of the pre- and post-incineration behavior of brick-shaped coffee ground briquettes and contrasted them with traditional sawdust-based briquettes to characterize the elements present and establish the durability of each throughout the combustion process in a home barbecue. The experiments were carried out using a plasma spectroscope. The results obtained in parts per million (ppm) were higher than 0.01 for both types of briquettes. In addition, ash from traditional briquettes was found to have a high concentration of aluminum, calcium, iron, magnesium, and sulfur, while ash from coffee ground briquettes was found to be rich in boron, copper, iron, potassium, manganese, and phosphorus.

The study conducted in Poland by Ciesielczuk et al. (2015) analyzed the energetic power of coffee grounds as an additive for the production of briquettes from polished wood dust -based on the BN-88/9103-07 standard, which defines solid biomass fuels. The tests were carried out on compositions of polished wood dust (PWD) and coffee grounds (CG) in the following proportions: 100:0, 90:10, and 75:25. The compression used for compaction was 120 bar for PWD and between 80 and 90 bar for those combined with CG. The PWD composition with 25 % of coffee grounds indicated the best calorific value, estimated at 20.32 MJ kg^{-1}. All the compositions exceeded the minimum parameter of the DIN 51731 standard, taking into account that the basis of the mixture was not the coffee grounds but the PWD. The calorific values are close to those of traditionally used mineral coals. It allows us to conclude that it would be an efficient and accessible resource for Polish communities, even when having PWD as a base could create the need to process larger quantities of wood with its exploitation consequences.

The company Bio-Bean has developed a project to recycle wood waste in coffee shops in the United Kingdom, aiming to manufacture briquettes or cylindrical logs similar to the ones shown in Figure 1. The advantages are a wood-like aroma and a 20 % longer life than dry wood. The coffee grounds from

Table 1. Summary of briquette research in Africa

Source	Evaluated parameter	Relevant contribution
Pilusa (2010)	Production with 32 % coffee grounds, 23 % fine charcoal, 11 % wood sawdust, 18 % cornhusks, 10 % recycled paper and 6 % paper pulp	Reduction of flue gases below permitted levels, according to OSHAS
Pilusa et al. (2013)	Production with 32 % coffee grounds, 23 % fine coal, 11 % wood sawdust, 18 % cornhusks, 10 % recycled paper and 6 % paper pulp	• Determination of calorific value at 18.9 MJ kg^{-1} • Reduction of flue gas emissions below permitted levels, according to OSHAS
Pilusa et al. (2012)	Production based on coffee grounds, fine charcoal, wood sawdust, without binder	Determination of calorific value at 18,9 MJ kg^{-1}
Eshetu (2019)	Preparation based on coffee grounds with glycerol in compositions of 15:85; 25:75 y 40:60	Determination of calorific value 13,64 MJ kg^{-1}
Shiferaw (2018)	Elaboration based on coffee ground, eucalyptus leaves with clay binders, wheat flour, soil and paper, in different proportions	The best calorific value with the mixture of coffee ground, eucalyptus leaves and wheat flour
Limousy et al. (2012)	Elaboration based on coffee grounds and pine sawdust at 100 %. Coffee grounds and combinations 80:20	Performance as a 12 kW boiler fuel. It showed very low efficiency compared to wood sawdust

Note. Source: authors' elaboration.

25 cups are used to make a 500 g briquette, suitable for use in both multi-fuel stoves and the open air. It is packaged in recyclable paper bags. Its combustion reduces greenhouse gases by 80 % since it is a waste that is not dumped in the landfill, where its decomposition produces methane (Bio-Bean, n. d.).

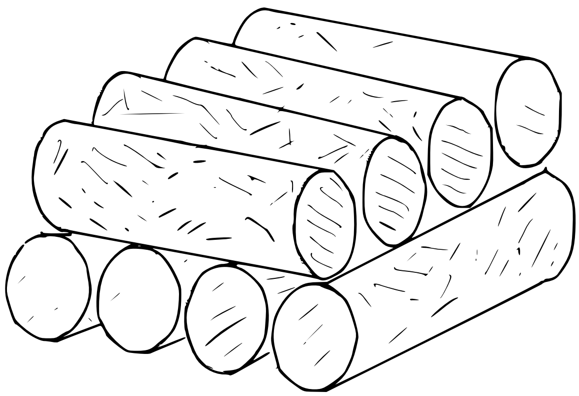

Figure 1. Commercial cylindrical briquettes.
Note. Source: authors' elaboration.

