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Environmental impact assessment of a cocoa shell pellet (CSP) combustion system: Effects of integrating an emission filtration system

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Abstract

Densified biomass in the form of pellets, made from cocoa shell pellet (CSP), represents a renewable thermal energy source. Experimental combustion tests and emission readings were then conducted over 15 minutes, both with and without the filter, resulting in significant average improvements; with CO levels decreasing from 1710 to 475 ppm, CO_2 levels dropping from 2.13% to 0.2%, H_2S levels reducing from 39.36 to 5.7 ppm, and N_2 decreasing from 76.64% to 74.71%. O_2 levels increased from 15.06% to 17.02%. This assessment showed a modification of environmental impact assessment with the installation of the filtration system, reducing the negative impacts from 18 to 13. It changed from a medium-impact project (without filter) to a low-impact project (with filter), demonstrating the capacity of the filter prototype to improve the environmental conditions of the surroundings. In addition, the potential energy was determined according to ASTM D4809-13, obtaining a higher heating value of up to 15.5 MJ/kg, thereby ensuring the efficient implementation of a combustion chamber with thermal storage that transfers heat to a forced-air drying system for food, replacing the use of fossil fuels in this methodology. The use of these compact drying systems involves the generation of emissions of O_2, CO, CO_2, N_2, and H_2S. Therefore, monitoring of these emissions is conducted using a gas analyser.

Keywords: Biomass, Combustion, Environmental management, Heat storage, Gas fuels

1. Introduction

The combustion of biomass pellets is considered one of the most viable renewable alternatives for the generation of heat, electricity, and steam [1], [2], [3]. This energy pathway is distinguished by its high calorific value, abundant availability of agricultural residues, and relatively low moisture content, all of which contribute to improved combustion efficiency. Consequently, it enables a cleaner and more sustainable energy production process [4], [5], [6].

Among the potential sources of biomass, cocoa pod shells (CPS) emerge as a notable by-product generated after the extraction of cocoa beans, representing approximately 70% to 80% of the fruit's dry weight. It is estimated that for every ton of cocoa beans produced, approximately 10 tons of CPS are generated [7], [8].

Typically, this residue is discarded at cultivation sites without prior treatment, often intended for use as fertilizer. However, such practices can lead to adverse environmental effects, as the accumulation of CPS provides a favorable substrate for the development of fungal diseases such as black pod rot [9], [10], [11]. Importantly, CPS is rich in cellulose, hemicellulose, lignin, pectin, oils, and waxes. As a result, it is considered a lignocellulosic material with significant potential for biofuel production [12], [13], exhibiting an estimated energy content of 4,063 kcal/kg [14].

Despite its potential, it is essential to acknowledge that biomass combustion can proceed either completely or incompletely, depending on the fuel-to-oxidizer ratio [15]. In cases of complete combustion, carbon is fully oxidized to carbon dioxide (CO_2), and hydrogen to water (H_2O) [16]. Conversely, incomplete combustion can lead to the formation of undesirable emissions, including organic carbon (~40–50%), black carbon (5–10%), fine particulate matter (with diameters ≤ 2.5 μm), and various other pollutant gases [17], [18], [19].

Among the pollutants generated, carbon monoxide (CO) must be highlighted, as it is a highly toxic gas whose inhalation can cause headaches, fatigue, dizziness, and, at elevated concentrations, tissue hypoxia with potentially serious cardiac consequences [20], [21], [22]. Furthermore, although CO_2 emissions from biomass combustion are generally considered carbon-neutral [23], [24], their accumulation in confined spaces may pose a health hazard [25], [26]. In addition, the presence of sulfur in the fuel can lead to the formation of hydrogen sulfide (H_2S), which, upon oxidation, results in the production of sulfur oxides (SO_x) compounds known for their high environmental pollutant potential [27], [28], [29].

These emissions can not only cause respiratory illnesses and adverse health effects, but also lead to significant environmental impacts such as air quality degradation, disruptions in the Earth's radiative balance, damage to ecosystems, and a substantial contribution to climate change [30], [31], [32]. Consequently, to control these emissions, various studies have proposed the implementation of secondary reduction technologies, among which filtration systems are particularly prominent [33].

In this context, fabric filters have been identified as one of the most effective solutions for medium-scale installations (50 MWth), as they enable efficient retention of solid particles with varying granulometries [34], [35], [36]. On the other hand, Environmental Impact Assessment (EIA) allows for the systematic review, identification, and analysis of potential environmental impacts of ongoing projects. It serves as a valuable tool for periodically evaluating and monitoring the performance and effectiveness of a given system [37]. Moreover, Environmental Impact Assessment (EIA) plays a critical role in supporting informed decision-making, thereby promoting sustainability and compliance with precautionary principles [38], [39].

2. Research method

The methodology adopted in this study is structured in sequential stages as illustrated in Figure 1. Initially, a comprehensive literature review is conducted to identify the main emissions generated during biomass combustion, with particular emphasis on pollutants relevant to the environment and human health. In parallel, the selection of appropriate filtration methods and materials is addressed, with the aim of determining the most effective solutions for particle mitigation. Subsequently, the knowledge obtained in the review serves as the basis for the design, simulation, and construction of a filter prototype designed for the treatment of biomass gases.

Finally, an environmental impact assessment is performed to evaluate the prototype's performance within the gas purification system, with the overall objective of supporting responsible and sustainable technological development.

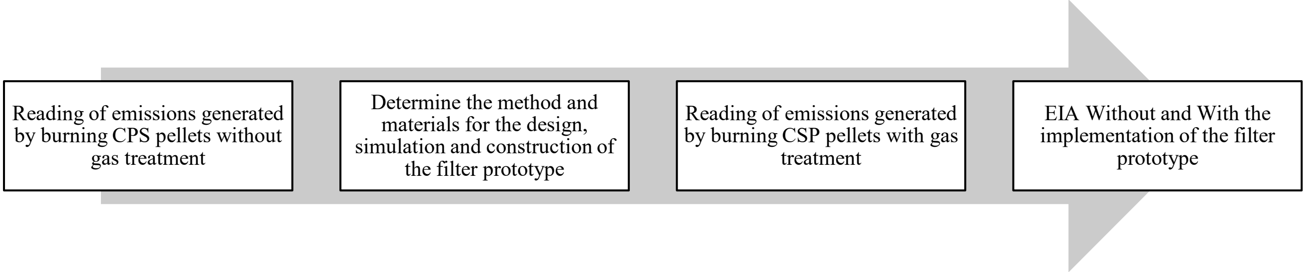

Figure 1. Schematic representation of the methodology

2.1. Technical and scientific review

Regarding the technical and scientific review, this is carried out through a bibliometric review. First, keywords are selected, and a search equation is formulated in scientific databases. Then, the documents are downloaded and processed using VosViewer software to construct bibliometric networks (Figure 2) focused on combustion, biomass, filters, and emissions.

