

Primary combustion control of cocoa pod husk pellets: Effects of kaolin additives and air velocity on efficiency and emissions

A. D. Rincon-Quintero^{1,2*}, Zirley Ardila-Caballero¹, C. L. Sandoval-Rodriguez³, Pedro José Almanza Merchán⁴ and Edilma Fernandez Fernandez⁴

^{1,3} Unidades Tecnológicas de Santander, Bucaramanga, Colombia

² Departamento de Ingeniería Energética, Universidad del País Vasco, Bilbao, Spain

⁴ Grupo de Investigación GIPSO, Universidad Pedagógica y Tecnológica de Colombia UPTC, Tunja, Colombia

*Corresponding author E-mail: arincon@correo.uts.edu.co

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Abstract

The control of primary combustion methods directly influences thermal efficiency and atmospheric emission concentrations. In this context, the objective of the present study was to evaluate the impact of the type of biofuel through the incorporation of additives, as well as the operating conditions of the equipment by regulating the oxidizing agent velocity. For this purpose, a densified biomass (pellet) burner was employed, equipped with a thermal storage tank, a centrifugal fan for supplying the oxidizing agent, and a feeding system based on a screw conveyor with ON/OFF control. Emission characterization (CO, CO₂, O₂, and H₂S) was conducted using a gas analyzer, while equipment efficiency was determined from the calculation of the experimental lower heating value (LHV) obtained from four (4) test runs. The results demonstrated that the addition of additives in the production of cocoa pod husk (CPH) pellets improved the compaction, durability, and structural stability of the biofuel, which led to more complete combustion. In particular, the use of kaolin, combined with an airflow velocity range between 5.0 and 6.5 m/s, provided the best system performance by enabling faster ignition, complete biofuel consumption, and an increase in bottom ash due to particle agglomeration. In conclusion, the incorporation of additives and the controlled adjustment of airflow velocity optimize the efficiency of the combustion process, while simultaneously reducing fly ash entrainment and lowering atmospheric emission concentrations.

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1. Introduction

After coal, oil, and natural gas, biomass constitutes the fourth most important energy source in terms of global consumption [1], [2]. This renewable resource is distinguished by its broad availability and substantial potential for energy and heat generation, and it is widely acknowledged as a carbon-neutral energy source [3], [4], [5].

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At present, nearly 40% of the global population relies on biomass for heating and cooking, underscoring its critical role within the global energy system [6], [7], [8]. In this context, the transition from fossil fuels to sustainable energy sources, aligned with the Sustainable Development Goals (SDGs), aims to mitigate atmospheric emissions by replacing conventional technologies with cleaner and more environmentally responsible systems [9], [10], [11].

Among the strategies to enhance fuel quality, biomass pelletization emerges as a key process, as it compacts the material, reduces moisture content, increases bulk density, and decreases overall volume, thereby facilitating more efficient storage, transport, and energy utilization [12], [13], [14]. The use of lignocellulosic feedstocks offers significant advantages in terms of ash content, heating value, and pellet geometric properties, positioning them as a promising alternative for the production of high-quality solid biofuels [15], [16], [17]. Efficient combustion and emission reduction, however, require strict control over both fuel quality and operating parameters [18], [19], [20]. Specifically, complete oxidation of the material, enabled by an adequate oxygen supply, maximizes energy recovery while limiting pollutant formation [21], [22], [23]. Conversely, incomplete combustion results in the presence of unburned residues and the release of gases such as carbon monoxide, nitrogen oxides, and volatile organic compounds, along with coarse, fine, and ultrafine particulate matter that compromise air quality and human health [24], [25], [26], [27].

To improve combustion performance, one alternative is the incorporation of additives in pellet formulation [28]. In particular, kaolin, composed primarily of kaolinite, has proven effective by promoting chemical reactions that immobilize pollutants in bottom ash [29], [30], [31]. This additive increases combustion temperature, enhances the thermal stability of ash, and facilitates particle fusion [32], [33]. Moreover, operating conditions, especially air velocity control, exert a decisive influence on pollutant formation, as maintaining an appropriate oxygen-to-fuel ratio reduces the concentration of hazardous gases [34], [35], [36]. Nevertheless, excessive air supply can alter combustion temperature, promote ash entrainment, and decrease thermal efficiency [37], [38], [39].