The experimental work developed by Allesina et al. (2017) describes how some coffee roasting companies use coffee grounds as an energy source to produce roasted coffee. They have been developing this process with natural gas, consuming around 400 m^3 per month. The experimentation showed that the use of coffee grounds as a source of energy reduces carbon dioxide emissions by up to 10 %. The efficiency of this process reaches up to 41 % and has allowed the development of a new business model where the product is made and reused. The process of roasting with the coffee ground as an energy source generates savings of EUR 10 398 per year on an energy input that demands 159 kW.

Seco et al. (2020) experimentally compared the behavior of briquettes composed of coffee ground and xanthan gum (XG) as a binder. This analysis was carried out taking moisture content and compaction pressure as independent variables. The values were compared for briquettes based only on coffee grounds with those based on coffee grounds and xanthan gum. The most relevant result of this study is the durability and integrity achieved by the briquette when mixed with the gum. However, its calorific value is reduced.

Nosek et al. (2020) experimented with four samples of pellets made with coffee grounds (CG) and sawdust (SD), in compositions 70:30; 60:40; 50:50, and 100:00. Their behavior as fuel was evaluated in a boiler burner. As a result, it was found that the 100 % dust pellets have the highest carbon content (54.56 %), which made them reach the highest calorific value of 21.08 MJ kg^{-1}. Nevertheless, the expected performance in the boiler operation was not achieved since the pellet does not reach a good consistency.

Brunerová et al. (2020) analyzed the solid fuel behavior of briquettes made from spruce shavings (SS), larch sawdust (LSD), mixed with coffee grounds (CG) in compositions of 100 % pure CG; 100 % pure LSD; CG:LSD, 50:50; CG:LSD, 25:75; 100 % pure SS; CG:SS, 50:50, and CG:SS, 25:75. As result of the study, the highest calorific value was obtained for briquettes made of 100 % pure coffee grounds, followed by briquettes made of sawdust and shavings at 100 %. However, they do not remain homogeneous for large-scale production. Therefore, the mixture with higher proportions, especially of sawdust, is indicated, despite the reduction of some physicochemical properties.

Table 2 summarizes the most relevant contributions of each of the investigations carried out in Europe.

Asia

A study conducted in Malaysia by Kansai et al. (2018) determined the physical and economic characteristics of carbonized briquette production from forest wood and a combination of coffee ground and tea, using yucca as a binder. Five ratios of forest wood residues (rain tree, RT) and coffee ground with tea (coffee-tea, CT) were performed. All residues were mixed after having been previously carbonized in the following ratios RT:CT. 100:0; 75:25; 50:50; 25:75; 0:100. The ratio of the CT mixture was not specified. To each of these, 1 kg of yucca was added and compacted to make briquettes of 1 cm internal diameter, 4 cm external diameter, and 10 cm long. The drying process was carried out in the open air for five days. It is noted that a high value was obtained but with an increase in the fixed carbon content of the fuel, which would bring similar problems to those generated by conventional mineral and vegetable coals.

Table 2. Summary of research on briquettes for Europe

Source	Evaluated parameter	Relevant contribution
Fröling (2015)	Processing of bricks made of coffee grounds and sawdust to evaluate the post-combustion behavior of biomasses	Concentrations of aluminum, calcium, copper, iron, magnesium, boron, sulfur and phosphorus found in the ashes of each one
Ciesielczuk et al. (2015)	Processing based on polished wood dust and coffee grounds in compositions of 100:0; 90:10; 75:25	Best calorific value 20.32 MJ kg^{-1} for the 75:25 composition
Bio-Bean (s. f.)	Utilization of coffee grounds generated in the UK	Reduction of greenhouse gases (GHG) by up to 80 %
Allesina et al. (2017)	Utilization as fuel in the roasting process of the same grains	10 % reduction in emissions generated compared to natural gas. Energy savings of up to EUR 10 398
Seco et al. (2020)	Processing based on coffee grounds and binder with xanthan gum	Improved physical integrity with increased gum but reduced calorific value
Nosek et al. (2020)	Processing based on coffee grounds and sawdust in compositions 70:30; 60:40; 50:50; 100:0, and boiler test	100 % coffee ground composition obtained the best calorific value (21.08 MJ kg^{-1}). Boiler efficiency decreases due to low pellet consistency
Brunerová et al (2020)	Production with mixtures of coffee ground, spruce chips and sawdust in different combinations	Briquettes with 100 % coffee ground had higher calorific value but worse physical consistency

Note. Source: authors' elaboration.