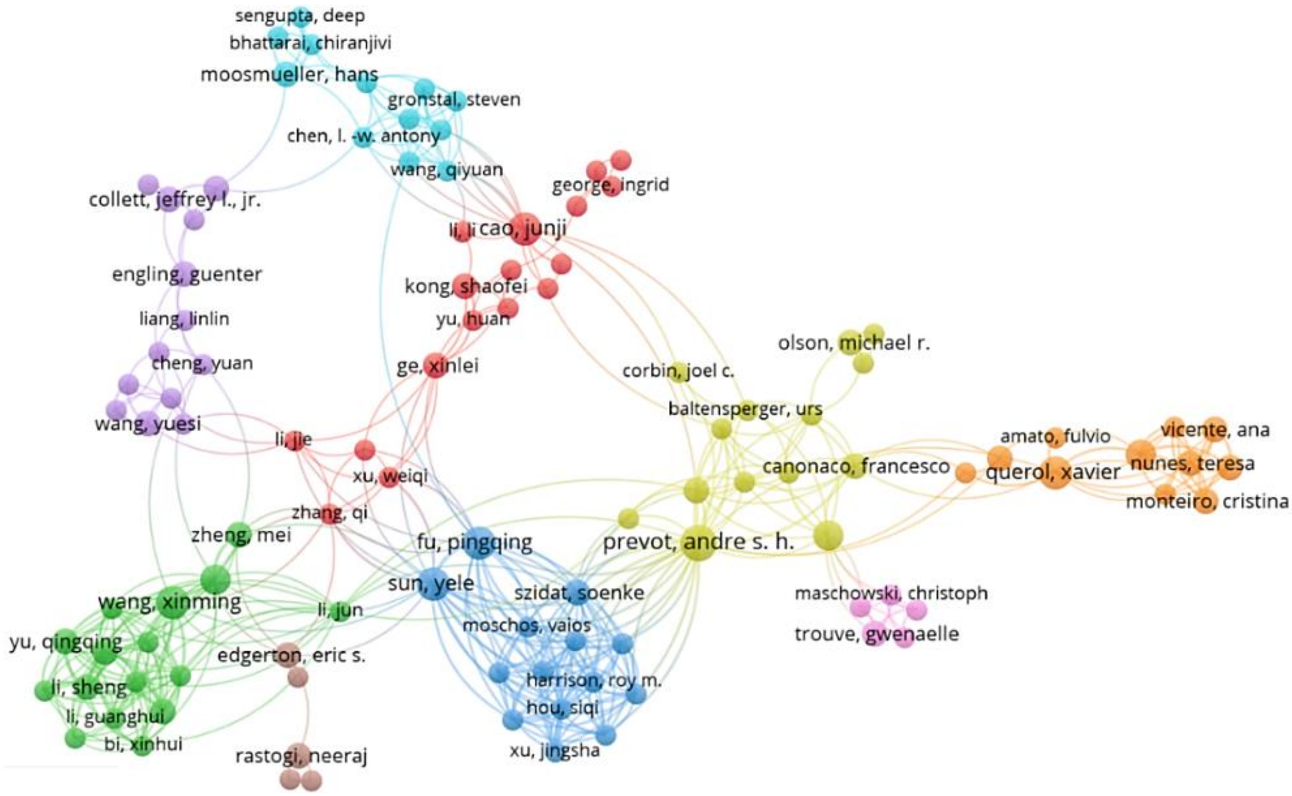

Figure 2. Main authors of the search equation: Biomass AND combustion AND filters AND particles

2.2. Environmental impact assessment

The environmental impact assessment was conducted for the operational stage of the pellet burner equipment during its biomass combustion phase. Within this context, activities susceptible to producing impacts (ASPI) were established: pellet fuel, combustion air from the fan, ignition source, and air supply for drying, along with their respective descriptions and environmental aspects. Direct and indirect impacts generated by the equipment were identified before and after the implementation of the filtration system and evaluated using the EPM-Arboleda method [40] through Equation 1.

$$Ca = P[7.0 \text{ x } Ev \text{ x } M + 3.0 \text{ x } D] \quad (1)$$

Where *Ca* corresponds to the impact rating, *P* is the presence, *Ev* represents the evolution, *M* is related to the magnitude, and *D* is the duration, all of which are evaluated considering Table 1.

Table 1. Evaluation of the criteria used by the method [40]

Criterion	Range	Value
Class (*C*)	Positive	+
	Negative	-
Presence (*P*)	Certain	1.0
	Highly Likely	0.7 < 0.99
	Likely	0.4 < 0.69
	Unlikely	0.01 < 0.39
Duration (*D*)	Very Long: > 10 years	1.0
	Long: > 7 years	0.7 < 0.99
	Medium: > 4 years	0.4 < 0.69
	Short: > 1 year	0.2 < 0.39
	Very Short: < 1 year	0.01 < 0.19
Evolution (*E*)	Very Rapid: < 1 month	1.0
	Rapid: < 12 months	0.7 < 0.99
	Medium: < 18 months	0.4 < 0.69
	Slow: < 24 months	0.2 < 0.39
	Very Slow: > 24 months	0.01 < 0.19
Magnitude (*M*)	Very High: > 80%	1.0
	High: 60% - 80%	0.7 < 0.99
	Medium: 40% - 60%	0.4 < 0.69
	Low: 20% - 40%	0.2 < 0.39
	Very Low: < 20%	0.01 < 0.19

Once the environmental impact assessment was established with its corresponding ratings, the significance of each impact was determined, as presented in Table 2.

Table 2. Rating and significance of environmental impacts assessment, EPM Methodology [40]

Environmental rating (Er)	Environmental impact assessment significance	Abbreviation
≤ 2.5	Minor or Irrelevant	*I*
> 2.5 y ≤ 5.0	Moderate	*M*
> 5.0 y ≤ 7.5	Significant	*S*
> 7.5	Very Significant	*Vs*

On the other hand, the environmental categorization of the project (CA) was carried out using Equation 2 in order to assess the overall impact caused by the project.

$$Ca = \frac{(NMs\ X\ 5) + (Ns\ x\ 4) + (Nm\ x\ 2) + (Ni\ x\ 1)}{Nt} \quad (2)$$

Where *Ca* represents the environmental rating of the project, *NMs* corresponds to the number of very significant impacts, *Ns* is the number of significant impacts, *Nm* is related to the number of moderate impacts, *Ni* is the number of irrelevant impacts, and *Nt* corresponds to the total number of impacts evaluated. Thus, with the value of *Cs*, the environmental categorization of the project could be (Table 3).

Table 3. Environmental categorization of the project [40]

Values	Importance of environmental impact assessment
1.0 – 1.99	Low-impact project
2.0 – 3.49	Medium-impact project
3.5 – 5.0	High-impact project

2.3. Structural identification of the pellet burner equipment coupled to a forced-air convection food drying system

The experimental phase of the research consists of the integration of a pellet burner with thermal storage capacity, designed to operate within a forced-air convection drying system. Specifically, the system incorporates a heat exchange unit located within a combustion chamber, which transfers the generated thermal energy to a tank filled with thermal oil. This stored heat is subsequently conveyed to a coil through which forced air is continuously circulated. As a result, the heated air is directed into a rotating drum equipped with trays, where the food products intended for drying are placed.

The pellet burner features a Programmable Logic Controller (PLC) equipped with a Human-Machine Interface (HMI) screen, enabling the configuration and control of key thermal process variables. Notably, the system includes: (a) a screw feeder mechanism with ON/OFF control for regulated fuel supply to the combustion chamber; (b) an inline duct fan capable of delivering up to 250 cubic feet per minute (CFM) of ambient air; and (c) a heat exchanger coil, immersed in the thermal oil tank, through which the drying air flows and acquires heat during combustion.

