

Life Cycle Assessment of Cashew Nutshell Briquettes Produced in Côte d'Ivoire

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Abstract

Now one of the main cash crops in Côte d'Ivoire, the cashew tree feeds an entire industrial sector based on the processing of its fruit. This processing generates a large volume of waste, consisting of cashew nutshells, the management of which poses environmental problems. With the aim of replacing charcoal and firewood with more environmentally friendly fuels, several studies are currently being carried out into the optimal use of cashew shells in fuel briquettes. To assess the environmental sustainability of these briquettes, this study calculates the environmental impacts associated with their life cycle, compares them with those of charcoal and firewood, and identifies the processes that contribute most to environmental pollution, with a view to improving them. Analysis of the results showed that cashew nutshell briquettes emit a range of pollutants over their life cycle that damage the environment and are responsible for the 7 impact categories considered: acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, photochemical oxidation and terrestrial ecotoxicity potential. However, they are more environmentally friendly than charcoal and firewood for 5 impact categories: freshwater aquatic ecotoxicity, global warming, human toxicity, photochemical oxidation and terrestrial ecotoxicity potential. The 3 elementary processes, *i.e.* transport of biomass raw materials, production, and combustion of briquettes, emit pollutants that contribute most to the creation of environmental impact categories. The most relevant pollutants are nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM).

Keywords

LCA, Briquettes, Cashew Nutshell, Biomass, Environmental Impact

1. Introduction

The use of fossil fuels as energy sources is at the heart of several environmental issues. Burning oil, coal or natural gas emits a range of environmental pollutants, including carbon dioxide and other greenhouse gases, which are responsible for global warming and climate change. The need to find renewable and abundant alternative fuels has become a matter of urgency for governments and scientists around the world. Biomass is emerging as an alternative. However, the increased exploitation of one of its many resources, wood, also poses an environmental problem. Through photosynthesis, forests act as carbon sinks for the planet. Photosynthesis involves the absorption of carbon dioxide (CO₂) by the plant and the production of oxygen (O₂), which is useful to living organisms.

In a bid to combat the destruction of its forest, Côte d'Ivoire has introduced the cashew tree to its orchards. Originating in the north-east of Brazil, the tree was introduced to Africa because of its ability to adapt to difficult soil and climatic conditions and has been used in several regions as a reforestation species since the 1970 [1] [2]. But since 1990, the tree has become one of the principal commercial crops in the country. The enthusiasm of growers has resulted in an extension of the area cultivated, an intensification of upkeep work and an improvement in activities linked to nut harvesting [2] [3]. The tree has become very important to the Ivorian economy, feeding an entire industrial sector based on processing its fruit. This processing generates a large volume of waste, consisting of cashew nutshells, the management of which poses environmental problems. According to several authors, converting these residues into fuel briquettes offers a potentially interesting solution that would contribute to the sustainable management of this agricultural waste, while providing a renewable energy source. Nurhayati *et al.* (2016) [4] and Randimbivololona *et al.* (2012) [5] consider that converting agricultural waste into bio-briquettes reduces the need for natural gas or oil as fuel in small industries. Moving in the same direction as the previous authors, Maninder *et al.* [6] consider that briquettes produced by briquetting biomass have many advantages and are a good substitute for charcoal, lignite, and firewood. Briquettes have better qualities and environmental benefits than charcoal, because they are made from renewable resources [6]. For Oliveira *et al.* [7], briquettes are a renewable fuel among the different types of solid fuels produced from biomass, and their use helps to reduce deforestation by partially replacing charcoal and fossil fuels.

The production of briquettes from cashew nutshells has been the subject of several scientific publications. These include, but are not limited to, Ifa *et al.* [8], Chungcharoen *et al.* [9] and Sawadogo *et al.* [10]. The work of [8] on "Technical and economic analysis of bio-briquettes made from cashew nutshell waste" established the economic feasibility of briquette production. The study [9] on "Preparation and characterization of fuel briquettes based on two types of agricultural waste: cashew nutshells and areca nuts" defined the operating parameters (mechanical properties, fuel properties and production rate) to produce high-performance briquettes. Also, the work of [10] on "Cleaner production in Burkina Faso:

a case study of fuel briquettes made from cashew nut industry waste” determined the physical, chemical, and mechanical parameters required for briquette production. In their work, these and other authors have analyzed and determined the technical and economic parameters for developing high-performance briquettes produced from cashew nutshells that can be used as a renewable energy source to replace firewood and charcoal. However, very few, if any, authors have analyzed and assessed the environmental impact of the life cycle, from extraction of the raw materials to disposal of the briquettes. To assess the environmental performance of briquettes made from cashew nutshells, this study analyses the life cycle of briquettes produced in Côte d’Ivoire. The analysis is based on the Life Cycle Assessment (LCA) methodological framework described in ISO 14040 and ISO 14044 (2006). ISO 14040 provides the terminology and structure to be followed when carrying out an LCA. While the ISO 14044 provides the requirements and important guidelines for carrying out an LCA. LCA studies are therefore carried out in a structured way, with certain principles guiding their development. According to Berg *et al.* [11], life cycle assessment (LCA) is a comprehensive tool often used to monitor the development of technical activities or to assess the environmental impact of products or services. It covers the entire life cycle of a product, from the extraction of raw materials through manufacture and use to end-of-life.