Naruephat and Patcharee (2015) conducted a study in Thailand, where briquettes were characterized with proportions for recycled paper (RP) and coffee grounds (CG) in 70:30; 60:40; 50:50; 40:60, and 30:70. The results are detailed when comparing the best-performing briquette with firewood and charcoal (Table 3). As the content of CG in the mixture increased, the heating value improved.

Another project carried out by Naruephat and Patcharee (2015) consisted of using different types of municipal waste for the production of briquettes, where food fats, coffee, and tea grounds. The characterization was carried out arranging three groups of waste as follows: group I - edible fats with coffee grounds; group II - edible fats with tea sawdust; group III - coffee grounds and tea sawdust. For each of these groups, mixtures were made in proportions of 50:50, 40:60, and 30:70, respectively. For groups I and II, it was observed that the 50:50 compositions yielded higher calorific values, such as that of the cooking grease and coffee ground mixture, estimated at 27.14 MJ kg^{-1}. Additionally, the study showed that the 50:50 ratio did not require any binder, while for group III a larger amount of binder had to be used since coffee grounds bind poorly with tea.

The project conducted by Kristanto and Wijaya (2018) analyzed the mixture of coffee grounds with coffee pulp for pellet production in Indonesia. One of the tests implemented allowed determining the influence of compaction on morphology for each type of pellet. For the characterization of the pellets as fuel, coffee ground-pulp compositions of 95:0; 85:10; 75:20; 65:30, and 55:40 were produced. For all samples, 5 % starch was used as adhesive material. The parameters of DIN 51731 were taken and the best calorific value was obtained for the composition of 95 % coffee grounds and 5 % starch. The

Table 3. Combustible properties of RP-CG briquettes, firewood and charcoal

Parameter	RP:CG briquettes	Firewood	Charcoal
Calorific value (MJ kg^{-1})	16.72-20.064	18.35	31.057
Moisture content (%)	7-9	8	9.4
Ash content (%)	3.8-8.5	3.9	5.4
Volatile material (%)	82-86	65	2
Fixed carbon (%)	1-3	22.8	84.6

Note. Source: Naruephat & Patcharee (2015).

pulp particles showed a denser fibrous structure compared to sawdust, which means that they have lower porosity. This value was estimated at 19.68 MJ kg^{-1}. As a key conclusion of the study, it is recommended not to add pulp in large quantities due to the NO_2 emissions produced.

In Malaysia, Mohd's work (2014) analyzes the production of briquettes from coffee grounds with two types of binder: rice husk and recycled paper. First, unroasted coffee grounds combined in a 50:50 ratio with each substance were evaluated. Then the compositions were modified to 70:30 and 80:20. The mechanical behavior of each composition was analyzed, obtaining the highest values for the 50:50 composition of recycled paper. Additionally, boiling tests were run on a mass of water, calorific value, percentage of fixed carbon, ash content, and volatile material, in which the 80:20 composition recorded the best performance. Subsequently, the coffee grounds were subjected to two roasting processes at 260 °C and 290 °C, which significantly improved the physicochemical properties.

In the study conducted in Thailand by Potip and Wongwuttanasatian (2018), samples of coffee grounds were collected from coffee shops. They produced blends of coffee grounds (CG) with crude glycerol (G) in ratios of 100:0 (G0), 95:5 (G5), and 90:10 (G10). The mixtures were compressed in a briquetting press at 10 MPa. The dimensions of the briquettes were 53 mm in diameter, 52 mm in length, and a weight of 100 g. The calorific value of the briquettes was determined based on ASTM-D240. The values obtained for the G0, G5, and G10 mixtures were 21.14, 21.21, and 21.55 MJ kg^{-1}, respectively, which exceeded other solid biomass fuels such as cornhusk, sugarcane bagasse, yucca stalk, and wood chips. Additionally, the emissions released from the combustion process (CO, NOx, CO_2, HC, O_2, and CO_2) were analyzed, which increase with the content of the husk. In conclusion, the emissions obtained showed low values due to the excess air used.