Consequently, the control of primary combustion methods, which encompasses both biofuel quality and burner operating parameters, is fundamental to optimizing energy efficiency and minimizing primary emissions [40], [41]. A more complete combustion process enables higher temperatures to be achieved with lower fuel consumption, while also improving heat transfer to practical applications such as food drying [42], [43], [44]. Within this framework, the remainder of this article is organized as follows: Section 2 details the experimental methodology, including the tests performed, the operation of the combustion equipment, and the characteristics of the biofuel employed. Section 3 presents the results, and Section 4 discusses the conclusions and recommendations.

2. Research method

2.1. General description of the pellet burner equipment

The burner design incorporates innovative features intended to maximize heat generation from biomass combustion within the combustion chamber. Specifically, the system operates on the principle of indirect heating, in which separation is maintained between the air employed for various functions and the combustion gases produced during burning. Moreover, the gas flow is channeled through a narrow duct surrounding the thermal storage tank, thereby facilitating its discharge toward the chimney and subsequent release into the atmosphere. Additionally, the equipment integrates an automated screw feeding mechanism that regulates pellet supply. This configuration, in turn, enables precise temperature control, thus ensuring that the system remains within the required operating range while preventing air overheating [45], [46].

2.1.1. Structural characteristics of the burner

The design of the thermal storage burner is structured into four main sectors, as shown in Figure 1. First, Sector 1 comprises the perforated basket, where the combustion process takes place. In this zone, the solid biofuel

(pellets) reacts with the oxidizing agent (oxygen) supplied by an in-line duct fan, generating the flame responsible for transferring heat to the storage tank.

Second, Sector 2 corresponds to the biofuel feeding system, which consists of a hopper and a screw conveyor. This mechanism ensures the continuous and regulated supply of pellets, thereby maintaining combustion stability under controlled operating conditions. Subsequently, Sector 3 houses the storage tank filled with thermal oil, inside which heat transfer occurs. This phenomenon is facilitated by a coil completely immersed in the tank, through which forced air circulates. During this process, the air absorbs thermal energy and is subsequently directed to the exterior for various applications, including food drying. Finally, Sector 4 is dedicated to the evacuation of combustion gases. In this section, in addition to gas discharge, emission monitoring is performed using a specialized analyzer (Optima 7 Biogas).

With regard to the control system, Sectors 1, 3, and 4 are equipped with temperature sensors for continuous monitoring of operating conditions, while Sector 2 incorporates an ON/OFF actuation system managed by a programmable logic controller (PLC) with a human-machine interface (HMI). Thus, the burner operates under an automated scheme that enables precise regulation and efficient monitoring of the critical process parameters [47].