In addition, the thermal oil employed in the system possesses a specific heat capacity (Cp) of 4186 J/kg·K and is capable of withstanding operating temperatures up to 320 °C, thus ensuring high thermal retention and transfer efficiency. Conversely, the exhaust gases generated during combustion are discharged through a chimney measuring 1.20 m in length and having a square cross-sectional area of 0.01 m^2. Furthermore, the pellet burner is equipped with an integrated system for the control, monitoring, and visualization of thermodynamic variables, as illustrated in Figure 3.

Figure 3. Pellet burning equipment coupled to a forced air convection drying system

Structurally, the drying unit comprises a vertical drum that integrates rotating trays fabricated from stainless-steel mesh. The food materials are arranged on the trays according to the optimal drying air temperature required for each product type, thereby allowing controlled and homogeneous dehydration conditions (Figure 4).

Figure 4. Vertical drying drum with rotating stainless steel mesh trays

2.4. Manufacture and determination of the calorific value of pellets made from CSP

The pellets used as fuel (Figure 5) are composed of completely dried cocoa pod shells (CPS) (64.3%), kaolin (7.14%), used cooking oil (4.46%), and water (24.1%). Each pellet has a diameter of 6 mm and a length ranging between 30 and 40 mm. Following the densification of the components, the pellets are subjected to drying under controlled environmental conditions to eliminate the water added during the manufacturing process. This step continues until a final moisture content of 6.3% is reached, in compliance with the European standard for wood pellet quality (ENplus) [41].

Figure 5. Production of CPS pellets

The final density of the fuel pellets was determined to be 0.528 g/cm³. The energy potential of the biomass fuel was quantified using the bomb calorimetry method, in accordance with ASTM D4809-13. For this purpose, representative samples were selected and weighed on a Kern PBF analytical balance, with sample masses ranging between 1 and 2 g. Subsequently, the samples were mounted and analysed using a C200 calorimeter unit, manufactured by P.A. Hilton Ltd.

The tests were carried out at a controlled ambient temperature of 24 °C, employing oxygen with a purity grade of 99.9999% to ensure an optimal combustion atmosphere. Under these conditions, the average higher heating value (HHV) was determined to be 15.5 MJ/kg. Nevertheless, for the purposes of experimental evaluation in the pellet burner system, only 80% of this calorific value was considered, yielding a lower heating value (LHV) of 12.4 MJ/kg. This adjustment aims to ensure greater accuracy and reliability in the assessment of the burner's thermal efficiency.

2.5. Operation of the integral system for food drying via forced air convection

Heat transfer and thermal storage are carried out under the following methodology:

1. A specified number of pellets (150 g) is placed in the combustion chamber.
2. Using a butane torch, the initial ignition of the fuel (pellets) is performed by simultaneously injecting and controlling the combustion air through an alternating fan, regulating flow rates of 80, 100, and 120 CFM based on the flame formed during the process.
3. After achieving a stable flame in the combustion chamber, the safety door is closed, and the pellet feeding mechanism is activated using the screw feeder, all controlled through ON/OFF programming, which allows for regulating the consumption and the ratio between fuel and oxidant.
4. The heat flow generated in the combustion chamber is transferred to a cubic tank filled with thermal oil, which initially is at an ambient temperature of approximately 20°C. Inside the tank, a coil made of stainless steel is immersed, through which forced air circulates and is heated at a constant flow, controlling an established temperature range.
5. Pellets are burned until the oil reaches a temperature of 150°C, ensuring that the forced air reaches a maximum of 70°C. This forced air is continuously injected into the drying drum, where the food to be dried is placed. In this case, drying food with forced air is carried out at temperatures ranging from 40°C to 70°C. Additionally, to achieve this regime, a time of up to 15 minutes is established, during which an average of 1.7 kg of pellets is consumed.
6. When the programmed temperature in the oil is reached, the pellet feeding is suspended. As a result, the oil stops receiving heat from combustion and begins a process of energy transfer to the air circulating through the coil, maintaining the forced air at an appropriate temperature for drying.
7. During this energy discharge process from the oil, a minimum drying forced air temperature of 40°C is established (at which point the oil temperature drops to approximately 58°C), all occurring over a period of approximately 150 minutes, completing a total initial cycle of 165 minutes (including the first 15 minutes of initial pellet combustion).
8. A specified number of pellets is again placed in the combustion chamber, and the flame is ignited for a second cycle. However, knowing that the oil is preheated (approximately 58°C), the pellet consumption decreases to 1.15 kg, and the combustion time is only 10 minutes, again reaching 150°C in the thermal oil and 70°C in the drying forced air. Finally, this second combustion cycle is completed in a time of 160 minutes, including the energy discharge in the tank.
9. In the experimental testing phase, three (3) discharge cycles are performed, resulting in the consumption of up to 4 kg of pellets over a total time of 480 minutes (8 continuous hours). It is important to clarify that during the three cycles, the total combustion duration was 35 minutes, considering the 15 minutes of the first cycle and 10 minutes for both the second and third cycles.

Based on the above and considering the operating principles of the equipment and its application in food dehydration, a comprehensive study is conducted on the gaseous emissions produced during pellet combustion in the absence of any gas treatment, as well as their environmental impacts. In this context, the design, simulation, and implementation of a filter prototype are carried out with the aim of reducing the emission of particulate matter and combustion gases through the chimney, accompanied by the corresponding environmental impact assessment.

For the experimental trials, both the temperature and the concentration of each gas emitted from the chimney are measured. As illustrated in the procedure begins with data acquisition under conditions without the filter, followed by a comparative analysis using the filter prototype installed at the chimney outlet. This comparison allows for the evaluation of the filter's effectiveness in mitigating atmospheric emissions and their associated environmental impacts.

Furthermore, in accordance with the operational dynamics of the system, measurements are recorded over a continuous 15-minute interval in each test condition, in order to obtain representative average values for each variable analysed. These results are subsequently compared with findings from specialized literature and international regulatory standards applicable to biomass combustion emissions. Figure 6, the procedure begins with data acquisition under conditions without the filter, followed by a comparative analysis using the filter prototype installed at the chimney outlet. This comparison allows for the evaluation of the filter's effectiveness in mitigating atmospheric emissions and their associated environmental impacts.

Furthermore, in accordance with the operational dynamics of the system, measurements are recorded over a continuous 15-minute interval in each test condition, in order to obtain representative average values for each variable analysed. These results are subsequently compared with findings from specialized literature and international regulatory standards applicable to biomass combustion emissions.