In Malaysia, Law et al. (2018) analyzed the mechanical behavior of briquettes made from different combinations of agricultural residues. They used rice husk (RH), sugarcane bagasse (SB), and coffee ground (CG) in RH:SB, RH:CG, and SB:CG mixtures, all in ratios of 80:20, 60:40, and 20:80. Impact resistance was evaluated to simulate the forces involved when the briquettes are transported or moved from one site to another, stacked in boxes one on top of the other. From a height of one meter, the briquettes are dropped ten times. The final weight is compared with the initial one to determine the weight loss as a percentage. Abrasion resistance was carried out in a rotating drum, where three briquette samples were deposited (Figure 2). They must be previously sieved for 30 seconds to remove fine particles. The drum is rotated for 5 minutes at 25 rpm clockwise. As in the impact resistance test, the weight loss is compared with the initial weight.

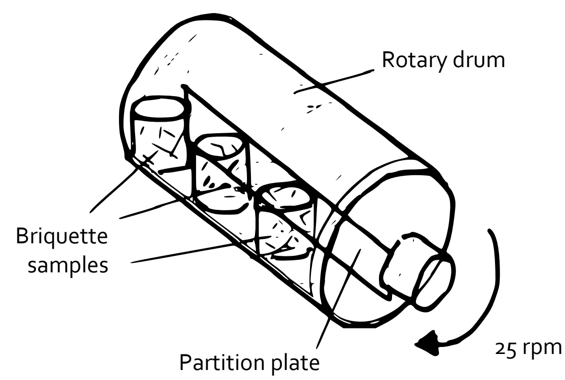

Figure 2. Rotating drum for abrasion testing
Source: own elaboration

The study concluded that the best mechanical behavior is obtained by increasing the coffee ground content.

Chen et al. (2017) presented in China the results of a study analyzing the drying response with infrared radiation for briquettes of the following types of biomass: tomentosa leaves, cotton stalks, coffee grounds, and eucalyptus bark. The samples were produced as 40 mm diameter pellets, with thicknesses of 3.2 mm for tomentosa leaves; 3.6 mm for cotton stalks; 2.6 mm for coffee ground; and 4.1 mm for eucalyptus bark. The compaction process was carried out at 20 MPa. The samples were subjected to temperatures between 100 and 200 °C. As a result, the drying rates of the briquettes with infrared radiation increase between 1.4 and 1.9 with the temperatures evaluated, compared to natural convection drying processes.

In South Korea, Kang et al. (2017) conducted a study similar to that of Limousy et al. (2012) to evaluate the performance of coffee ground as a fuel for a 6.5 kW residential boiler. They air-dried the samples such that the moisture content was below 15 %. The dry coffee ground passed through 100, 250, 500, 850, and 1000 µm sieves. As they were not uniform, the particles were defined in ranges of less than 100, 250-500, and 500-800 µm. Because of this test, the combustion time it took for the water in the storage tank to reach 75 ^{0}C (146 min) is highlighted. Low CO and NOx emissions were also recorded which were estimated at 643 and 163 ppm, respectively. It also highlights the interest on the part of the South Korean authorities about the implementation of this type of device with alternative fuels.

The isothermal combustion characteristics of briquettes made from anthracite and coffee ground were studied in China by Wei et al. (2019). This was monitored by thermogravimetric analysis at temperatures between 873 and 1173 K. They compared the performance during combustion for two briquettes, whose compositions were 60 % coffee ground - 40 % anthracite, 40 % coffee ground- 60 % anthracite to two individual compositions of 100 % coffee ground and 100 % anthracite. At a temperature of 973 K, they found that the burning rate of the coffee ground briquette is eight times higher than that of anthracite. The four samples had much lower NO_2 emissions than other gaseous emissions.

Table 4 summarizes the most relevant contributions of each of the investigations conducted in Asia.

