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Recycling Urban Solid Waste in Senegal to Produce Green Coal

Kalidou Ba[1*], Alpha Ousmane Toure[1], Mamadou Faye[1], Cheikhou Kane[1], Moussa Diop[1], Amy Pene[1], Ibrahima Balde[1], Khady Diaye[1], Yapi Joel Angba[2], Adama Diop[1], Edouard Barick Ndiaye[1], Moustapha Diouf[1], Mohamed Ndoye[1]

[1]Ecole Supérieure Polytechnique, Université Cheikh Anta DIOP de Dakar, Laboratoire Eau, Energie, Environnement et Procédés Industriels (LE3PI), Dakar, Senegal

[2]Institut National Polytechnique Félix Houphouet-Boigny, Laboratoire des Procédés Industriels, de Synthèse, de l'environnement et des Energies Nouvelles, Yamoussoukro, Côte d'Ivoire

Email: *ba.kalidou@esp.sn

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Abstract

The technique of briquetting biomass to produce green charcoal offers considerable potential to meet the need of the high energy demand and help protect the environment in rural areas. This study aims to formulate a green charcoal with a high calorific value and low ash content. The green charcoal was prepared from coconut shells, peanut shells, sawdust, potato peelings, and cow dung and used as a binder. These residues were mixed in the proportions suggested by the Box-Behnken plan in order to model and optimise the manufacturing process. The physico-chemical analyses revealed that the best results were obtained with briquettes prepared from 50% cow dung, 10.17% coconut husk, 19.83% potato peelings, 12.42% peanut husk and 7.58% sawdust. These have a calorific value of 3031 kcal/kg and an ash content of 47.49%. Mechanical and combustion tests confirmed the quality of the green coal produced despite the white smoke and high ash content.

Keywords

Urban Waste, Green Charcoal, Optimisation, Experimental Design

1. Introduction

The presence of urban waste in nature leads to environmental pollution. Waste can play an interesting role in the production of energy as an alternative to open incineration or landfill [1]. Senegal, a developing country, is also faced with a waste management problem that has an impact on the environment and the population. Urban waste is collected by the Waste Management Coordination Unit and deposited at the Mbeubeuss landfill site. The Mbeubeuss landfill is the subject of a number of studies and experiments, as it is rich in solid household waste with considerable energy potential, making it the focus of a new initiative aimed at widening access to energy. However, the country is struggling to achieve energy self-sufficiency, which remains a major concern. Very remote villages have no access to energy sources because of low incomes, high gas prices and inadequate electricity generation [2], and use butane gas, firewood, charcoal or other plant-based cooking fuels such as maize stalks to meet their needs [3] [4]. As a result, Senegal's natural resources are under great pressure from excessive cutting of firewood, unsustainable agricultural practices, high population growth and bushfires [5] [6]. As a result, a number of researchers have investigated the possibility of converting biomass into briquettes. Examples include the production of biochar from sewage sludge, the only drawback of which is that it requires significant heat treatment to obtain an attractive calorific value [7], the use of sawdust from different woods and the combination of sawdust and other agricultural waste to produce briquettes [8] [9]. Other works, such as those by Niedzio'łka *et al.* [10] [11], have used other agricultural wastes such as rape and oat straw, maize straw and cobs, as well as their mixture, for the production of briquettes. With the aim of reducing the energy deficit and preserving the environment, the Senegalese government is adopting a strategy that involves a complete paradigm, moving from waste management to the waste economy by exploiting its energy potential [12]. This is the context in which the subject is set so as to be able to participate in the fight against climate change and the uncontrolled dumping of waste. The idea is to transform waste such as cow dung, coconut shells, peanut shells, potato peelings and sawdust into combustible briquettes. The main aim of this work is to add value to solid urban waste and protect the environment by recycling urban waste, proposing sustainable production and consumption methods, and creating alternative sources of income. To achieve this, the raw materials will first be characterised, then the physico-chemical properties of the fuel briquettes formulated will be determined in order to find the optimum briquette, and finally combustion tests will be carried out to verify the effectiveness of the optimum briquette.