The aim of this study is to assess the environmental sustainability of green charcoal produced from cashew nut waste in Côte d’Ivoire. The environmental impacts associated with the life cycle of the briquettes are assessed and compared with those produced by charcoal and firewood from other LCA studies.

2. Materials

2.1. Cashew Nutshell Briquettes

Cashew nutshell briquettes are solid fuels produced from a compacted mixture, in a single block, of plant matter from cashew nutshells and cassava crop waste. These briquettes are made from two raw materials: cashew nutshell biochar and cassava starch. Cashew nutshell is a by-product of cashew nut processing. Cassava starch, on the other hand, is produced from the tuberous root of the cassava plant.

Because of its physicochemical characteristics, cassava starch acts as a binder between the cashew nutshell biochar particles in the manufacture of these briquettes. Since materials made from cashew nutshell biochar do not hold together, starch is added as a binding substance. Binders are very often used to ensure the cohesion of briquettes [12]-[18]. **Figure 1** shows cashew nutshell briquettes burning in a scrap furnace.

2.2. Availability of Biomass Raw Materials

The cashew tree (*Anacardium occidentale*) is a tropical tree grown in five main regions of the world: north-east Brazil, west Africa, east Africa, south-east Asia, and southern Indonesia [19]. The cashew fruit consists of two parts: the apple and the nut, which fall together from the tree when ripe. **Figure 2** shows the cashew

tree and its fruit [10].



Figure 1. Cashew nutshell briquettes burning in a scrap metal furnace.



Figure 2. Cashew tree and its fruit.

In Côte d'Ivoire, the cashew tree supports an entire industrial sector based on nut processing [1]. Over the past decade, national cashew nut production has virtually doubled, rising from 400,000 tons in 2011 to around 1 million tons in 2022. Given this growth, the country has set itself the goal of further improving the quality and quantity of its production. The ambition clearly stated by the Ivorian government is to process more than 50% of its cashew nut production locally by 2030. Since 2020, several processing units have been installed in the country [20]. In future years, these initiatives will increase the quantities of waste (mainly nutshells) already generated by the cashew nut industry.

Cassava cultivation is relatively recent in Côte d'Ivoire. However, it makes a major contribution to food security and poverty reduction by generating income for all the players in the value chain. Cassava remains the second most important food crop after yam and ahead of rice. It is grown for its tuberous roots, which are rich in starch. In small-scale processing units such as families or cooperatives,

starch is a by-product of attiéké processing. A traditional product typical of Côte d'Ivoire, attiéké is a fermented cassava semolina cooked in fresh steam. It is white or cream-colored, with a slightly acidic taste, a floury smell and a texture that is not sticky to the touch. The starch is extracted by collecting the liquids from pressing the fermented cassava paste. Considered a waste product, the starch is disposed of without being recycled [21].

Production of tuberous cassava roots in Côte d'Ivoire is also growing. It has risen from 2.35 tons in 2011 to around 6.3 tons in 2022 [22]. **Figure 3** shows the cashew nut and cassava producing regions in Côte d'Ivoire [23].



Figure 3. Cashew nut and cassava producing regions in Côte d'Ivoire [23].

2.3. Briquette Production Process

2.3.1. Description

The process of manufacturing briquettes from biomass varies depending on whether the desired briquette is carbonaceous or non-carbonaceous. The briquettes

produced in the context of this study are carbonaceous. Sorted and dried cashew nutshell waste is placed in a reactor to undergo slow pyrolysis at a temperature of around 350°C [10]. At the end of the carbonization process, the biochar obtained is ground into fine particles. According to the work of Kalivau *et al.* [14], the optimum particle size of fine biochar particles to produce fuel briquettes should be between 0.5 and 1 mm. The fine biochar particles are then mixed with cassava starch. The cassava starch ensures adhesion between the biochar particles and the strength of the briquettes. The mixture is then densified. This stage can be carried out either manually or mechanically using a press. The principle of densification is to expel the air contained in the particles and ensure that they agglomerate properly. In fact, the air trapped between the particles must be expelled to avoid the formation of spongy briquettes. A spongy briquette deteriorates during storage and produces poor combustion efficiency [24]. Finally, the briquetting process is completed by air-drying the briquettes. The drying stage is essential because briquettes are produced in wet form [25]. **Figure 4** shows the stages in the cashew nutshells briquette production process.