Table 4. Summary of briquette research for Asia

Source	Evaluated parameter	Relevant contribution
Kansai et al. (2018)	Processing based on coffee grounds and discarded tea, using yucca as a binder and forest wood residues	The calorific value is increased but also the carbon content by augmenting the wood residues. Therefore, CO_2 emissions would be increased.
Naruephat & Patcharee (2015)	Processing based on coffee ground and recycled paper in compositions of 70:30; 60:40; 50:50; 40:60 and 30:70	They found that the calorific value increases with coffee ground content compared to wood and charcoal
Naruephat & Patcharee (2015)	Processing based on coffee ground, discarded tea, and cooking fats	The heating value increases with decreasing amount of coffee ground or tea. The best value was obtained for the composition coffee ground: fat 50:50 (27,14 MJ kg^{-1})
Kristanto & Wijaya (2018)	Mixture of coffee grounds and pulp of coffee and 5 % starch, in compositions of 95:0; 85:10; 75:20; 65:30, and 55:40	Determination of calorific value at 19.68 MJ kg^{-1} for composition 95:5. Increasing pulp content increases NO_2 emissions
Mohd (2014)	Processing based on coffee ground, rice husk and recycled paper in compositions of 70:30, 50:50; 80:20	Rice husk affects briquette compaction despite improving calorific value
Potip & Wongwuttanasatian (2018)	Processing based on coffee grounds, blended with glycerol in ratios of 100:0, 95:5; 90:10	Calorific value on average 21.30 MJ kg^{-1}, higher than other biomasses
Law et al. (2018)	Analysis of the mechanical behavior of briquettes from coffee grounds blended with rice husk, sugarcane bagasse at residue: coffee ground ratios of 80:20; 60:40, and 20:80	The content of coffee ground improves the crushing, impact and abrasion resistance of the briquettes
Chen et al. (2017)	Infrared radiation drying for coffee ground briquettes mixed with cotton stalks, eucalyptus bark, and tomentosa leaves	Faster drying speed compared to other conventional methods
Kang et al. (2017)	Use of ground coffee pellets as fuel in 6.5 kW domestic boiler	A time of 146 min was obtained for the feed water to reach 75 ^{0}C, which is a low efficiency process
Wei et al. (2019)	Evaluation of isothermal combustion based on anthracite and coffee ground in compositions of 60:40; 40:60; 100:0, and 0:100	Briquettes with higher coffee ground content showed higher burning velocity. NO_2 emissions were low for all compositions

Note. Source: authors' elaboration.

America

A study of the properties of briquettes made from coffee ground and wood sawdust was conducted by Soares et al. (2015) in Brazil. They collected the coffee grounds from coffee shops and automatic machines. They sieved them in 60, 35, and 20 mm grids. They made briquettes of coffee ground-wood sawdust compositions of 80:20; 70:30; 60:40; 50:50, and 40:60, respectively. A diametral compression test was performed instead of the standardized vertical test, and the best strength was obtained with the 60:40 composition (13.53 MPa). Increasing the proportion of wood sawdust reduced the crushing strength and the modulus of elasticity. The highest heating values were 84.64 MJ kg^{-1} for the 100 % sawdust composition and 85.84 MJ kg^{-1} for the 60 % coffee ground composition.

A global mechanical engineering project in which a briquetting press was designed to characterize coffee ground-based briquettes with yucca starch as a binder was developed by Balseca-Sampedro et al. (2018) in Ecuador. The composition and briquette making parameters were coffee ground as base material 72.68 %; yucca starch as a binder, 12.82 %; and water as the solvent, 14.5 %. The pressure applied to compact the mixture was 2.77 MPa. The dimensions were 47 mm in diameter by 50 mm in length. They did not produce compositions in different proportions but worked with other mass quantities. The average crushing strength load obtained for a batch of 20 briquettes was 237.74 N, which does not meet the parameters of the NTC2060 standard. As for energy characterization, they determined that the briquette's higher calorific value was 17.21 MJ kg^{-1}. The ash content was 1.76 %, while the moisture content was 9.12 %. The calorific value of these briquettes is lower than other biomasses such as charcoal, pine bark, bagasse, or coffee stalks. However, it is similar to rice and paper husks and higher than dry wood chips, straw, sawdust, coconut, and sugarcane bark.

In the study conducted by Vargas (2018), pellets that used coffee ground were characterized with three different binders as base material: glycerin, biodiesel, and palm oil. For each group of binders, they were used in proportions by weight of 2, 5, and 8 %, and with moisture contents of 4, 6, and 8 %, respectively. The pellets were produced with an average length of 25 mm and a diameter of 5.3 mm. The study showed that the calorific value of the pellets made from just coffee grounds was 23.08 MJ kg^{-1}. With the other binders, values between 20 and 24 MJ kg^{-1} were obtained.