2. Materials and Methods

2.1. Raw Materials

Cow dung is used as a binding agent. Cow dung is the dung of cattle and oxen, made up of 80% - 90% water and dry matter. Cow dung is the most productive product in terms of energy, with around 2 kW for 20 kg. Once dried, dung can be used as a fuel for heating [13]. This was obtained from a farm in Dakar, where 2 × 50 kg bags were collected and sent to the laboratory for pre-treatment. Coconut, the fruit of the coconut palm, is widely available and can be used for a variety of purposes, offering an alternative to charcoal [14]. Charcoal was obtained from coconut vendors, and a 50 kg bag was purchased. Groundnut shells are used as fuel in oil mills or as fertiliser, and represent a potential of 175,000 t/year, according to the programme for the promotion of renewable energy, rural electrification and the sustainable supply of domestic fuel [15]. The hulls came from SONACOS, a groundnut oil producer based in Senegal, and we were given a 50 kg bag of groundnut hulls. The sawdust is used as fuel, litter or adsorbent. A 50kg bag of sawdust is bought from a local sawmill in Dakar. Potato peelings are edible tubers with several uses. Potato peelings are one of the best organic fertilisers, and were collected at the market from women vendors. 30 kg of potato peelings were purchased. The different raw materials used are shown in Figure 1.

(a) (b) (c) (d) (e)

Figure 1. Raw materials: cow dung (a), peanut shells (b), coconut shells (c), sawdust (d), potato peelings (e).

2.2. Preparing Raw Materials

The raw materials are first sorted to remove all undesirable particles such as plastics, broken glass and stones, then dried in a calorimetric oven at a temperature of 105˚C for 24 hours. The waste is then shredded and ground using a SAACHI-type shredder-mixer. At the end of the shredding stage, the samples were prepared for characterisation to determine their physico-chemical properties. These included gross calorific value (GCV), ash content (ASH), moisture content (H), volatile matter content (VMC) and fixed carbon content (C).

2.3. Extruding Briquettes

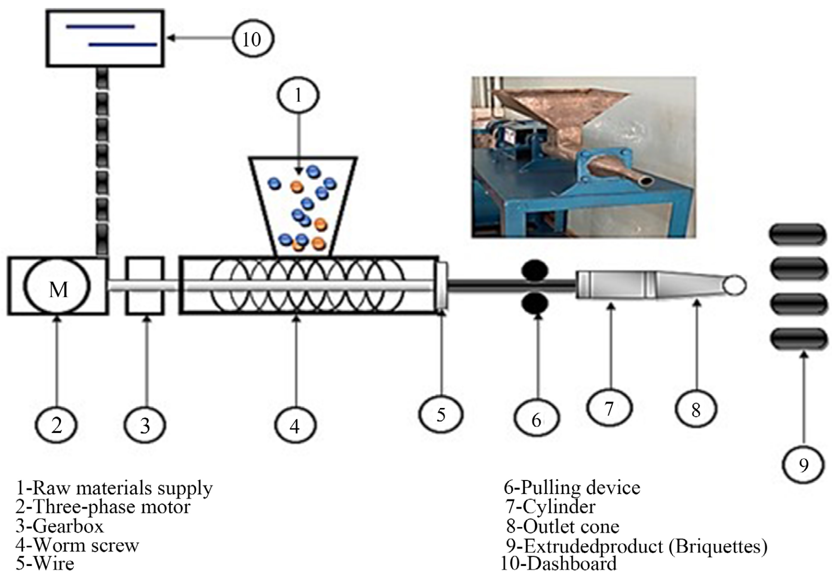

Figure 2. EMIE type extruder.

The extruder used to compress the briquettes consists of a 0.075 kW three-phase motor weighing 16.29 kg. Inside the cylinder is an internal screw propeller which rotates at a speed of 280 rpm, compressing the material. After this compression stage, the fuel briquettes emerge in a cylindrical shape thanks to a cone placed at the outlet of the extruder. The production capacity of this machine is around 200 kg/h, and it is illustrated in Figure 2 with its various component parts.

2.4. Experimental Procedure

It consists of defining the ranges for the study of raw materials for 100 g of coal, then varying the factors in steps of 10 g in order to obtain the range of variation of the factors. These are: the ratio of coconut shell mass to potato peel mass (X_1), the ratio of groundnut shell mass to sawdust mass (X_2) and the percentage of cow dung (X_3). The experimental matrix consists of 17 trials, with calorific value (HCV) and ash content (ASH) as the variables of interest. Based on the ratios in the experimental matrix, the masses of cow dung, coconut and peanut shells, sawdust and peelings were calculated for each experiment. The quantity of water used for the different tests varied to ensure good adhesion between the materials. The different experiments were carried out using the production diagram shown in Figure 3.