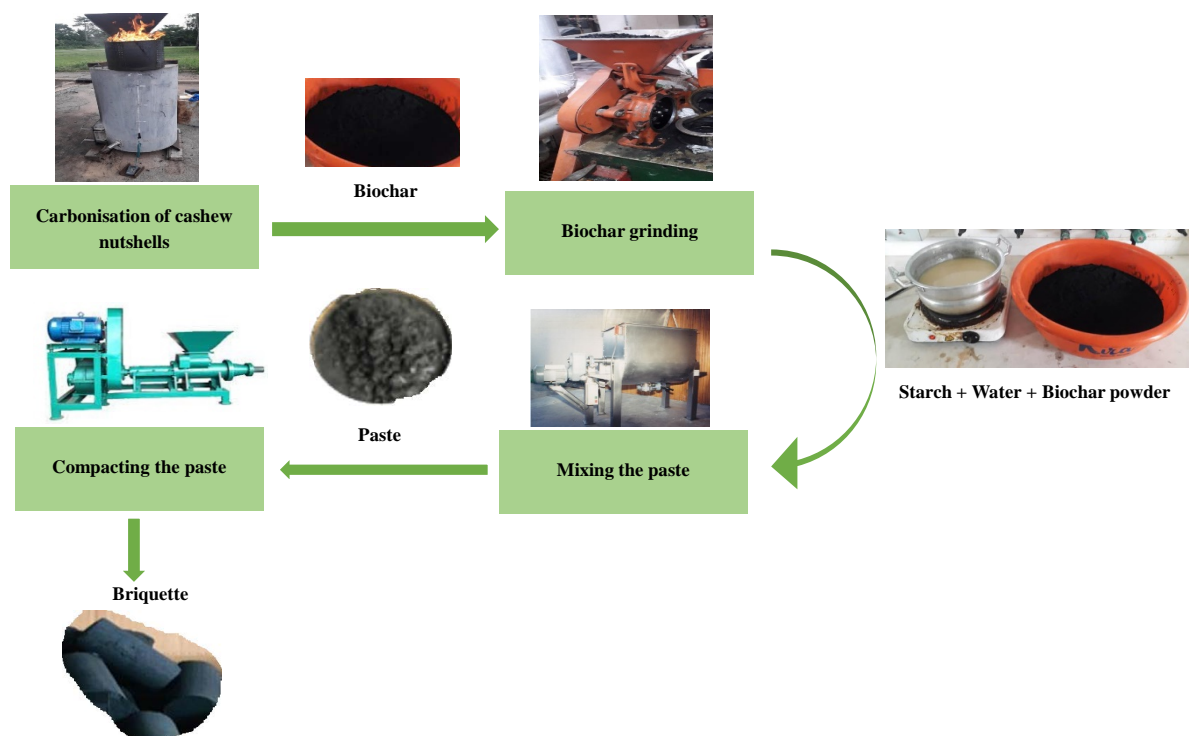


Figure 4. Stages in the cashew nutshell briquette production process.

2.3.2. Prototype of Briquette Production Unit

For the purposes of the study, a prototype of briquette production unit from cashew nutshells was installed at the LAPISEN laboratory (laboratoire des procédés industriels, de synthèse, de l'environnement et des énergies nouvelles) at the INP-HB in Yamoussoukro. The district of Yamoussoukro is in the center of Côte d'Ivoire, between latitudes 6° 15 and 7° 35 north and longitudes 4° 40 and 5° 40

west. The data needed to size the production unit were collected from the literature and from fuel briquette producers in Côte d'Ivoire. The unit consists of a pyrolysis reactor, a hammer mill, a mixer, and a compacting press. **Table 1** gives the characteristics of the equipment constituting the prototype of briquette production unit. The pyrolysis reactor is an H2CP (High Calorific Cashew Pyrolizer) type furnace. This type of reactor is suitable for processing cashew nutshell biomass. The cashew nutshells can be recovered in two by-product forms: pyrolysis gas and biochar. Pyrolysis gas is essentially composed of CO₂, CO, H₂ and CH₄ [26].

Table 1. Characteristics of the equipment constituting the prototype of briquette production unit.

Equipment	Power	Capacities
Pyrolysis reactor		87 kg/h
Hammer Mill	4 kW	150 kg/h
Mixer	4 kW	250 liters
Compacting press	4 kW	40 kg/h

In the present study, the pyrolysis gas was burned by a flare at the outlet of the pyrolysis reactor. However, in a cashew nut processing unit, the pyrolysis reactor is coupled to the cashew nut cooker. Therefore, the gases from the pyrolysis oven are burnt directly in the cooker furnace. In this case, around 130 kg of shells are pyrolyzed in 1 hour 30 minutes. Total combustion of the synthesis gases produced takes place in 4 hours 20 minutes and ensures the embrittlement of around 1280 kg of cashew nuts in the cooker [27]. **Figure 5** shows the pyrolysis process.



Pyrolysis reactor



Pyrolysis reactor coupled to the cashew nut cooker

Figure 5. Pyrolysis process.