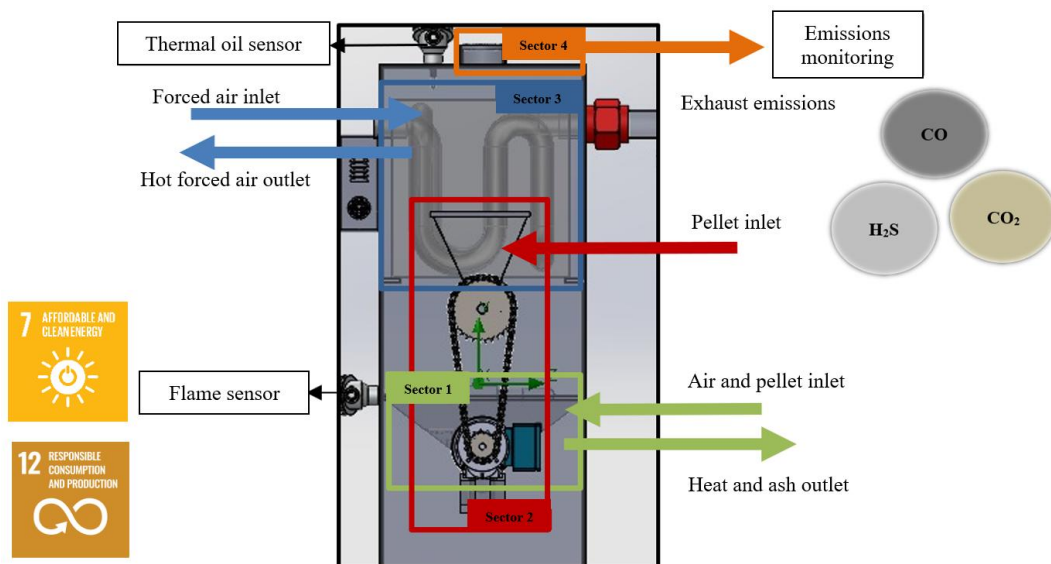


Figure 1. Inlet and outlet streams of the biomass pellet combustion system

2.2. Properties of the biomass pellet fuel

The control of variables associated with pellets, such as the type of raw material used, the addition of compounds, moisture content, bulk density, and length, largely determines the properties of the biofuel [48], [49]. These conditions influence both the calorific value and the behavior of the residues generated during combustion, particularly the quantity and composition of ash [50]. Figure 2 shows type A pellets, produced without additives, and type B pellets, produced with kaolin as an additive.



Figure 2. Length of pellets: type A and type B

In order to obtain representative values, 30 units of each pellet type were selected, from which the averages of the evaluated variables were calculated [51], [52]. Additionally, the components used in the production of the biofuel are specified, as presented in Table 1.

Table 1. General characteristics of the biofuel

Property	Pellet Type A	Pellet type B
Raw Material	cocoa pod husk (CPH)	cocoa pod husk (CPH)
Dry Basis (%)	71,43	64,3
Oil Content (%)	4,5	4,46
Water Content (%)	24,1	24,1
Kaolin (%)	-	7,14
Diameter (mm)	4,5 a 5	5
Length (cm)	3 a 4	3 a 4
Moisture Content (%)	6,6	6,3
Density (kg/m ³)	312	496

2.3. Properties of the oxidizing agent or combustion air

For the combustion process, the supply of air to provide oxygen as the oxidizing agent is carried out using an inline duct fan, with a flow capacity of up to 100, 150, and 250 CFM, regulated through Pulse Width Modulation (PWM). This fan directs an airflow through a duct to the perforated hopper where the pellets are arranged, generating an upward forced draft. In this way, a direct flame is produced, oriented toward the thermal oil storage tank, ensuring efficient energy transfer.

Figure 3 illustrates the entry of the combustion airflow, as well as the inlet and outlet of the hot forced air produced by the system.

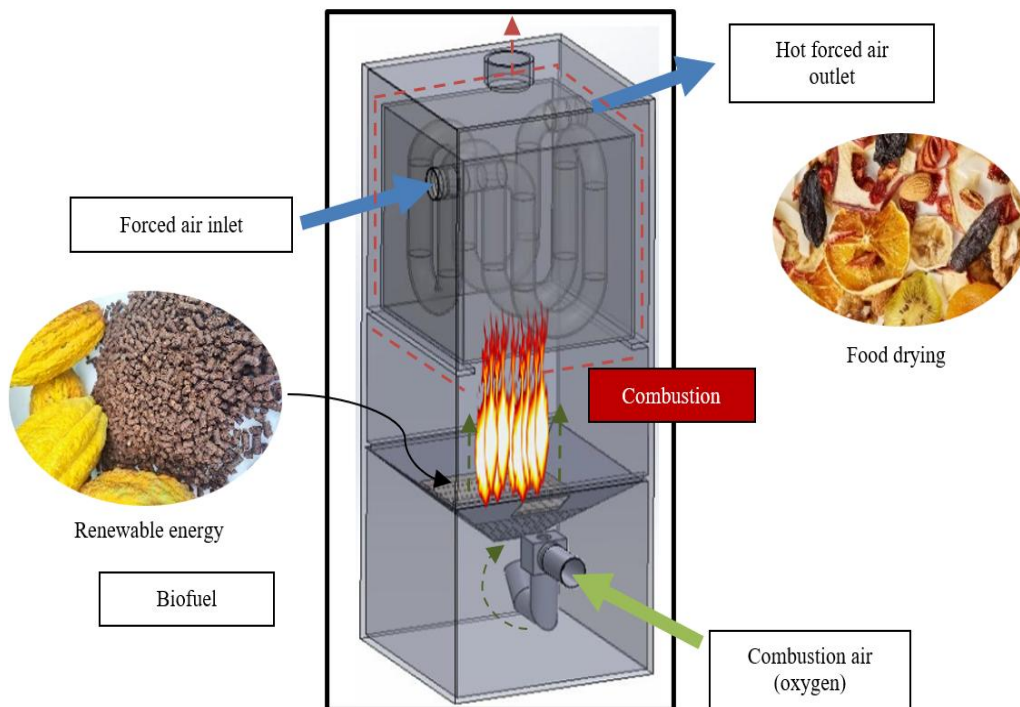


Figure 3. Biomass pellet combustion for food drying processes

2.4. Experimental procedure

In order to evaluate the effectiveness of the pellet burner, the system's operational performance is established based on the overall programming of inputs, processes, and outputs. In this context, a logical sequence is structured to identify and analyze the stages involved in the operation cycle, as shown in Figure 4.