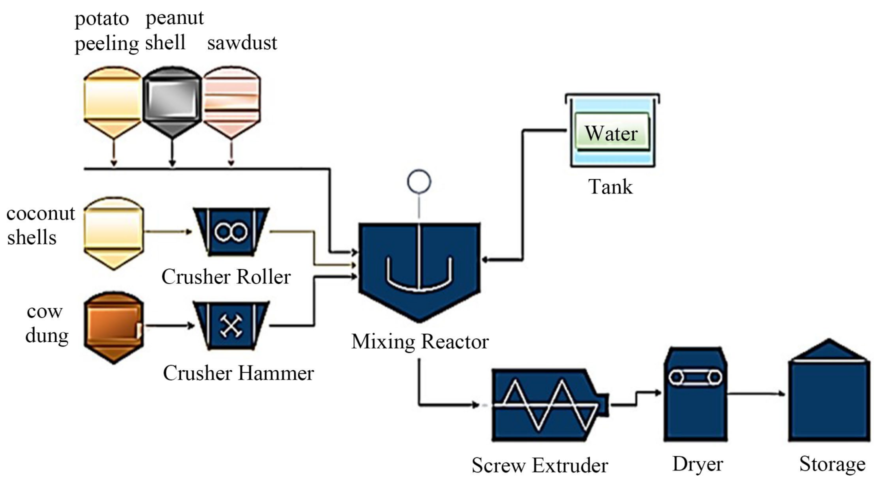

Figure 3. Production diagram for fuel briquettes.

2.5. Optimisation of Operating Conditions

It is used to obtain a mathematical model linking the responses (PCS and ASH and the factors X_1, X_2 and X_3) and to validate the mathematical model on the basis of the statistical results provided by the Design-Expert version 8.0.6 software. The interpretation of the results obtained is based on the analysis of variance (ANOVA), which assesses the significance of one or more factors by comparing their probabilities with the threshold value ($\alpha = 5\%$), and the search for the optimum operating conditions to satisfy two objectives, maximising the PCS and minimising ASH. The desirability function is used to obtain an optimal pair of factors leading to the best performance.

2.6. Physico-Chemical Characterization

2.6.1. Physico-Chemical Analyses

The analyses carried out included ash content, moisture, fixed carbon, volatile organic matter and gross calorific value. They were carried out by DANGOTE Cement's analysis laboratory using standard NF B55-101.

2.6.2. Mechanical Testing

These were applied to extruded optimum briquettes to achieve friability and compressive strength. These were carried out using ASTM D440. The briquettes were air-dried until they reached a mass of 14% and their initial masses were recorded. They were dropped from a regular height of 2 m onto a concrete floor. The number of broken pieces (weighing >5% of their initial mass) was recorded. The number of drops was set at 10 for each sample. The friability and compressive strength are calculated using Equation (1) and Equation (2) respectively:

$$F = \frac{M_i - M_f}{M_i} \times 100 \quad (1)$$

$$R = \frac{F_{app}}{S} \quad (2)$$

with:

M_i the initial mass of the briquette before dropping in g.

M_f the mass of the briquette after dropping in g.

F_{app} the force applied in N.

S cross-section in mm^2.

R compressive strength in MPa.

2.6.3. The Combustion Test

This test consists of determining the burning time, flammability and boiling point of optimal briquettes. These tests will also be carried out on charcoal sold in Senegal. This will enable a real comparison to be made and confirm the quality of the briquettes produced.

2.6.4. Experimental Field

Table 1. Experimental area.

Factors	Level	
	Low level (−1)	High level (+1)
X1	0.5	5
X2	1	1.67
X3	0.5	0.6

It represents the range of variation of the factors, which is between a low and a high value. Table 1 shows the levels of these three factors chosen for the formulation of fuel briquettes.

3. Results and Discussion

3.1. Characterisation of Raw Materials

The results of the physico-chemical analyses obtained are presented in Table 2.

Table 2. Characterisation of raw materials.