The equipment used to grind the biochar is a hammer mill with a maximum grinding capacity of 150 kg per hour and a power rating of 4 kW. The mixing unit is a G-250 horizontal mixer, which rotates at a speed of 120 revolutions per minute, has a power rating of 4 kW and a capacity of 250 liters. Finally, the compacting press is a worm screw driven by a 4 kW power motor, with a production capacity of 40 kg per hour. **Figure 6** shows the different motorized equipment used in the briquetting process. The briquettes produced are cylindrical in size, with a radius of 5.5 cm and a length of 10 cm [10].



Figure 6. Different motorized equipment used in the briquetting process.

3. Objective and Scope of the Study

The objective of the study is to assess the environmental sustainability of the production of ecologically green charcoal from cashew nutshells waste in Côte d'Ivoire. In this context, the specific objectives are to: 1) Calculate the environmental impacts associated with briquettes produced from cashew nutshells; 2) Compare these environmental impacts with those of charcoal and firewood from the LCA study; 3) Identify the most polluting processes in the briquette life cycle for potential improvement.

To include the important stages of the life cycle in the analysis, the boundaries of the system are established in LCA. The life cycle of briquettes can be broken down into 5 basic processes: collection and transport of residues, production, distribution and burning of briquettes. **Figure 7** shows the cashew nutshells briquette life cycle process boundaries. They start with the collection of residues and end with the combustion of briquettes, thus covering the main aspects of the life cycle. However, the processes relating to: the manufacture of transport infrastructure (lorries and roads); the manufacture of combustion equipment (boilers, furnaces, reactors, etc.); the treatment of wastewater; the production of agricultural products (cashew nuts and tuberous cassava roots), indirect activities related to fuel production, such as marketing, accounting, commuting and legal activities; the establishment of farms are excluded from the boundaries of the system, either because of their negligible contributions or because of lack of data or high uncertainties.

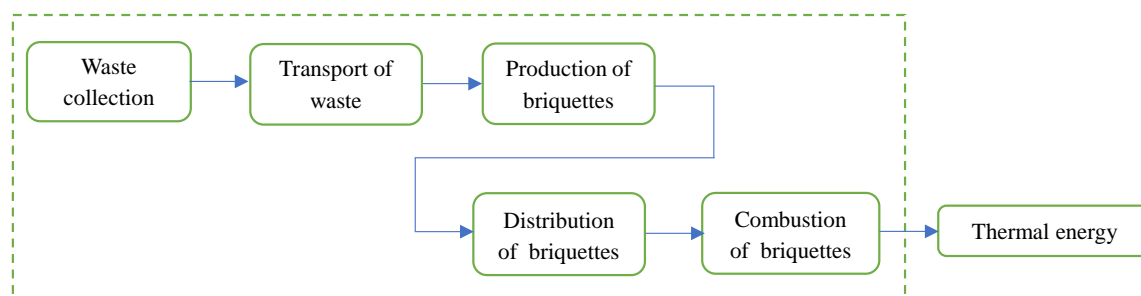


Figure 7. Cashew nutshells briquette life cycle process boundaries.

To allow a valid comparison between different types of cooking fuel, it is necessary to define a common reference. This common reference is known as the functional unit in LCA studies [28]. It defines the quantified performance of the product system. Since the end use of briquettes is the production of thermal energy for cooking [29], the functional unit is defined based on the production of this form of energy. Thus, for reasons of convenience, the production of 1 MJ of thermal energy [28] by the combustion of briquettes is defined as the functional unit in the present LCA study. The study then assesses the environmental pollutants emitted by briquettes, during the processes ranging from the collection of residues to the briquette combustion phase in a dedicated appliance, to produce 1 MJ of thermal energy.

4. Methodology

4.1. Life Cycle Inventory

According to Jolliet *et al* [30], the inventory of elementary flows or inventory of extractions and emissions is the quantitative description of the flows of materials, energy and pollutants that cross the boundaries of the system. It therefore covers the quantities of polluting substances emitted as well as the resources extracted (ores, energy carriers, soil surfaces) during the life cycle of the product or service analysed [30]. Data collection for the briquette life cycle inventory was based on the examination and compilation of data from a wide range of sources, including publications, industrial and government statistics, data from a laboratory prototype, and survey responses from various operators in the sector.