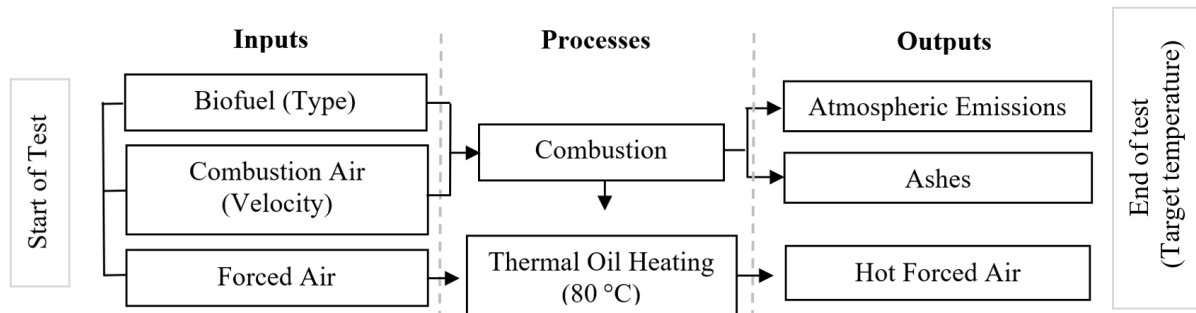


Figure 4. Experimental procedure

In a preliminary stage, an initial mass of pellets is placed in the perforated basket located within the combustion chamber. A butane gas torch is then used as the ignition source for the biofuel, while simultaneously injecting a flow of air (oxidizing agent) through a duct arranged to provide a forced draft at an angle that directs the flame vertically toward the thermal storage tank. Additionally, as the pellets are consumed, a screw conveyor is programmed to continuously feed the biofuel into the combustion chamber, maintaining a stable and continuous flame. It is also important to note that the perforations in the basket allow the ashes to be evacuated by gravity and deposited at the bottom of the equipment without interrupting the process. Figure 5 shows the pellet burner used during the experimental tests, through which the operational conditions and system behavior under the established parameters were evaluated.



Figure 5. Burner equipment, perforated basket, pellet hopper, and HMI screen

2.4.1 PLC programming: Inputs to the burner equipment

Once the initial flame is established, the pellet feeding system is activated via the PLC. This device is configured with a cyclic sequence consisting of 20 seconds of operation followed by a 2-second pause, ensuring an intermittent and controlled supply of the solid biofuel. Concurrently, during the test, the velocity of the airflow acting as the oxidizing agent (oxygen) is recorded according to the parameters defined for each experimental scenario (see Table 2).

2.4.2 Combustion and heat transfer process

As the availability of biofuel and oxygen increases, combustion intensifies, causing the flame to expand and heat generation to rise. As a result, the energy released is transferred to the storage tank, where the thermal oil temperature increases. Additionally, the fan responsible for producing the working fluid is activated, introducing air into the tank at a velocity of 12 m/s, thus enabling the absorption of the thermal energy generated in the combustion chamber. In this way, hot forced air is obtained as the system's final output, suitable for heat-requiring processes such as food drying [53], [54].

2.4.3 Analysis of the burner equipment outputs

As part of the system monitoring, a gas analyzer is installed and connected to the chimney located at the top of the equipment, which has a square geometry with a 10 cm side and a total length of 125 cm. At the sampling point, a probe is positioned to direct the gas sample toward the sensors integrated into the analyzer. These

sensors allow for the simultaneous detection of gaseous compounds, while the collected data are integrated, visualized in real time, and processed for subsequent storage and transfer to a computer to facilitate the analysis of emission behavior. The monitored parameters include oxygen (O₂), carbon monoxide (CO), carbon dioxide (CO₂), and hydrogen sulfide (H₂S).

Additionally, the combustion process generates solid residues referred to as ashes. These may appear as fine or coarse particles, depending on whether combustion is complete or incomplete, and accumulate at the bottom of the equipment [20]. Consequently, to evaluate the biofuel performance and the impact of oxidizing air supply conditions, the percentage of ashes produced in each test is quantified.