Raw materials \ Analyses	H (%)	ASH (%)	MOV (%)	HCV (kcal/kg)
Peanut shells	09.72	11.47	67.88	4699.43
Coconut shells	4.94	1.20	76.13	4443
Sawdust	11.23	06.31	75.76	4399.57
Potato peelings	2.52	82.40	17.46	713
Cow dung	7.93	9.08	69.65	2930

Peanut shells have a moisture content, ash content and calorific value of 9.72%, 11.47% and 4699.43 kcal/kg respectively. These values show that peanuts have a very high energy capacity. This is why they are widely used in industry as a fuel for boilers [16]. Coconut shells have a moisture content of 4.94%, a low ash content of 1.2% and a High Calorific Value (HCV) of 4443 kcal/kg. Sawdust, with a High Calorific Value (HCV) of 4399.57 kcal/kg, a low ash content of 6.31% and a slightly high moisture content of 11.23%, also has real energy potential, which is why it has long been used directly in rural areas as a fuel. However, the problems associated with these residues are transport, storage and handling [17]. Apple peelings, with their low calorific value of 713 kcal/kg and high ash content of 82.4%, are added to the formulation process in small quantities in order to contribute to the density of the briquette. In addition, large quantities of peelings in the briquettes will slow down combustion because of their high ash content, which represents the mineral matter [18]. The cow dung used acts as a binder, enabling the various components to adhere together. Because of its calorific value of 2930 kcal/kg, it is also used as a source of energy in some localities. Analysis of the volatile organic matter content of peanut shells, coconut shells, sawdust, potato peelings and cow dung gave values of 67.88%, 76.13%, 75.76%, 17.46% and 69.65% respectively, which would explain the fumes given off by the briquettes during the combustion process.

3.2. Experience Matrix

The operating conditions of the planned tests and the results of the analyses obtained are shown in Table 3. These results will be used to carry out a statistical analysis in order to determine the mathematical models that will link the experimental factors to the responses. On the other hand, the models obtained will be used to optimise the formula to find the optimum one.

Table 3. Results of the experiment matrix.

Test number	Actual values (g)					Responses	
	Cow dung	Coconut shells	Potato peelings	Peanut shells	Sawdus	High calorific value (kcal/kg)	Ash (%)
1	55	9.0	18.0	9.0	9.0	2321	51.24
2	55	19.8	7.2	10.3	7.7	2188	48.46
3	55	22.5	4.5	9.0	9.0	2145	55.6
4	55	9.0	18.0	11.3	6.7	2433	47.57
5	55	19.8	7.2	10.3	7.7	2188	48.46
6	55	22.5	4.5	11.3	6.7	2494	46.96
7	50	22.0	8.0	10.0	10.0	2729	43.59
8	55	19.8	7.2	10.3	7.7	2188	48.46
9	60	17.6	6.4	8.0	8.0	2757	50.11
10	50	25.0	5.0	11.4	8.6	2597	48.2
11	55	19.8	7.2	10.3	7.7	2188	48.46
12	50	22.0	8.0	12.5	7.5	2753	44.39
13	60	20.0	4.0	9.1	6.9	2459	43.81
14	60	17.6	6.4	10.0	6.0	2566	48.69
15	60	8.0	16.0	9.1	6.9	2226	49.24
16	50	10.0	20.0	11.4	8.6	2835	41.96
17	55	19.8	7.2	10.3	7.7	2188	48.46

3.3. Mathematical Model

The two responses (HCV and ASH) are linked to the various study factors by quadratic models represented by the following equations:

$$\begin{aligned}\text{HCV} = {} & +47452.675 - 680.890 \times X_1 - 2293.9036 \times X_2 - 153594.3781 \times X_3 + 78.6069 \times X_1 \times X_2 \\ & +1046.6666 \times X_1 \times X_3 - 3208.955 \times X_2 \times X_3 - 1.16049 \times X_1^2 + 1480.285 * X_2^2 + 138850 \times X_3^2\end{aligned} \tag{3}$$

$$\begin{aligned}\text{ASH} = {} & -392.9302 + 16.1795 \times X_1 - 15.0782 \times X_2 + 1536.9259 \times X_3 - 1.6484 \times X_1 \times X_2 \\ & -25.9333 \times X_1 \times X_3 - 33.1343 \times X_2 \times X_3 + 0.0977 \times X_1^2 + 12.3635 \times X_2^2 - 1261 \times X_3^2\end{aligned} \tag{4}$$

3.4. Analysis of Variance

This analysis enables us to study the influence of the factors on the variables of interest. This influence is all the more significant when the p.value of the effect of the factors is less than the threshold value of 5%. Terms with a p.value greater than 5% are not significant. The analysis of variance for the HCV and ASH is given in Table 4 and Table 5 respectively.

Table 4. Analysis of variance for High calorific value (HCV).