Scientific publications are widely recognized as essential sources of reliable and relevant information. To guarantee the quality of the data, only studies published in academic journals, which have generally undergone a rigorous peer review process, have been selected. In addition, only publications complying with ISO standards 14040 and 14044, which are aligned with best practice in life cycle assessment, were selected. This approach made it possible to focus the study on the most recent work on life cycle assessment of fuel briquettes, thus providing a complete and up-to-date overview of this specific field. Statistics provided by industry and government bodies were also examined with rigor to ensure their accuracy and timeliness. Government data, from recognized institutions such as the National Statistics Agency and the Cotton and Cashew Council, focus mainly on the distribution of

players in the emerging sector of fuel briquette production from agricultural residues in Côte d'Ivoire. This sector, still in the development phase, is characterized by a notable concentration in agricultural areas. For example, experiments are underway in various cocoa-producing regions, with artisanal units using cocoa pod husk. In addition, artisanal units have been set up using rice husks. On the coast, small-scale units process waste from coconut cultivation. It is important to note that most of these producers do not keep detailed records of their technical processes. However, precise descriptions of the operations carried out, as well as quantitative data on inputs and yields obtained, are provided. The statistics available for industrial producers include detailed information on the location of units, the organization of production, inputs (such as electricity and raw material balances) and yields (notably production capacity). These data were used to produce an exhaustive inventory of elementary flows, providing an accurate and detailed overview of the sector. Regarding the laboratory model, the experimental conditions were carefully examined to ensure that they accurately reflected the actual briquette production conditions. The results were compared with those of other similar studies, as well as with quality data from industrial briquette producers, to verify their validity and reliability. Good reproducibility of the results was a key indicator of the validity of the data. Finally, the surveys were designed to be clear, precise and relevant. The questions were designed to obtain specific information while avoiding distortions. Responses were analyzed for consistency and credibility, with inconsistent or suspect data either examined in more detail or excluded.

When data was not available, data of acceptable quality from other LCA studies was considered. The material and energy flows (inputs and outputs) for each life cycle process, from the collection of the biomass raw material to the combustion of the briquettes, were identified. This first involved determining the quantities of biomass feedstock required to produce briquettes capable of producing 1MJ of thermal energy. The amount of biomass feedstock pulp is defined by Equation (1). **Table 2** gives the mass proportions of the various briquette constituents [10]. **Table 3** gives the approximate analysis (% by weight) and calorific value of briquettes [10]. The approximate analysis and determination of the calorific value of the briquette sample required the use of an oven, a muffle furnace, and a calorimetric bomb, respectively. The protocols used are available in the study [31].

Table 2. Mass proportions (%) of the components of briquettes [10].

Water	Cashew nutshell biochar	Cassava starch
35	55	10

Table 3. Approximate analysis (% by weight) and calorific value of cashew shell briquettes.

Humidity (%)	Volatile matter (%)	Fixed carbon (%)	Ash (%)	LCV (MJ/kg)
8	47	35	10	25.7

$$M_p = \frac{UF}{PCI * (1 - W)} \quad (1)$$

With,

UF: Functional unit (1 MJ);

LCV: Lower calorific value of the briquette (MJ/kg);

W : Moisture content of briquette (%);

M_p : Mass of paste (kg).

The production of briquettes capable of supplying 1 MJ of thermal energy requires the use of 158.16 g of dried cashew nutshells and 4.23 g of cassava starch. According to the literature, the mass of biochar represents on average 14.70% of the cashew nutshells mass. In fact, the mass proportions of biochar and gases from cashew nutshell pyrolysis are 21% and 79% respectively [32]. Cashew nutshells represent approximately 65% to 70% of the cashew nut mass [33] [34].

The various residues, *i.e.* cashew nutshells and starch, were collected from cashew nut processing units and small-scale attiéké production units. Most of these units are in agricultural production areas. The residues collected are transported to the briquette production unit. The briquettes produced are distributed to the different district capitals in the country. The study considers average distances of 50 km for the residue collection process and 600 km for the briquette transport and distribution processes. **Table 4** shows the distances between the Yamoussoukro district and the other district capitals of Côte d'Ivoire. These distances were determined using Google Maps. The collection process uses a light vehicle capable of carrying a load of at least 2 tonnes, while the transport and distribution processes use a road truck with a total load of 40 tonnes. Diesel is the energy source for the various delivery vehicles. The quantity of diesel consumed by each vehicle is the essential inventory data for the collection, transport, and distribution processes. To calculate this fuel quantity, average consumption data can be used if no other data is available [35]. It can also be directly linked to the mass transported and the distance travelled.

Table 4. Distances between Yamoussoukro district and district capitals

Districts	District capitals	Transport distance (km)
Yamoussoukro	Yamoussoukro	-
Abidjan	Abidjan	234
Bas Sassandra	San-Pedro	438
Comoé	Abengourou	245
Denguélé	Odienné	560
Gôh-Djiboua	Gagnoa	137
Lacs	Dimbokro	82
Lagunes	Dabou	221
Mountains	Man	329
Sassandra-Marahoué	Daloa	139
Savannes	Korhogo	331
Vallée du Bandama	Bouaké	110
Woroba	Séguéla	267
Zanzan	Bondoukou	439

During the briquette production process, the biochar grinding, mixing and leg compacting stages require the use of electrical energy. In Côte d'Ivoire, electricity is produced mainly from fossil fuels (natural gas and oil) and hydroelectricity. **Table 5** shows the contribution of each energy source to electricity production in Côte d'Ivoire [36]. The inventory data for the crushing, mixing and compacting stages depend on the consumption of electrical energy produced from natural gas, oil, and hydroelectricity. The electrical energy consumed by each piece of motorised equipment in the briquetting process is defined by Equation (2).