In this context, in order to analyze the influence of biofuel type and oxidizing air velocity on the system's thermal efficiency, four (4) experimental tests were conducted, as shown in Table 2. In each test, the operational condition was set to reach a thermal oil temperature of 80 °C, aiming to obtain forced hot air close to 50 °C. This temperature is required for food drying processes [55], [56], [57], [58].

Table 2. Experimental test design

Test	Pellet type	Oxidizing Air Velocity (m/s)
1	A	6,5 a 9,0
2	B	6,5 a 9,0
3	A	5,0 a 6,5
4	B	5,0 a 6,5

3. Results and discussion

3.1. Experimental tests

The variation of the primary control method produces changes in flame behavior, which in turn is reflected in differences in the amount of pellets consumed, the time required to reach the target temperature, and the quantity of ashes generated in each test. Additionally, variations in emission concentrations are observed, as shown in Table 3.

Table 3. Results obtained from experimental tests

Test	Biofuel				Combustion air Velocity (m/s)	Thermal oil		Emissions monitoring			
	Pellet Type	Quantity (kg)	Consumption Time (min)	Ashes (kg)		Temperature (°C)		O ₂ (%)	CO (ppm)	CO ₂ (%)	H ₂ S (ppm)
						Initial	Final				
1	A	1,484	28	0,108	6,5 a 9,0	30	81,7	16,30	13763	2,31	367,08
2	B	1,194	22	0,202	6,5 a 9,0	30	93,5	17,26	4506	2,51	129,87
3	A	1,188	43	0,080	5,0 a 6,5	30	82	18,08	3682,72	0,57	332,11
4	B	0,858	13	0,136	5,0 a 6,5	30,4	86,8	17,30	3649,52	2,02	120,26

According to the experimental results obtained, it was observed that in Test 1, conducted with an oxidizing air velocity between 6.5 and 9.0 m/s using pellets without kaolin, the highest biofuel consumption was recorded;

however, the thermal oil temperatures achieved were relatively low. In Test 3, employing pellets without kaolin and an air velocity between 5.0 and 6.5 m/s, limited utilization of the lower heating value (LHV) was demonstrated. In contrast, Tests 2 and 4, using pellets with additives, exhibited the highest thermal oil temperatures along with shorter consumption times, indicating greater efficiency in heat transfer.

Regarding the emission readings, tests carried out at velocities of 6.5 and 9.0 m/s showed elevated carbon monoxide concentrations, reflecting an inadequate biofuel-to-oxidizing air ratio. However, by maintaining a constant pellet feeding program and reducing the amount of oxidizing air, significant improvements were observed in the reduction of CO levels.

3.2. Emissions monitoring

Using the KNIME tool, the emission data recorded after igniting the biofuel in each test were consolidated and normalized to visualize and analyze the behavior of the gases in a unified manner. Readings were taken over a period of 800 seconds following flame ignition. Figure 6 and Figure 7 show the emission concentrations of oxygen (O_2), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and carbon monoxide (CO) throughout the four tests.