Source	Sum of squares	Average of squares	F-value	p-value
Model	8.494E + 05	94372.28	7.03	0.0088
X_1	1800.00	1800.00	0.1340	0.7251
X_2	10804.50	10804.50	0.8043	0.3996
X_3	1.026E + 05	1.026E+05	7.64	0.0279
X_1X_2	14042.25	14042.25	1.05	0.3406
X_1X_3	55460.25	55460.25	4.13	0.0817
X_2X_3	11556.25	11556.25	0.8603	0.3845
X_1^2	145.33	145.33	0.0108	0.9201
X_2^2	1.162E + 05	1.162E + 05	8.65	0.0217
X_3^2	5.074E + 05	5.074E + 05	37.77	0.0005

Table 5. Analysis of variance for ASH.

Source	Sum of squares	Average of squares	F-value	p-value
Model	137.26	15.25	4.10	0.0381
X_1	2.60	2.60	0.6992	0.4307
X_2	20.90	20.90	5.62	0.0495
X_3	23.50	23.50	6.32	0.0402
X_1X_2	6.18	6.18	1.66	0.2384
X_1X_3	34.05	34.05	9.16	0.0192
$X_2 X_3$	1.23	1.23	0.3314	0.5828
X_1^2	1.03	1.03	0.2775	0.6146
X_2^2	8.11	8.11	2.18	0.1833
X_3^2	41.85	41.85	11.26	0.0122

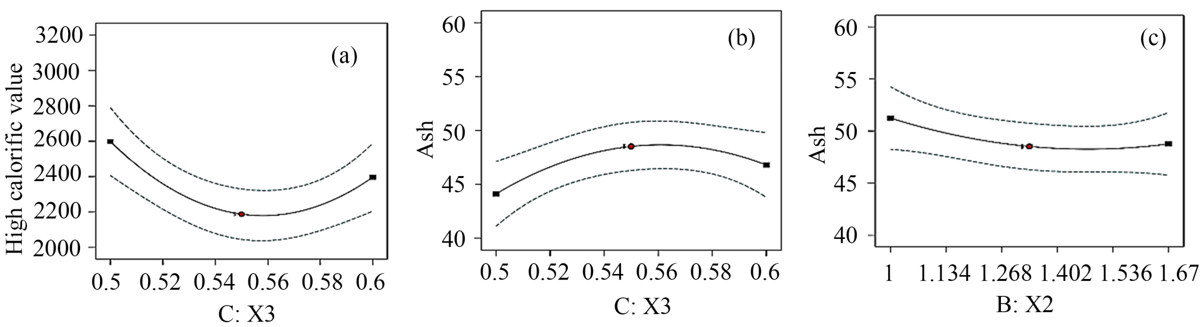

Figure 4. Effect of X_3 on HCV (a), effect of X_3 on ash content (b) and effect of X_2 on ash content (c).

The results in **Table 4** show that X_3 is a significant term since the p-value is less than 0.05. This can be explained by the large quantity of cow dung used in production, which has a major influence on the HCV. This can be explained by the large quantity of cow dung used in production, which has a major influence on the HCV. Increasing the cow dung content to certain values will result in a decrease in the HCV, as shown in **Figure 4(a)**. This decrease can be explained by the fact that cow dung comes with sand during the sampling process, which constitutes mineral matter and therefore has a negative impact on the HCV. Those in **Table 5** show that X_2 (ratio of groundnut shell mass to sawdust mass) and X_3 (percentage of cow dung) are also significant terms. This is due to the high ash content of potato peelings and cow dung, which increases the overall ash content of the briquette. This can be seen in **Figure 4(b)** and **Figure 4(c)**.

3.5. Optimisation

The desirability function was used to maximise the calorific value and minimise the ash content of the briquettes in order to obtain the best formula. The possible solutions provided by this function are given in **Table 6**. The experimental conditions predicted from this function were reformulated in order to validate the mathematical model. The latter effectively showed that formula No. 3 was better with a HCV of 3031 kcal/kg and a composition of 50% binder (cow dung), 10.17% coconut shell, 19.83% potato peelings, 12.42% peanut shell and 7.58% sawdust.

Table 6. Results predicted by the desirability function and those obtained experimentally.