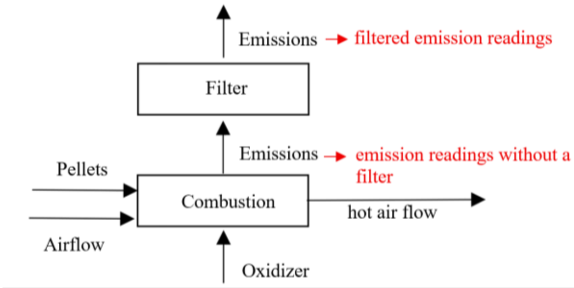

Figure 6. Diagram of the pellet combustion process and emission readings

2.6. Design and simulation of a filter prototype using SolidWorks software

After analysing the technical and scientific background, the filter design is developed. To do this, an initial computational model is built that simulates the behaviour of exhaust gases, assuming they behave similarly to air. Hot air is assumed to enter through the bottom of the filter due to its lower density, which promotes an upward flow of the gas stream. The filtration system consists of two stages: the first filter (a) is made of polyester fiber, designed to retain larger particles, with a pore diameter of 1 µm and a thickness of 20 mm. The second filter (b) is composed of activated carbon, capable of adsorbing finer particles, with a pore diameter of 0.3 µm and a thickness of 5 mm. As the gas passes through both filtration stages, particles and gaseous pollutants are progressively intercepted, allowing the cleaned gases to be subsequently released into the atmosphere (Figure 7).

To evaluate the behaviour of pollutant emissions within the filtration system, the necessary inlet parameters were defined in the SolidWorks Simulation environment. These included a gas inlet velocity (approximated with standard air) of 1 m/s, a mass flow rate of 0.0094 kg/s, and an outlet pressure of 1 atm. Simulation results revealed a velocity reduction from inlet to outlet, indicating the development of turbulence within the filtration chamber (Figure 8a).

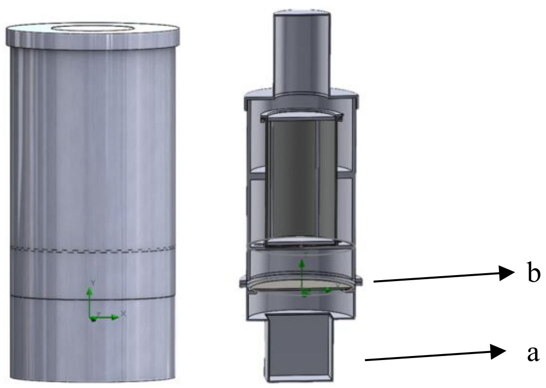

Figure 7. External and internal design of the filter

To simulate the behavior of fly ash, particles with an average diameter of 75 µm were introduced into the simulation model. These particles, representative of typical combustion residues, were used to assess the retention efficiency of the filtering system. As shown in Figure 8b, the polyester fiber filter effectively captures these particles, validating its function as the primary stage for coarse particulate matter separation.

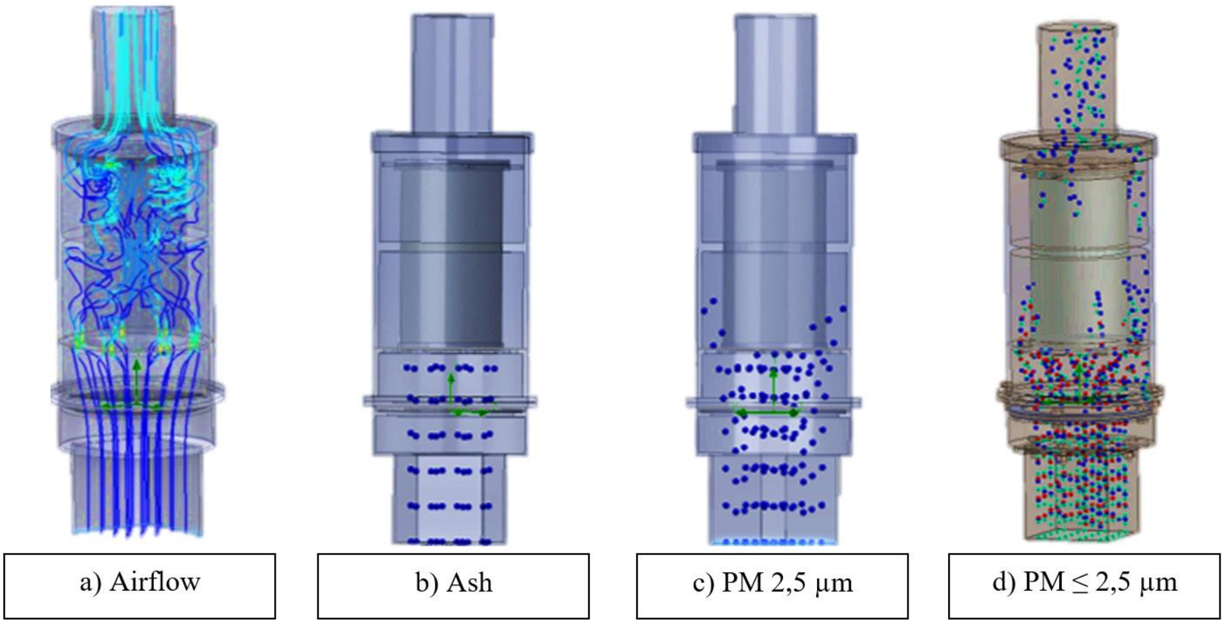

Figure 8. Input simulation of a) Airflow, b) Ash, c) PM 2,5, d) PM (1,0 µm, 2,5 µm, and 10 µm)

In the PM2.5 particulate matter simulation (Figure 8c), it is observed that particles with a diameter of 2.5 µm partially penetrate the polyester fiber filter; however, upon reaching the activated carbon filter, a significant proportion of these particles are retained. In parallel, an analysis was performed with particles of different diameters (1.0 µm, 2.5 µm, and 10 µm), demonstrating that the 2.5 µm particles (highlighted in red) were effectively captured by the dual-stage filtration system. In contrast, particles with diameters smaller than 1.0 µm (represented in blue and green) were able to pass through the filter medium and escape into the atmosphere, as illustrated in Figure 8d.

After completing the design and simulation stages, the filter prototype is built using 14-gauge A36 structural steel. The manufactured unit has a total length of 25.4 cm and a diameter of 15 cm, and is installed at the top end of the pellet burner system chimney Figure 9.

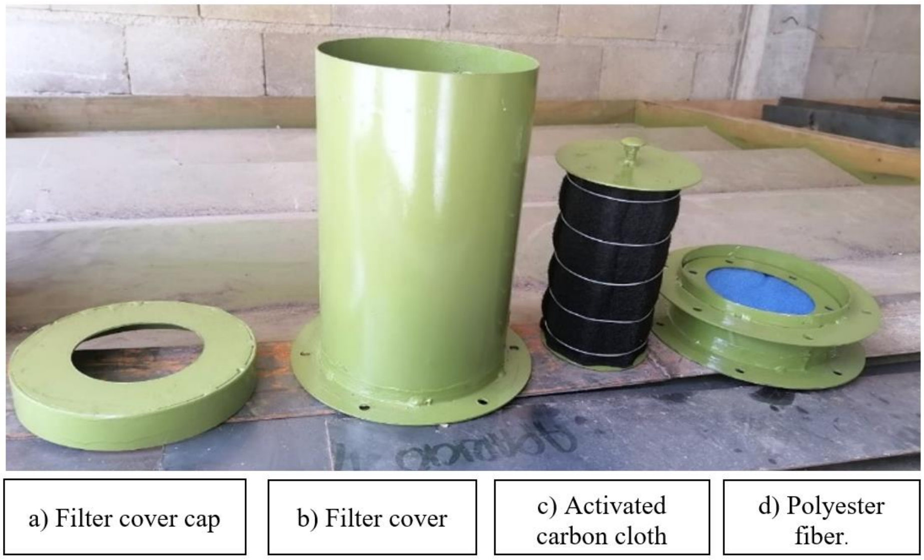

Figure 9. Prototype parts and exploded view of the filtration system

3. Results and discussion

The results obtained from the literature review reveal that cocoa pod shells (CPS) contain 43.87% carbon, 37.20% oxygen, 5.84% hydrogen, 1.23% nitrogen, and 0.17% sulfur, in addition to a volatile matter content of 58.46% and a fixed carbon fraction of 16.8% [42], [43]. These compositional characteristics suggest a high potential for the formation of atmospheric pollutants, particularly nitrogen oxides (NO_x) and sulfur dioxide (SO_2), as well as elevated emissions of particulate matter during combustion processes [44], [45]. Moreover, parameters intrinsic to the raw material, such as high initial moisture content and the densification stage, exert a significant influence on the calorific value of CSP, thereby affecting its performance as a biofuel [46], [47], [48].