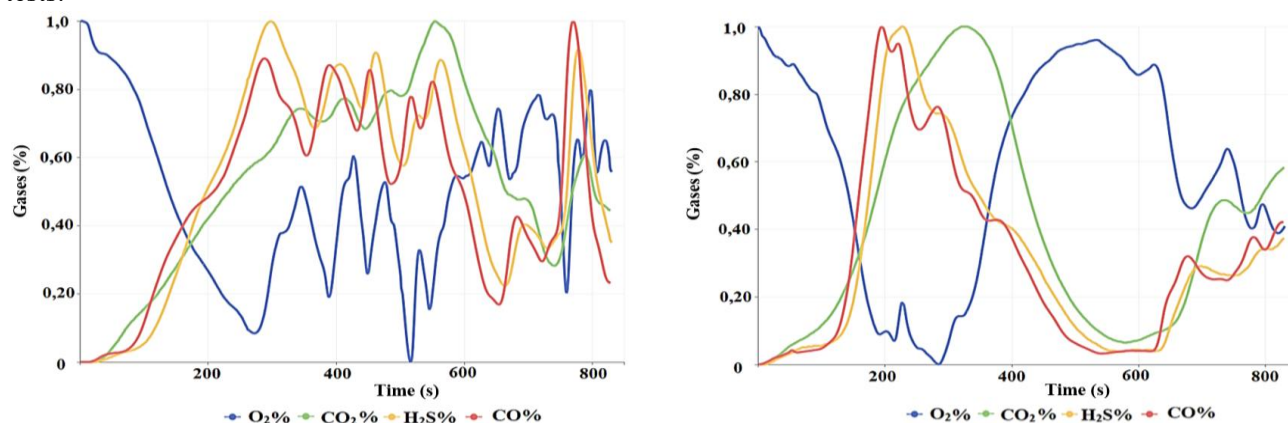


Figure 6. Emission readings for test 1 and test 2

In Test 1, the use of Type A biofuel (without kaolin) within the airflow velocity range of 6.5 – 9.0 m/s resulted in combustion instability, characterized by continuous oxygen fluctuations throughout the experiment. This condition caused irregularities in air supply and flame stability. Carbon dioxide exhibited a progressive upward trend, indicating incomplete and variable combustion. Simultaneously, CO concentrations remained relatively high, associated with deficiencies in the oxidation of the biofuel. Regarding H_2S , pronounced variations were observed, suggesting discontinuous release of sulfur compounds due to unstable combustion conditions.

In contrast, in Test 2, the use of Type B pellets with kaolin addition contributed to more stable and efficient combustion. At the beginning of the test, O_2 concentrations dropped sharply, accompanied by a pronounced increase in CO_2 and CO. This behavior reflects intense and accelerated combustion, in which oxygen was rapidly consumed to oxidize the biofuel. Subsequently, a partial recovery of oxygen was observed, while CO_2 levels remained elevated and CO concentrations decreased. This trend suggests that combustion began to stabilize, reducing CO formation and favoring CO_2 production as a result of more complete oxidation. With respect to H_2S , elevated levels were recorded in the initial phase, coinciding with the stage of highest combustion intensity. At the end of Test 2, a simultaneous increase in both CO and O_2 emissions was detected, which may be attributed to the progressive depletion of the available biofuel.

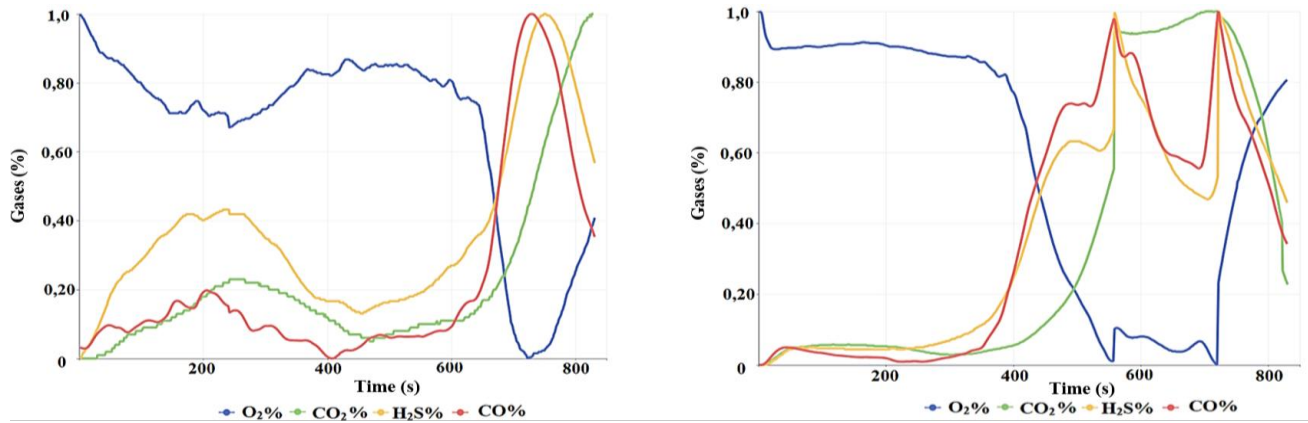


Figure 7. Emission readings for test 3 and test 4

In Test 3, using Type A pellets (without kaolin) and a reduced oxidizing air velocity from a range of 6.5 – 9.0 m/s to 5.0 – 6.5 m/s, the O₂ behavior shows a gradual downward trend at the beginning, without an abrupt drop. However, O₂ levels remain relatively high for most of the test, indicating that the available air is not fully utilized during combustion, while CO₂ and CO emissions remain low until the final phase. This behavior suggests delayed and inefficient oxidation, resulting in incomplete combustion. H₂S concentrations are moderate during the first half of the test, increasing notably near the end alongside CO and CO₂. This phenomenon is attributed to the absence of kaolin and the higher availability of air, conditions that limit combustion uniformity, restrict oxygen utilization, and favor pollutant generation in the final phase of the process.