Number	Optimal factors			Expected results		Results obtained		Desirability
	X_1	X_2	X_3	HCV (kcal/kg)	ASH (%)	HCV (kcal/kg)	ASH (%)	
1	0.885	1.557	0.500	2846.137	41.719	2342	44.92	1.000
2	0.857	1.576	0.500	2860.529	41.865	2269	37.95	1.000
3	0.513	1.637	0.500	2936.102	41.912	3031	47.49	1.000
4	0.578	1.083	0.500	2835.869	41.429	2663	43.23	1.000
5	0.537	1.045	0.500	2860.806	41.668	2483	51.72	1.000

3.6. Analysis of the Optimum Briquette

3.6.1. Physico-Chemical Tests

The physico-chemical results obtained for optimal green charcoal and charcoal are shown in **Figure 5**. The calorific value of the green charcoal obtained is lower than that of the charcoal. This can be explained firstly by the significant presence of one of the materials making up the green charcoal (19.83% potato peelings), which has a very low calorific value, and also by the absence of carbonisation during production. The moisture content of green charcoal is within the stated limit. The moisture content is highly dependent on the type of biomass selected, ranging from less than 15% for cereal straw to more than 90% for algal biomass [19]. It is comparable to that obtained by Huang *et al.*, with values of between 3% and 7% [20]. The high ash content of green charcoal is due to the binder, which makes up half of the dry matter. As indicated by Supatata *et al.* [21], an ash percentage of around 4% for agricultural residues is the most appropriate for biomass briquette to avoid an increase in particulate emissions during the combustion process. The high ash content is thought to be due to the high content of inorganic compounds that can have an intrinsic catalytic effect on overall thermal conversion technologies. However, a high ash content poses huge problems as its accumulation obstructs the flow of flue gases inside biomass boilers, causing corrosion and abrasion [22]. The rather lower volatile organic matter content of charcoal compared with green coal is justified by the carbonisation it has undergone, which eliminates a large proportion of the gasifiable matter. Green charcoal that has not undergone a carbonisation stage therefore has a high volatile matter content, which corroborates the studies by Ajimotokan *et al.* [23], who showed that the volatile matter content of biomass was between 41% and 78%. As stated by Cuvilas *et al.* (2014) that species with less volatile matter burn more slowly than those with more volatile matter [24]. In addition, a low volatile matter content promotes clean combustion of charcoal, which is therefore important according to Luxán Jimenez (2003) to be used in thermoelectric power plants. The amount of fixed carbon influences the calorific value of the briquette, equal to 30.23% for the optimum briquette, which is low compared with charcoal, which contains 50% carbon. The briquettes studied by Huang *et al.* have low fixed carbon values, less than 50%. Even lower values (36.6% - 43.3%) were obtained by Dias Júnior *et al.* [25]. Consequently, the higher the fixed carbon content, the greater the heat produced during combustion [26]. The European market requires more than 75% fixed carbon for industrial applications, although values < 75% are accepted for other industrial applications and many non-industrial applications, for example, cooking and smoking [27].

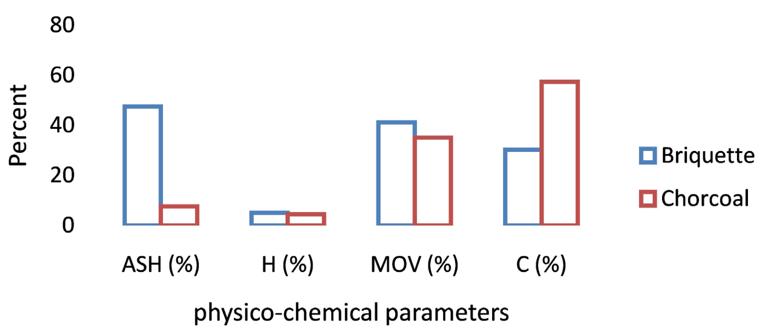

Figure 5. Comparison of the characteristics of the two coals.

3.6.2. Mechanical Testing

The briquettes coming out of the extruder and then dried in the oven are very strong, cylindrical in shape, around 5 - 6 cm high and 4 cm in diameter (**Figure 6**). Similar drop tests were carried out on charcoal and green coal in order to obtain their average friability (**Table 7** and **Table 8**). The fall on the height side and on the section side was carried out in two series.

Figure 6. Green coal.

Table 7. Friability of charcoal.

Charcoal	Initial mass (g)	Final mass (g)	Friability (%)
Test 1	21.07	21.01	0.2848
Test 2	17.76	17.71	0.2815
	Average		0.2831

Table 8. Friability of green coal.