On the other hand, the operational performance of the combustion system, combined with adequate control of process variables (oxygen concentration, air velocity, temperature, and flow rate), enhances thermal efficiency and contributes to a reduction in the concentration of pollutants, while simultaneously preventing the formation of secondary gaseous compounds [49]. For the development of the filtration prototype, materials with high retention capacity were selected. Activated carbon fabric was chosen due to its rapid adsorption kinetics, attributed to its fibrous morphology and high porosity, which facilitate efficient gas capture [50]. In parallel, polyester fiber was included based on its proven capability to retain particulate matter, in addition to its resistance to high temperatures and humid environments [51], [52].

Figure 10 presents the general framework for the environmental impact assessment, highlighting the activities susceptible to generating impacts (ASPI) and their corresponding environmental aspects, both under conditions with and without the filter prototype installed. In both scenarios, the identification of environmental impacts is carried out, classifying them as direct or indirect depending on the magnitude and scope of their influence on environmental components.

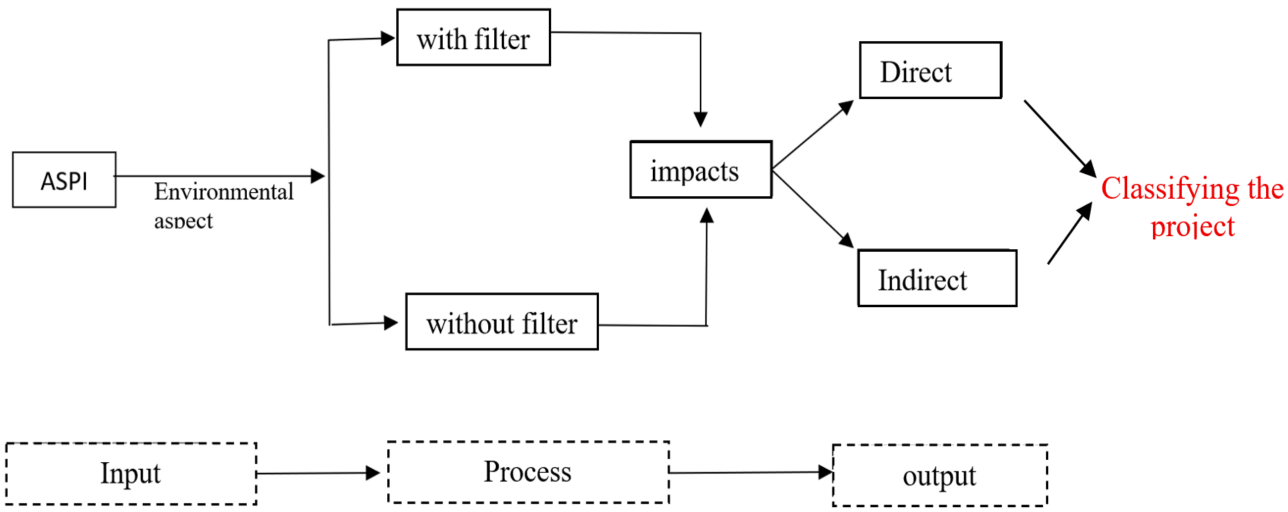

Figure 10. General scheme of inputs, processes, and outputs for environmental impact evaluation

3.1. Environmental impact assessment - EPM Arboleda method

During the project's operational phase, four activities susceptible to generating impacts (ASPIs) were identified: the use of fuel pellets, the operation of the oxidizer fan, the ignition source, and the air supply system for drying. From these ASPIs, a total of nine environmental aspects were derived, resulting in the identification of nine direct and twelve indirect impacts at the different stages of the system's operation, as detailed in Table 4.

Subsequently, once the direct and indirect environmental impacts were established and classified according to the defined evaluation criteria (Table 5), their significance was determined using the EPM method (Environmental Performance Matrix) adopted for the project. This methodology facilitates a structured assessment of the potential environmental consequences associated with each operational activity.

Table 4. Environmental aspects generated in the project without filter installation for the biomass combustion process in the Operation Stage and Biomass Combustion Phase of the project

ASPI	Without filter				With filter			
	Description of ASPI	**Environmental Aspects**	**Direct impacts**	**Indirect impacts**	**Description of ASPI**	**Environmental Aspects**	**Direct impacts**	**Indirect impacts**
Pellet fuel	In combustion, pellets made from cocoa pod shells are used as an energy source, which, when burned, generate waste such as wood shavings, ash, particulate matter, odors, and gases.	• Generation of pellet shavings. • Generation of ash. • Generation of particulate matter. • Generation of odors. • Consumption of pellets. • Emission of gases.	a. Increase in pellet shavings waste. b. Increase in ash waste. c. Atmospheric pollution from particulate matter. d. Increase in offensive odors. e. Increase in pellet consumption. f. Atmospheric pollution from gases.	a1. Increase in organic waste. b1. Equipment obstruction. b2. Impact on plant structures. b3. Increase in ash in soil and water sources. c1. Increase in respiratory diseases. d1. Community nuisance. e1. Use of biomass as raw material. f1. Increase in greenhouse gases. f2. Deterioration of air quality. f3. Increase in respiratory diseases.	In combustion, pellets made from CSP are used as an energy source. When installing the filter and increasing the oxidizer, more fuel is required, which necessitates readjusting the amount of pellet consumption.	• Generation of pellet shavings waste. • Generation of ash. • Generation of particulate matter. • Generation of odors. • Consumption of pellets. • Emission of gases.	a. Increase in pellet shavings waste. b. Increase in ash waste. c. Decrease in atmospheric pollution from particulate matter. d. Increase in offensive odors. e. Increase in pellet. consumption f. Decrease in atmospheric pollution from gases.	a1. Increase in organic waste. b1. Equipment obstruction b2. Impact on plant. structures b3. Reduction of ash in soil and water sources. c1. Reduction of respiratory diseases. d1. Community nuisance. e1. Use of biomass as a raw material. f1. Decrease in greenhouse gases. f2. Improvement of air quality. f3. Reduction of respiratory diseases.