Conversely, in Test 4, with kaolin added to the biofuel, a controlled and efficient behavior is observed. At the start of the test, O₂ decreases sharply while CO₂ and CO increase simultaneously, reflecting an intense combustion phase with a higher degree of oxidation. Subsequently, CO₂ continues to rise, accompanied by elevated levels of CO and H₂S, indicating accelerated biofuel consumption and the release of volatile compounds. Finally, O₂ recovers while CO, CO₂, and H₂S decrease simultaneously, signaling the biofuel depletion phase and a reduction in combustion intensity.

3.3. Performance evaluation

3.3.1. Lower heating value of the pellets

The composition of the biofuel, along with variations in the system's operating conditions, causes differences in the lower heating value (LHV) obtained in each experiment. Consequently, for the calculation of energy utilization, the relationship between the amount of pellet consumed and the change in thermal oil temperature is established. Table 4 presents the initial and final oil temperature values, as well as the biofuel consumption recorded in each test.

Table 4. Variation of the lower heating value (LHV) in each test

Test	Thermal Oil Temperature		C _{PHP} (Kg)	LHV	
	Initial (°C)	Final (°C)		J/Kg	MJ/Kg
1	30	81,7	1,484	3962283,123	3,96
2	30	83,5	1,194	5096104,414	5,1
3	30	80,1	1,188	4796342,056	4,79
4	30,4	86,8	0,858	7476196	7,47

The obtained data allow establishing the relationship between pellet consumption and the increase in thermal oil temperature in each test, reflecting the efficiency of the lower heating value utilization. Test 1 recorded the lowest energy efficiency, likely associated with combustion instability.

In contrast, Test 2 showed a better conversion of the biofuel's energy into useful heat. Test 3, with similar pellet consumption, exhibited slightly lower energy utilization compared to Test 2, highlighting the effect of combustion conditions on efficiency. Finally, Test 4 achieved the highest energy utilization from the biofuel.

3.3.2. Flame temperature

The flame generated during combustion, as well as the temperature reached in the process, depends directly on the primary control method. Figure 8 shows the flame size under the different conditions evaluated, along with the maximum temperature recorded in each test.

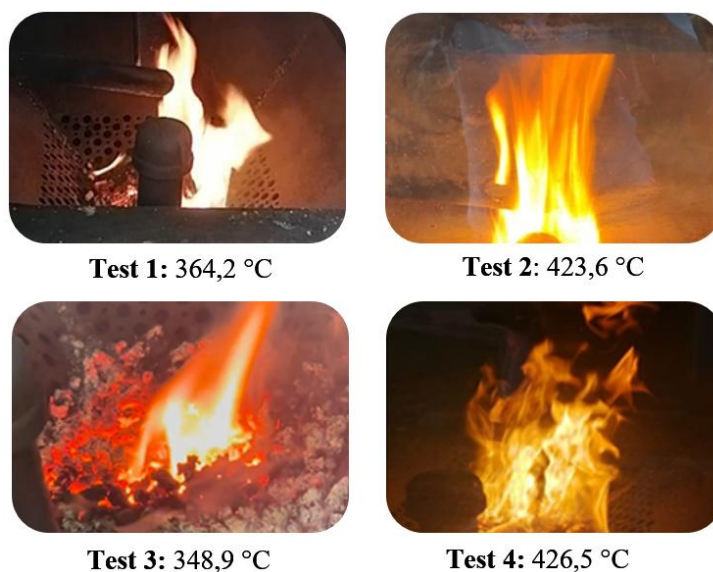


Figure 8. Flame behavior in the experimental tests

A key variable for evaluating combustion process efficiency and its impact on emitted gases is the flame temperature [59], [60]. In tests conducted with pellets without kaolin, smaller flames and lower temperatures were recorded, resulting from limited combustion. In contrast, the addition of an additive promoted process stability and development, leading to larger flame sizes and higher temperatures, a condition attributed to more efficient combustion [61], [62], [63].