Briquette	Initial mass (g)	Final mass (g)	Friability (%)
Test 1	33.28	33.26	0.06
Test 2	33.26	33.24	0.06
	Average		0.06

The friability of green charcoal is very low and much lower than that of charcoal. Using an extruder coupled with a cutting machine or harmonising the cuts after extrusion should reduce friability [28]. This is a good indicator that the briquette is clean and resistant. The higher the fixed carbon content, the better the briquette will resist handling forces. On the other hand, a low fixed carbon content increases the friability of charcoal [29].

3.6.3. Combustion Test

Figure 7. Boiling water test.

Table 9. Combustion test results.

Parameters	Briquette
Ignition time	9 min 35 s
Odour	Present
Smoke	White and plentiful
Suede	Missing
Ash	Hot
Consumption time	59 min 41 s
Water boiling time	30 min

This test was carried out using 150 g of green charcoal for 1/2 L of water. A thermometer was used to measure the temperature of the water until it boiled (**Figure 7**). The test was carried out in a well-ventilated area to ensure good combustion, and the results are shown in **Table 9**.

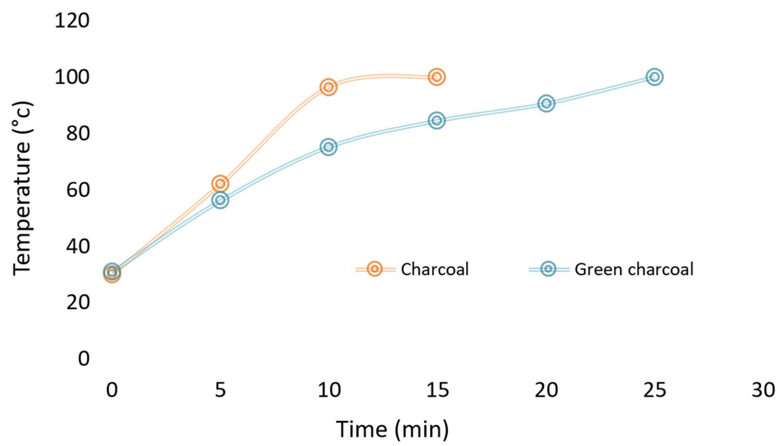

Figure 8. Evolution of water temperature to boiling point.

The green charcoal ignites after the indicated time, but its flame is smoky, which may be due to the high quantity of volatile matter. It should be noted that the fire was started with pieces of paper. The smell is due to the large quantity of binder, cow dung. The briquettes give off a little smoke when they burn. It varies, decreasing with the time it burns. The smoke is white and odourless. Its origin may lie in the species of organic matter or may be due to the large quantity of volatile matter present in the briquette. Smoke can be reduced by designing a suitable, well-ventilated firebox and sieving and adjusting the proportions of the briquette components. The high ash content of green coal could be justified by the very high ash content of potato peelings (82.40%). This raw material, which accounts for 19.83% of the mass of the briquette, has a huge influence on its characteristics. The briquettes were left to burn in order to record the ignition time. It should be noted that the heat is retained even inside the ashes. This means that there is an advantage when cooking food, in that fewer briquettes have to be used in terms of kilograms. According to Carnaje [30], the factors that could be responsible for the rate of briquette combustion are the volatile matter content and the geometry of the briquettes. It took 30 min to boil the water. The heat released by briquettes is less intense but more even. This is why they are favoured for recipes that require long, constant cooking or for ovens. The temperature was recorded every 5 minutes for both green charcoal and charcoal in order to follow its development until boiling (**Figure 8**).

4. Conclusion

The objective of this work was to recover the value of urban solid waste by producing green charcoal, which meets the need for cooking energy in households, and to replace the fuels that exist on the market and which appear to be scarce. The results obtained showed that the mixture composed of 50% binder (cow dung), 10.17% coconut shell, 19.83% potato peelings, 12.42% groundnut shell and 7.58% sawdust had the best characteristics. The calorific value of the green charcoal obtained was 3031 Kcal/kg, and the briquettes were neither crumbly nor dirty. They ignite quickly and evenly. However, the disadvantages of simple briquetting include the high volatile matter content of the charcoal and the emission of white fumes during combustion. However, other studies are underway to carbonise certain raw materials with a highly volatile organic matter content and to design a fireplace suitable for using these briquettes. This will make it possible to combat the fumes detected during the carbonisation stage.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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