ASPI	Without filter				With filter			
	Description of ASPI	**Environmental Aspects**	**Direct impacts**	**Indirect impacts**	**Description of ASPI**	**Environmental Aspects**	**Direct impacts**	**Indirect impacts**
Oxidizer fan	For combustion, the supply of an oxidizing agent (oxygen) is essential, in this case provided by a centrifugal fan with a frequency inverter. The generated gases have an approximate temperature of 30 to 50°C.	• Energy consumption. • Generation of particulate matter. • Emission of gases. • Generation of noise.	a. Increased energy consumption. b. Atmospheric pollution from particulate matter. c. Atmospheric pollution from gases. d. Noise pollution.	a1. Reduction of resources. b1. Increase in respiratory diseases. c1. Increase in greenhouse gases. c2. Deterioration of air quality. d1. Community nuisance.	For combustion, the supply of an oxidizing agent (oxygen) is necessary, in this case provided by a centrifugal fan with a frequency inverter. The generated gases have an approximate temperature of 30 to 50°C. When the filter is installed, the emissions encounter resistance, requiring greater energy consumption to allow the gases to pass through the filtering medium.	• Energy consumption. • Generation of particulate matter. • Emission of gases. • Generation of noise.	a. Increase in energy consumption. b. Decrease in atmospheric pollution from particulate matter. c. Reduction of atmospheric pollution from gases. d. Noise pollution.	a1. Reduction of resources. b1. Reduction of respiratory diseases. c1. Decrease in greenhouse gases. c2. Improvement of air quality. d1. Community nuisance.
Ignition source	To generate the initial flame, a flammable butane fuel cartridge with a gas odor is required.	• Generation of odors. • Emission of heat. • Emission of gases.	a. Increase in offensive odors. b. Increase in air temperature. c. Atmospheric pollution from gases,	a1. Community disturbances. b1. Climate modification. c1. Increase in greenhouse gases. c2. Deterioration of air quality.	To generate the initial flame, a flammable butane fuel cartridge with a gas odor is required. When the filter is installed, the ignition source generates gases within the burner, which are directed by the fan (oxidizer) to the chimney and subsequently to the filter.	• Generation of odors. • Emission of heat. • Emission of gases.	a. Increase in offensive odors. b. Increase in air temperature. c. Decrease in atmospheric pollution from gases.	a1. Community nuisance. b1. Climate modification. c1. Decrease in greenhouse gases. c2. Improvement of air quality.

ASPI	Without filter				With filter			
	Description of ASPI	**Environmental Aspects**	**Direct impacts**	**Indirect impacts**	**Description of ASPI**	**Environmental Aspects**	**Direct impacts**	**Indirect impacts**
Air supply for drying	For food drying, the burner equipment provides airflow at temperatures of 70°C, produced by a centrifugal fan and directed to a cylindrical compartment with rotating trays where moisture is removed. Once the air circulates and performs heat transfer, it is discharged through a chimney.	• Generation of odors. • Energy consumption.	a. Increase in offensive odors. b. Increase in energy consumption.	a1. Community nuisance. b1. Reduction of resources.	For food drying, the burner equipment provides airflow at temperatures of 70°C, produced by a centrifugal fan and directed to a cylindrical compartment with rotating trays where moisture is removed. Once the air circulates and performs heat transfer, it is discharged through a chimney. The installation of the filtering system does not result in modifications to the airflow for drying.	• Generation of odors. • Energy consumption.	a. Increase in offensive odors. b. Increase in energy consumption.	a1. Community nuisance. b1. Reduction of resources.

Table 5. Environmental impact assessment with and without filter installation

No.	Without filter				With filter			
	Environmental impacts	Er	Ca	Class	Environmental impacts	Er	Ca	Class
1	Increase in pellet shavings waste	*I*	0.14	-	Increase in pellet shavings waste	*I*	0.14	-
2	Increase in ash waste	*S*	5.21	-	Increase in ash waste	*S*	5.21	-
3	Increase in offensive odors	*I*	0.21	-	Increase in offensive odors	*I*	0.21	-
4	Air pollution from particles	*S*	5.47	-	Decrease in air pollution from particles	*M*	2.64	+
5	Increase in pellet consumption	*Vs*	8.22	+	Increase in pellet consumption	*Vs*	9.17	+
6	Noise pollution	*I*	0.02	-	Noise pollution	*I*	0.07	-
7	Air pollution from gases	*S*	5.80	-	Decrease in air pollution from gases	*M*	4.40	+
8	Increase in energy consumption	*M*	3.74	-	Increase in energy consumption	*M*	3.88	-
9	Increase in air temperature	*I*	0.48	-	Increase in air temperature	*I*	0.48	-
10	Increase in organic waste	*I*	0.36	-	Increase in organic waste	*I*	0.36	-
11	Equipment blockage	*I*	1.84	-	Equipment blockage	*I*	1.84	-
12	Impact on plant structures	*I*	0.58	-	Impact on plant structures	*I*	0.58	-
13	Increase in ash in soil and water sources	*I*	2.16	-	Increase in ash in soil and water sources	*I*	2.16	-
14	Community nuisance	*I*	0.00	-	Community nuisance	*I*	0.00	-
15	Increase in respiratory diseases	*M*	4.45	-	Decrease in respiratory diseases	*I*	2.30	+
16	Use of biomass as raw material	*Vs*	8.02	+	Use of biomass as raw material	*Vs*	8.02	+
17	Increase in greenhouse gases	*S*	5.53	-	Decrease in greenhouse gases	*M*	4.50	+
18	Deterioration of air quality	*M*	3.47	-	Improvement of air quality	*M*	3.08	+
19	Reduction of resources	*I*	0.03	-	Reduction of resources	*I*	0.05	-
20	Climate modification	*I*	0.49	-	Climate modification	*I*	0.49	-

Based on the information presented above, Table 6 shows the results obtained from the environmental impact assessment of the pellet burner system without emission treatment, specifically during the Operation Stage and the Biomass Combustion Phase of the project.

Table 6. Evaluation of environmental impacts without the implementation of a filtering system

ASPI	environmental aspects	Direct impacts	Indirect impacts	Environmental impact assessment significance				Environmental categorization of the project.
				Vs	S	M	I	
4	9	9	12	2	4	3	11	Medium-impact project

Accordingly, the implementation of the filtration system associated with the fuel pellet supply results in several direct environmental impacts, specifically: (a) a reduction in atmospheric particulate emissions, and (b) a decrease in gaseous pollutants. In addition, various indirect impacts are identified, including: (a) a reduction in ash deposition in soil and water bodies, (b) a decline in respiratory disease incidence, (c) mitigation of greenhouse gas (GHG) emissions, (d) improvement in ambient air quality, and (e) enhanced public health conditions.

Similarly, the operation of the combustion fan produces the following direct impacts: (a) a reduction in particulate emissions and (b) a decrease in atmospheric gas concentrations. Consequently, the corresponding indirect effects include: (a) lower respiratory health risks, (b) reduced GHG emissions, and (c) improved air quality.

In contrast, the ignition source generates only one direct environmental impact, namely (a) a reduction in atmospheric gas emissions. This is accompanied by two indirect impacts: (a) a decrease in GHG emissions and (b) an improvement in air quality. Although the installation of the filtration prototype does not induce structural changes in the air supply system for drying, two adverse direct impacts are observed: (a) an increase in offensive odors and (b) higher energy consumption. These, in turn, give rise to indirect effects such as disturbances to surrounding communities and increased resource usage.