3.3.3. Ash content obtained in each test

Figure 9 presents the ash content percentage retained in the perforated basket, along with corresponding photographic documentation for each experimental test.



Figure 9. Ash content percentage obtained in each test

The ash analysis shows that pellets without kaolin (Tests 1 and 3) produce a lower percentage of solid residue, characterized by a finer texture, which reflects a higher proportion of volatile material. In contrast, tests with kaolin (Tests 2 and 4) exhibit higher ash content, which is consistent since this additive is non-combustible and remains as inert material after combustion, causing ash accumulation at the bottom of the perforated basket.

From a combustion efficiency perspective, the addition of kaolin increases the amount of ash obtained. This behavior is associated with more efficient combustion, as confirmed by the LHV values and the temperatures reached. Consequently, this leads to better control of atmospheric emissions and improved heat transfer. However, a high percentage of solid residues may compromise the continuous operation of the burner, requiring more frequent cleaning of the perforated basket to prevent obstruction of the oxidizing air flow, which could in turn cause flame instability and reduce the overall system efficiency.

3.3.4. Equipment efficiency according to primary control methods

According to the bomb calorimeter method and in compliance with ASTM D4809-13, the heating value of 15.5 MJ/kg is established for pellets produced from cocoa pod husk (CPH). However, for experimental purposes in the pellet burner, only 80% of this value is considered, corresponding to the lower heating value (LHV), which equals 12.4048 MJ/kg.

Regarding the tests conducted, the LHV in the four experimental trials shows significant differences compared to the theoretical LHV of the CPH pellets. An energy utilization of 31.94% was achieved in Test 1, 41.08% in Test 2, 38.66% in Test 3, and 60.43% in Test 4. Furthermore, it was observed that pellets containing additives improved the LHV compared to those without kaolin. This behavior demonstrates greater energy utilization, resulting from efficient combustion characterized by a stable flame, ultimately leading to higher levels of system efficiency.

4. Conclusions

Biomass densification as a primary control strategy demonstrates controlled ignition of biofuel produced from cocoa pod husk byproducts. In this context, the addition of kaolin has a positive effect, as it contributes to improving pellet compaction, durability, and structural stability, promoting more complete combustion of the compressed material. Experimental tests also showed an increase in density and heating value, along with the formation of bottom ash structures, a phenomenon associated with particle agglomeration due to the presence of silicates. This behavior is beneficial as it facilitates ash retention in the perforated basket and reduces particulate matter entrainment into the atmosphere.

Regarding emissions, pellets without additives result in high and fluctuating CO and H₂S concentrations, associated with unstable and incomplete combustion, even under different oxidizing air velocities. In contrast, pellets with kaolin addition show a progressive reduction in CO and increased CO₂ formation, reflecting more efficient and stable oxidation. Additionally, the presence of the additive helps decrease the continuous release of sulfur compounds, mitigating environmental impact.

Furthermore, it was determined that the amount of oxidizing air supplied is a critical factor affecting emission concentrations, as excessive fan velocity produces significant variations in results. Specifically, injecting high oxygen levels without a proportional amount of biofuel leads to low temperatures, reduced flame size, and black smoke emission. Consequently, proper air supply directly influences thermal performance.

Finally, it is concluded that the intrinsic properties of the biofuel govern incineration efficiency, as irregularities in parameters such as particle size and moisture content hinder ignition and favor flame instability. In this regard, an inadequate oxygen-to-fuel ratio results in increased emissions and particulate matter. Comparative analysis of the experimental tests indicates that pellets with additives, combined with an oxidizing air velocity between 5.0 and 6.5 m/s, achieve the best performance, attaining higher heating value with lower biofuel consumption, elevated flame and thermal oil temperatures, ensuring the required air temperature, and significantly reducing emissions to the atmosphere.

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

The contribution to the paper is as follows: A. D. Rincon-Quintero contributed to conceptualization, design, analysis, interpretation of results, and manuscript writing. Zirley Ardila-Caballero was responsible for the

investigation, environmental analysis, interpretation, and drafting of the original manuscript. C. L. Sandoval Rodriguez: contributed to the investigation, methodology, and preparation of the original draft. Pedro José Almanza Merchán: contributed to investigation, methodology, and preparation of the original draft, and Edilma Fernandez Fernandez: contributed to investigation, methodology, and preparation of the original draft. All authors approved the final version of the manuscript.

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