Table 5 summarizes the most relevant contributions of each of the investigations carried out in the Americas.

Combinations in different proportions with different binders generate other characterizations. Thus lower calorific value with briquettes or pellets made 100 % from coffee grounds (Nosek et al., 2020). Similarly, different mixtures will influence the composition and are related to emissions (Colantoni et al., 2021) during combustion. The current possibilities using coffee grounds have led to studies on the feasibility of further technifying the manufacturing process and analyzing quantitative

Table 5. Summary of research on briquettes for America

Source	Evaluated parameter	Relevant contribution
Soares et al. (2015)	Processing based on coffee grounds, wood sawdust in compositions of 80:20, 70:30; 60:40; 50:50, and 40:60	The heating value is increased; the crushing resistance is reduced as the sawdust content is increased. The best value was obtained with 60 % for coffee grounds (85,84 MJ kg^{-1})
Balseca-Sampedro et al. (2018)	Preparation based on coffee ground and yucca starch, using water as a solvent. Single composition 72.68:12.82. Water 14.5 %	A crushing strength of 237.74 N was obtained, which is below the standard used in NTC 2060. But it is acceptable for conditions of stacking in boxes of the product. The calorific value was estimated at 17.21 MJ kg^{-1}
Vargas (2018)	Base of coffee ground, agglomerated with glycerin, biodiesel and palm oil in proportions of 2, 5 and 8 % each one. Moisture contents were 4, 6 and 8 %	The calorific value increases with the content of the coffee ground (23.08 MJ kg^{-1}) but the consistency of the pellet decreases

Note. Source: authors' elaboration.

valuations with logistic models supported by Information and Communication Technologies (ICT) (Bottani et al., 2019).

Regarding the calorific value of this solid biofuel, the present review showed that most research obtained values between 17 and 27 MJ, when it is more abundant in the coffee ground base and depending on the binder used. The studies that evaluated the emissions produced during the combustion process showed a decrease in greenhouse gases and particulate matter. However, alternatives must still be explored to reduce the still present NOx. The studies show that the calorific value of solid biofuels based on husks exceeds that of those made from other residues such as husks, with around 16 MJ kg^{-1}.

On the other hand, the mechanical behavior in the evaluated studies showed that the solid biofuels based on coffee ground achieve good consistency and physical stability properties when the binder content increases. This property is of utmost importance in transportation, distribution, and storage operations, where the integrity and physical presentation of the product are guaranteed.

Coffee grounds arise as an input that is practically inexhaustible due to the amount of coffee produced and consumed in the world. In a country like Colombia, this source is entirely available to obtain the coffee grounds and take advantage of its energy potential and other characteristics in different applications, among which stand out: removal of lead from water, biodiesel production, improvements in compost, soil nutrient and source of antioxidants and other nutrients for the food and cosmetic industry (Edward Group, 2013). Circular economy opportunities also appear around ventures such as the production of garments, utensils, furniture, and others, which would boost the local economy (Trujillo, 2019).

Conclusions

The literature review demonstrates how coffee waste has had a relevant position as a sustainable energy source since its uses as a raw material do not need to be purchased and do not affect the environment.

The calorific value of the briquettes does not exceed that of charcoal or firewood, but it is high, presents good yields, and emerges as a good substitute for these traditional fuels.

Most of the experiences with wood pellets as raw material use other wastes such as leaves, stalks, sawdust, or cardboard paper to improve their shape and consistency, making them economically sustainable products since they do not require raw material investment. The exceptions were the yucca starch, glycerin, biodiesel, and palm oil, which are inputs that must be purchased (Vargas, 2018).

The development and commercialization of this type of biofuels mitigate the deforestation problems due to the firewood procurement and the accumulation of waste in landfills, causing methane.

Colombia is emerging as an area for this type of initiative, as it is a principal producer and consumer of the beverage. The impacts on the population health using this type of fuel or suggesting their implementation with adequate ventilation systems should be evaluated.

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Authorship contributions

Claudio Alberto Moreno Arias - Principal Researcher. Consolidation of the review of sources and contributions for the article.

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