As part of the environmental impact assessment under operating conditions without the filtration system, a total of 20 impacts were identified: 2 were categorized as very significant, 4 as significant, 3 as moderate, and 11 as of low significance. Based on the Environmental Performance Matrix (EPM) evaluation, the project obtained a score of 2.15, corresponding to a medium environmental impact classification (Type II). Furthermore, in this scenario, only 2 impacts were considered positive, whereas 18 were identified as negative during the operation of the biomass combustion system.

It is important to highlight that biomass combustion constitutes a complex thermochemical process, characterized by successive homogeneous and heterogeneous reactions [53]. Within this framework, pollutant generation may arise from primary mechanisms directly related to the combustion process or from secondary mechanisms associated with post-combustion emission control strategies aimed at mitigating environmental impacts [54]. A summary of the environmental impact assessment results with the filter prototype installed is presented in Table 7.

Table 7. Evaluation of environmental impacts with the implementation of a filtering system

ASPI	environmental aspects	Direct impacts	Indirect impacts	Environmental impact assessment significance				Environmental categorization of the project
				Vs	S	M	I	
4	9	9	12	2	1	5	12	Low-impact project

As a result of the environmental impact assessment conducted after the installation of the filtration system, two impacts were classified as very significant, one as significant, five as moderate, and 12 as of low significance. The addition of the filtration system to the combustion chamber increased the positive impacts to a total of seven, while the negative impacts were reduced to 13. These findings demonstrate tangible progress in environmental restoration, both direct and indirect, within the system's area of influence. Improvements were also observed across multiple assessment criteria, leading to a revised environmental rating (Ca) of 1.8, thus reclassifying the project as low-impact or Type III.

Among the most significant positive impacts generated by the installation of the filtration system, two highly significant impacts stand out: the increased use of pellets and the replacement of fossil fuels with biomass as a renewable raw material. Moderately significant impacts include reduced particulate air pollution, decreased atmospheric gas emissions, reduced greenhouse gas concentrations, and overall improved air quality. A less significant but still relevant impact is the reduction in the incidence of respiratory diseases in the surrounding population.

Consequently, the implementation of a biomass-fired filtration system offers numerous environmental benefits and aligns with global sustainable energy generation goals. When biomass is sustainably sourced and managed, it constitutes a renewable energy alternative with comparatively low CO_2 emissions [54]. Furthermore, it supports the transition to sustainable agricultural practices with an emphasis on environmental preservation and resource efficiency [55].

However, several negative impacts were also identified. Significant adverse effects included increased ash generation. In the moderate category, an increase in energy consumption was observed due to pressure losses in the filter medium.

Less significant impacts include pellet chip accumulation, unpleasant odor emission, increased noise levels, increased air temperature, organic waste generation, potential equipment blockage, impact on nearby plant structures, ash deposition on soil and water bodies, community disruption, resource depletion, and minor alterations in local climate conditions.

Although these impacts are less significant, they are comparable to those associated with uncontrolled agricultural residue burning, which has been widely documented to cause nutrient depletion, soil degradation, and the release of climate-altering pollutants such as greenhouse gases [56], [57].

3.2. Operating conditions and monitoring of the burner equipment for taking emissions readings with a gas analyzer and emissions control products "Optima 7" (MRU Instruments)

To achieve temperatures of 150°C in the tank with thermal storage (thermal oil), it was necessary to burn 1.7 kg of pellets, applying an air injection for combustion with a flow rate of 100 CFM. Given this, in the reading with the gas analyser without the filter installation (Test 1), the maximum gas temperature was determined to be 190°C, in addition to the data on emissions caused by combustion every second. Table 8 shows the average for a sample lasting 15 minutes for gases such as O_2, CO, CO_2, and H_2S at the outlet of the burner equipment chimney. In combustion, one of the main parameters that must be monitored is the amount of air, which will result in either complete or incomplete combustion [58], [59], [60]. In the readings taken during the combustion of pellets (CSP), O_2 values of up to 15.06% were observed without the filter installation, leading to unburned products.

Table 8. Emission readings from the chimney outlet of the burner equipment (Test 1)

Test	O_2 (%)	CO (ppm)	CO_2 (%)	H_2S (ppm)	N_2 (%)
1	15.06	1710	2.13	39.36	76.64

Additionally, carbon monoxide (CO) emissions from the burner system, in the absence of any gas treatment, were measured during a 15-minute combustion cycle, as presented in Table 9. However, considering that the combustion process operates intermittently for a total of approximately 35 minutes throughout the 8-hour drying cycle, the estimated cumulative CO emissions amount to approximately 3990 ppm. According to the report published by [61], the World Health Organization (WHO), in alignment with both North American and European standards, establishes a maximum recommended CO exposure concentration of 8995 ppm for an 8-hour period.

Moreover, in accordance with the short term exposure limits set by the Occupational Safety and Health Administration (OSHA), carbon dioxide (CO_2) concentrations should not exceed 3% (30,000 ppm) [62], Based on the experimental data obtained in this study, the average CO_2 concentration during the test remained well below this threshold, as shown in Table 9.

Regarding hydrogen sulphide (H_2S), average emissions reached 39.36 ppm. In this context, the U.S. Environmental Protection Agency (EPA) and OSHA recommend limiting exposure to concentrations between 20 and 50 ppm for a maximum of 10 minutes, whereas values exceeding 100 ppm are classified as immediately dangerous to life or health [63]. It is important to note that the emissions data for H_2S were collected over a 15-minute continuous test period, remaining within acceptable exposure limits.

The behaviour of pollutant emissions is largely dependent on the fuel-to-oxidizer ratio [64]. To better interpret the combustion dynamics, gas emission values were normalized to a scale from 0 to 1. It was observed that during the initial phase of combustion, when the fuel first contacts the ignition source (spark or flame), the concentrations of emitted gases reached their peak. As combustion progresses and oxygen is increasingly supplied to facilitate complete oxidation, the emission levels of pollutants gradually decline, indicating improved combustion efficiency.

Figure 11 illustrates that, at the chimney outlet, lower oxygen concentrations correspond to higher levels of CO and CO_2, reflecting incomplete combustion. Conversely, as O_2 levels rise, a noticeable reduction in these gases is observed. This inverse relationship also highlights the dynamic interplay between CO and CO_2: as CO concentrations decrease, CO_2 levels tend to increase, indicating more complete oxidation of the fuel material.

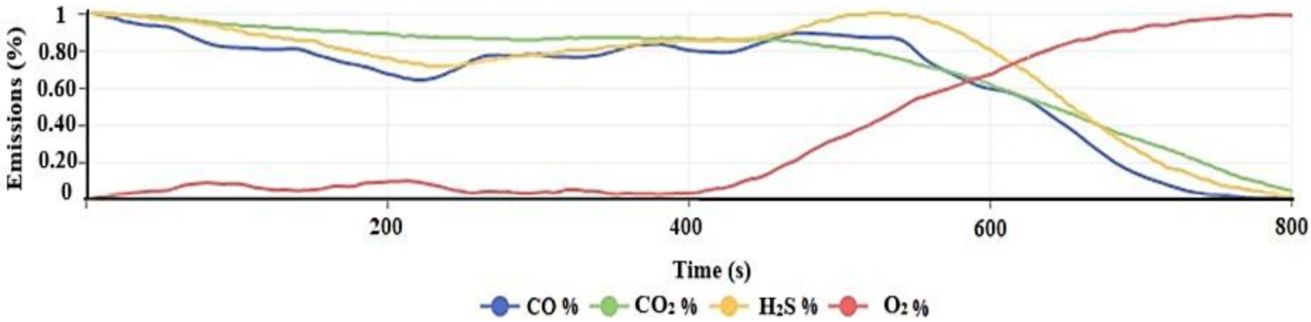

Figure 11. Behavior of gas emissions as a function of combustion time without filter (Test 1)

Following the design, construction, and installation of the filtration system, emissions measurements were taken on the prototype under the operating conditions corresponding to Test 2. In this case, the combustion process required 1.7 kg of fuel and an increased air flow of 120 CFM to achieve a thermal oil temperature of 150°C and a heated forced air outlet of 70°C. According to the gas analyser readings, the maximum flue gas temperature reached during this test was 130°C.