Table 5. Breakdown of electricity generation in Côte d'Ivoire by energy source [36].

Energy sources	Contribution (%)
Natural gas	74.38
Oil	2.62
Hydropower	23

$$E_c = \frac{P_e * M}{\eta_u} \quad (2)$$

With,

E_c : Electrical energy consumed (kWh);

P_e : Electrical power of equipment (kW);

M : Mass of product processed (kg);

η_u : Equipment processing capacity (kg/h).

Given the lack of lifecycle inventory data specific to the transport and electricity sector in Côte d'Ivoire, the inventory data was taken from the ELCD 3.2 database used for this study. Since its first publication in 2006, the ELCD (Ecoinvent Life Cycle Database) has included life cycle inventory (LCI) data from European Union trade associations and other sources for key materials, energy carriers, transport, and waste management. 190 datasets compliant with the input level of the ILCD data network can currently be found in ELCD 3.2 [37]. The ELCD database is widely used for life cycle assessment (LCA) of products.

For the nutshell carbonization stage, the pollutant emission factors (CO, NO_x and SO₂) from the combustion of synthesis gas are taken from reference [38]. **Table 6** shows the emission factors for the pollutants produced during the combustion of cashew nutshells pyrolysis gases.

Table 6. Emission factor for pollutants from the combustion of cashew nutshells pyrolysis gases [38].

Particles	CO	NO _x	SO ₂
Emission factors (g/MJ)	4.32×10^{-3}	0.22×10^{-3}	0.712×10^{-3}

Table 7 gives the elemental composition (% on a dry basis) of the cashew nutshells. Elemental analysis of the cashew nutshells sample required the use of an elemental analyser, and the analysis protocol is also available in the study [31].

Table 7. Elemental composition (% on dry basis) of cashew nutshells.

C	H	O	N	S	Cl	Reference
56.5	7.2	34.2	0.5	0.1		[40]
52.91	6.84	29.88	0.25	0.00		[41]
58.1	7.3	34.4	0.62	0.01	<0.1	[42]
63.20	6.74	21.9	0.63	-	-	[43]
61.85	5.96	28.52	0.94	0.11	0.52	This study

As well as being used as cooking fuel, briquettes can also be used in industrial furnaces. Combustion equipment using cashew nutshell briquettes includes biomass boilers, gasification equipment and charcoal kilns. Given the limited sources of data on pollutant emissions from the combustion of briquettes in such combustion equipment, the data on emissions from the combustion of dry wood in boilers taken from the report [39]. The Model does not consider the efficiency of the combustion equipment. **Table 8** shows the emission factor for pollutants from the combustion of cashew nutshell briquettes.

Table 8. Emission factor for pollutants from the combustion of cashew nutshell briquettes [39].

Particles	NO _x	CO	SO ₂	VOC	PM
Emission factors (g/MJ)	0.211	0.258	0.010	0.017	0.172

4.2. Environmental Impact Assessment

Environmental impact is defined as a change in the environment, whether beneficial or detrimental, due to a human activity. Each resource extraction or substance emission, *i.e.* each elementary flow resulting from the inventory, can influence the environment through different categories of impact. Impact assessment therefore involves transforming an inventory of substance flows emitted and resources consumed into a series of clearly identifiable impacts. Life cycle impact assessment methods are used in life cycle analysis to convert life cycle inventory data into a set of environmental impacts using impact factors. There is no standard method for evaluating environmental impact categories. However, to facilitate the use of the LCA method, various assessment methods have been developed over the years [39]. The CML method [28] was chosen to quantify the environmental impact categories in this study. This method contains more than 1700 different flows and is made up of CML-Baseline and CML-non-Baseline [44]. OpenLCA software (version 2.1) was used to calculate the environmental impacts of the life cycle (LCA) and the sustainability analyses. It is an open-source software widely used to carry out life cycle assessments (LCA) of products and processes.

The impact categories taken into account because of their relevance to the systems studied are: acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, photochemical ozone creation (smog) and terrestrial ecotoxicity potential. Several definitions of these indicators are available in the literature. This study briefly summarises each of these definitions. Acidification is

an increase in the acidity of a soil or watercourse because of human activity, through acid rain for example. Sulphur and nitrogen oxides are the main culprits. Eutrophication is mainly caused by excessive levels of phosphorus (P) and nitrogen (N) nutrients in the environment. The release of organic matter can also contribute to the eutrophication of aquatic environments. This can result in the proliferation of algae. Climate change deals with the contribution of man-made emissions to radiative forcing in the atmosphere (greenhouse effect). Greenhouse gases are gases that can absorb infrared radiation from the Earth. The increase in radiative forcing leads to a warming of the surface temperature of the Earth, which can have an impact on ecosystems, human health and material goods. Human toxicity deals with the impact of toxic substances emitted into the environment on human health. The characterisation of toxic substances is based on the concepts of persistence in the environment, exposure (by inhalation or ingestion) and effect on human health (carcinogenic and non-carcinogenic). Ecotoxicity covers the impact of toxic substances on aquatic ecosystems (freshwater aquatic ecotoxicity) and on fauna, flora, and ecological processes in terrestrial ecosystems (terrestrial). Photochemical ozone is an atmospheric pollutant formed by complex chemical reactions involving volatile organic compounds (VOC), nitrogen oxides (NO_x) and sunlight. It has harmful effects on human health and the environment, and can cause respiratory problems, cardiovascular disease, damage to crops and vegetation, and effects on aquatic ecosystems [45].

5. Results

Life Cycle Assessment (LCA) was used, in accordance with ISO 14040/14044, as a tool to assess the environmental impacts at all stages of the life cycle of briquettes produced from cashew nutshells, waste from cashew nut processing units. The energy conversion systems in this LCA were modelled based on data from various sources (measurements taken on laboratory prototypes, data from the literature, results of on-site surveys, etc.). These data were used to estimate inventory data that could be adapted to real conditions for larger-scale processes in the study area.

The assessment reveals that, over their life cycle, cashew nutshell briquettes emit a range of pollutants that have led to the creation of 7 environmental impact categories. The results of the assessment for the 7 impact categories are compiled in **Table 9**.

Table 9. Results of environmental impact assessment per MJ.

Impact category	Result	Unit
Acidification	1.55E-04	kg SO ₂ eq
Eutrophication	3.52E-05	kg PO ₄ eq
Fresh water aquatic ecotox.	7.36E-06	kg 1,4-DB eq
Global warming (GWP100a)	1.05E-02	kg CO ₂ eq
Human toxicity	6.55E-04	kg 1,4-DB eq
Photochemical oxidation	1.01E-05	kg C ₂ H ₄ eq
Terrestrial ecotoxicity	1.61E-06	kg 1,4-DB eq

6. Discussion

The pollutants emitted during cashew nutshell briquettes combustion contribute more than 60% to the creation of 4 environmental impacts: eutrophication (78%), acidification (76%), photochemical ozone creation (73%) and human toxicity (60%). The cashew nutshell briquette production process contributes more than 30% to the creation of 3 categories of impacts: potential terrestrial ecotoxicity (81%), freshwater aquatic ecotoxicity (51%) and global warming (32%). The process of transporting biomass raw materials contributes to the creation of the 7 impact categories with rates ranging from 13% to 46%. The highest contributions from this process are attributed to global warming (46%), freshwater aquatic ecotoxicity (33%) and human toxicity (21%). Contributions to the creation of the 4 other environmental impacts remain below 14%. Finally, the contribution of the biomass raw material collection and briquette distribution processes to the creation of the 7 impact categories remains below 11%. **Figure 8** shows the contribution of the elementary processes to the various environmental impact categories.

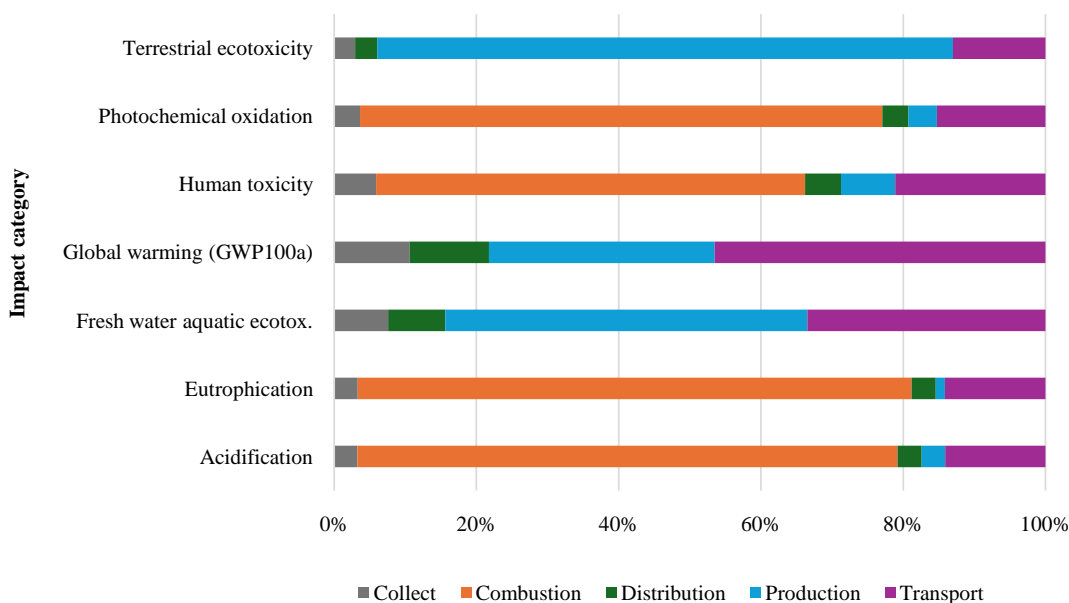


Figure 8. Contribution of elementary processes to environmental impact.