As a result of the filter installation, a change in the system's operating dynamics was observed. Specifically, it was necessary to increase the oxidant flow rate and adjust the pellet feed rate to compensate for the additional resistance introduced at the stack outlet by the filtration system. These modifications resulted in variations in oxygen consumption and an overall reduction in emissions levels, reflecting the equipment's adaptability and filter effectiveness under modified combustion conditions. The summarized results are presented in Table 9.

Table 9. Emission readings from the filtration system (Test 2)

Test	O_2 (%)	CO (ppm)	CO_2 (%)	H_2S (ppm)	N_2 (%)
2	17.02	475	0.2	5.7	74.71

As mentioned above, excess air is a key indicator of combustion efficiency. Figure 12 illustrates the variation in normalized parameters, confirming that regulating oxidant levels and fuel consumption can effectively reduce pollutant emissions. Similarly, once the oxidizer is introduced and combustion begins, emissions levels begin to decrease, while oxygen (O_2) concentrations increase. This behavior is attributed to the control of primary and secondary combustion parameters implemented during Test 2.

As a result, carbon dioxide (CO_2) concentrations increase, while carbon monoxide (CO) and hydrogen sulphide (H_2S) levels decrease, indicating a more complete combustion process. These changes reflect an overall improvement in the system's operating efficiency under optimized combustion conditions.

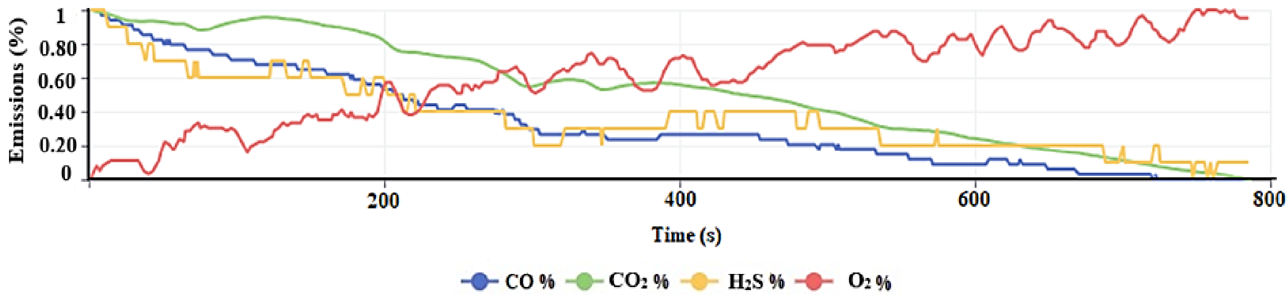

Figure 12. Behavior of gas emissions as a function of combustion time using a filter (Test 2)

3.3. Challenges & future directions

Despite the favourable results obtained in reducing pollutant emissions through the implementation of the filter prototype, several technical and operational challenges have been identified that warrant consideration for future research and technological development.

One of the primary challenges lies in the increased flow resistance introduced by the filtration system, which results in higher pellet consumption and greater energy demand by the combustion air fan. This highlights the need to optimize the gas extraction system design and to explore filtration alternatives that offer lower pressure drop without compromising pollutant removal efficiency.

Additionally, the limited retention of ultrafine particulate matter ($PM < 1.0$ µm), as observed in simulation results, represents a technical limitation, given the high health risk posed by these particles due to their capacity to penetrate deep into the respiratory tract. Future research should focus on the development of advanced filtration media with improved selectivity and capture efficiency for submicron particles, potentially incorporating nanomaterials or multilayer functional filters.

Another important consideration involves the life cycle assessment of the filtering materials, particularly activated carbon and polyester fiber, evaluating their long-term adsorption performance as well as the environmental impact associated with their disposal. The use of biodegradable or recyclable filter media could provide a more sustainable solution from both environmental and economic perspectives.

From a methodological standpoint, future studies should aim to incorporate real-time emission monitoring systems, along with intelligent control algorithms capable of autonomously adjusting operational parameters based on combustion conditions and thermal efficiency.

Finally, it is essential to validate the scalability and operational performance of the prototype under real-world conditions, especially in rural or agro-industrial settings, where operational loads may vary and extended continuous operation is required. Pilot-scale implementations with longer monitoring periods are recommended, along with comparative assessments against commercially available emission control technologies, in order to establish the technical, economic, and environmental feasibility of widespread deployment.

4. Conclusions

Firstly, the environmental impact assessment conducted using the EPM-Arboleda methodology confirms that the implementation of the filter prototype in the combustion system utilizing cocoa pod shell (CSP) pellets leads to a significant improvement in environmental indicators. Specifically, a reduction in pollutant gas emissions such as CO, CO_2, and H_2S is observed, along with a decrease in particulate matter emissions. These outcomes generate positive indirect effects, including a reduction in respiratory illnesses, improved air quality, and a decrease in greenhouse gas emissions.

Moreover, the comparative analysis between the scenarios with and without the filter demonstrates a shift in the project's environmental classification, from medium to low impact. This finding confirms the technical and environmental feasibility of the proposed filtration system, which contributes to more sustainable biomass-based thermal processes.

However, it is important to note that the installation of the filter introduces certain operational changes, such as increased energy and fuel consumption, due to the added resistance at the gas outlet. Nevertheless, the environmental benefits outweigh these moderate negative impacts, provided that operational parameters are adequately controlled.

In addition, the use of filtering materials such as polyester fiber and activated carbon has proven effective for the retention of particulate matter and the adsorption of pollutant gases, even under demanding thermal conditions. Therefore, the selection of these materials represents an appropriate strategy for secondary emission mitigation in biomass combustion systems.

Finally, it is concluded that the controlled combustion of CSP pellets, combined with the design and implementation of a low-cost filtration system, constitutes a replicable technological alternative for rural or agro-industrial contexts. This approach holds the potential to replace fossil fuel sources while minimizing the environmental impacts associated with the energy recovery of agricultural residues.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

Arly Dario Rincón Quintero: Participated in the design and development of the study methodology; Camilo Leonardo Sandoval Rodriguez: Supported the formulation of the methodology and the collection of information; Zirley Dayana Ardila Caballero: Established the evaluation of the direct and indirect impacts caused by the project; Mauricio Andres Ruiz Ochoa: Performed the analysis and interpretation of the environmental assessment results; Luis del Portillo Valdes: Assisted in the drafting and revision of the document. All authors participated in the writing, analysis, and approval of the final manuscript.

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