Table 10 compares the life cycle environmental impacts of cashew nutshell briquettes from this study with those of corn stover briquettes, firewood, and charcoal from previous LCA studies. Only those studies that reported on the 7 impact categories of acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, photochemical ozone creation (smog) and terrestrial ecotoxicity potential were considered, as they are directly comparable to the results of this study. This comparison shows that all the impact categories for cashew nutshell briquettes remain well below those for maize stalk briquettes. They also remain lower than the impact categories of fuelwood and charcoal, except for two impact categories: acidification and eutrophication.

Table 10. Comparison of the life cycle environmental impacts of cashew nutshell briquettes with those of maize stalk briquettes, firewood, and charcoal.

References	[46]	[47]	[28]	This study	
Impact category	Cornstalk briquettes	Firewood	Charcoal	Cashew nutshell briquettes	Unit
Acidification	1.10E-01	9.38E-05	1.69E-05	1.55E-04	kg SO ₂ eq
Eutrophication	1.60E-03	1.35E-05	3.02E-05	3.52E-05	kg PO ₄ eq
Fresh water aquatic ecotox.	1.10E-01	1.49E-04	1.00E-03	7.36E-06	kg 1,4-DB eq
Global warming (GWP100a)	1.10E+01	1.03E+00	1.45E+00	1.05E-02	kg CO ₂ eq
Human toxicity	3.90E-01	2.49E-02	2.00E-03	6.55E-04	kg 1,4-DB eq
Photochemical oxidation	7.50E-02	3.27E-03	1.00E-02	1.01E-05	kg C ₂ H ₄ eq
Terrestrial ecotoxicity	7.00E-03	1.69E-05	1.29E-04	1.61E-06	kg 1,4-DB eq

There are opportunities to reduce the environmental impacts of the cashew nutshell briquettes life cycle. These improvements can be focused on the 3 basic processes: transport of the biomass raw materials, production and combustion of the briquettes. For the transport of biomass raw materials, improvement actions focus on optimizing routes and means of transport, as well as on the use of environmentally friendly vehicles. This includes efficient logistics management to reduce distances travelled and maximize vehicle payload, as well as the adoption of more environmentally friendly means of transport such as electric, hybrid or biofuel trucks. As regards the briquette production process, improvements are focusing on energy efficiency and the use of renewable energy sources. Implementing more energy-efficient technologies, such as high-efficiency briquette presses, can reduce energy consumption. It is also possible to replace non-renewable energy sources with renewable energies such as solar, wind or biomass. For briquette combustion, improvement actions include the use of advanced combustion technologies, such as high-efficiency boilers or stoves equipped with particle filters. Implementing emission monitoring systems ensures clean combustion. In addition, user awareness and training in optimal combustion techniques and equipment maintenance are crucial to maximizing efficiency and reducing environmental impact.

7. Conclusions

This study used the standard life cycle assessment method to evaluate the environmental impacts of briquettes made from cashew nutshells in Côte d'Ivoire. It was carried out in accordance with ISO 14040/14044 standards based on a life cycle inventory covering the processes from the collection of the biomass raw materials to the combustion of the briquettes to produce 1 MJ of thermal energy. The inventory data came from a wide range of sources, including publications, industry and government statistics, a laboratory prototype briquetting unit, survey responses from several operators in the sector, and other LCA studies. The study revealed that the life cycle of briquettes emits pollutants that give rise to 7

categories: acidification, eutrophication, freshwater aquatic ecotoxicity, global warming, human toxicity, photochemical oxidation and terrestrial ecotoxicity potential. Also, the 3 elementary processes: transport of biomass raw materials, production and combustion of briquettes emit pollutants that contribute most to the creation of environmental impact categories. However, except for acidification and eutrophication, cashew nutshell briquettes are more environmentally friendly than charcoal and firewood for 5 impact categories: freshwater aquatic ecotoxicity, global warming, human toxicity, photochemical oxidation and terrestrial ecotoxicity potential.

To improve the environmental performance of cashew nutshell briquettes, it is essential to optimize production processes by adopting cleaner technologies and developing more efficient and less polluting briquetting methods. Combustion technologies also need to be improved to reduce pollutant emissions and increase energy efficiency. Promoting the environmental benefits of briquettes to producers and consumers is crucial to encouraging their uptake. Regular monitoring of environmental impacts is necessary to adjust practices and minimize negative effects. These measures aim to maximize the ecological benefits while reducing the overall environmental impact of briquettes.

Conflicts of Interest

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

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