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Co-Incineration of Rice Straw-Wood Pellets: A Sustainable Strategy for the Valorisation of Rice Waste

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Received: 8 October 2020; Accepted: 30 October 2020; Published: 3 November 2020

Abstract: Agricultural activities produce an estimated amount of 32.7 MToe/year of residues in EU countries. They are mostly disposed in landfills, incinerated without any control, or abandoned in fields, causing severe impacts on human health and environment. Rice is one of the most consumed crops worldwide with an annual production of 782 million tons according to the Food and Agriculture Organization of the United Nations database. In this context, the EU-funded project LIFE LIBERNITRATE promotes the use of renewable residual sources (i.e., rice straw) to obtain new materials with an added value. The methodology is based on the incineration of rice straw in an own-designed and constructed valorization system. Rice straw/wood pellets are burned in optimized conditions to produce a maximized quantity of ashes with high silica content. These materials will be then used to treat water polluted with nitrates, representing an optimal example of circular economy strategy. In this work, the own-designed valorization unit is described, with special focus on its main constituting elements. The theoretical study of the co-incineration of rice straw and wood pellets identified the optimised combustion conditions. Experimental tests using the theoretical inputs confirmed the most adequate operational conditions (10 g rice straw pellets/min + 10 g wood pellets/min, 6–7 Nm^3/h of air, T = 500 °C) and helped in the definition of improvements on the experimental plant.

Keywords: circular economy; rice straw; co-incineration

1. Introduction

The annual production of paddy rice amounts to 782 million tonnes (2018) according to the Food and Agriculture Organization of the United Nations database [1]. In Europe, Italy is the leading producer with 1,512,241 tonnes of rice produced in 2018. Spain follows in the ranking with a production of 808,167 tonnes. The two main residual products from the rice industry are rice straw (crop residue that remains in fields after harvest) and rice husk (by-product obtained after rice post-processing). For every kilogram of harvested paddy, 1 kg of straw and 0.2 kg of husk are produced [2], which turn into a large quantity of waste to deal with.

Current practices like landfill or incineration present severe environmental and human health problems. Undesirable increased CO_2 emissions and the abandonment on fields constitute an important hazard to fight against, due to the high land and water contamination that the decomposition of the materials exacerbate. Economic problems are also derived from an incorrect management of residual streams as they constitute extra costs for their producers, who need to pay for a correct waste dealing. In this framework, efficient resource use plays a key role in activating economic agents, ensuring a social welfare state and life quality. The development of new strategies for resource supply and for promoting new markets must be paramount in policies all over the European Union.

Several strategies have been proposed to manage rice residues efficiently. The incorporation of rice straw (partially or completely) into the soil remains the most common option. This increases the nutrients contents (N, P and K) resulting in improved yields. However, an incorrect incorporation of rice straw can generate adverse effects a reduction on the N uptake [3]. Rice straw has a poor nutritive value and a high content of silica, which lowers its digestibility, and it is used as an additive rather than an only food source. Straw can also be used in the manufacturing sector, including the production of paper [4], food packaging [5] and activated carbon materials; the construction sector as building material [6] or thermal isolation [7], and as renewable energy source to produce biofuel (bioethanol [8]), biogas [9] and electricity [10].

Rice straw can also be the precursor of new added value material chains. The high percentage of ash in the straw produces a high quantity of residual product when it is submitted to thermal conversion processes. This residue is rich in silica (SiO_2), an inorganic material extensively used in a wide range of applications such as glasses, optical fibres, food additives, electrical and thermal insulators, absorbents, pharmaceutical products [11]. The obtainment of silica from rice straw is one of the objectives of the European project LIFE LIBERNITRATE [12]. This silica will be then activated and used in water treatment for removal of nitrates. In this framework, the obtainment of maximised quantities of good quality ash is a crucial step in the whole process.

In previous work [13], we studied the suitability of rice straw as a renewable energy source through gasification technologies in a spouted bed reactor. The main products were a combustible syngas and a residual carbonous material, char, with nearly no production of ash. In this work, direct combustion of rice straw is carried out with the objective of maximising ash yields. Direct combustion of rice straw presents high energy efficiencies with respect to other thermo-chemical conversions [14]. It entails, however, difficulties due to its low caloric value and its high ash content [15], resulting in low temperatures and flame stability [10], sintering, deposition of material (slagging) or accumulation of unwanted particles on solid surfaces (fouling) due to melting of potassium silicates [16]. It is also important a good control of emissions due to the N and S content of biomass that can lead to undesired toxic compounds [17,18].

Controlled burning of rice straw has been performed in fluidised reactors [16,19] with successful results and minimised slagging problems if the bed temperature was kept below 750 °C. Compared to fluidized beds, boilers are more flexible to fuel type and less sensitive to slagging/fouling. They have been used for heat and power generation with efficiencies of 70–80% using fixed, moving and vibrating grates [20]. Direct combustion rice straw in a furnace at bench scale raised the air temperature from 14 to more than 30 °C above ambient, proving to be sufficient for paddy drying applications [21]. To the knowledge of the authors, no large-scale direct combustion power plants using rice straw have been reported. Small-scale units near farming fields are more common to optimise the collection and transport of rice straw to power plants. The use of the sub-products (i.e., ash, char) can provide extra value to these plants, increasing the degree of profitability, especially at small scale. That is the case of the valorisation of rice straw ashes that can be applied to numerous applications [22] as their use as adsorbent materials.

In this framework, the main aim of this work is to present the design, construction, and operation of an incineration unit for the valorisation of rice straw pellets at pilot scale. Based on this objective, theoretical (Section 2.1) and experimental activities (Section 2.2) have been discussed to finally obtain an optimized functioning of the valorisation unit to produce rice straw ashes (Section 3). This work shows a successful strategy to promote the use of agricultural residues to obtain added value products (energy and ashes) and to foster a circular economy approach in waste management, making these technologies more convenient both in economic and environmental ways.

2. Materials and Methods

The valorisation of rice straw was carried out through two complementary paths. Feasibility studies were initially performed from a theoretical point of view (Section 2.1). The optimized operational parameters were obtained and were the basis for the design of the experimental campaign (Section 2.2).

2.1. Simulation strategy

Modelling activities provide a useful tool for the design and assessment of operational conditions for industrial processes. They also help in defining the technological limits and constraints of a certain process and enable the obtaining of the optimum conditions of work in a low time-consuming way.

The study of the process variables (i.e., percentage of mixture rice straw-wood, air inflow rate, temperature, amount of gas and solid products) was carried out using Aspen Plus© (Bedford, MA, USA). The model has been previously described in [23] with the input data according to the characterization of feedstock shown in Table 1. The model is based on equilibrium assumptions which are retained valid to simulate combustion reactions. Accordingly, these results represent the ideal conditions and can be used to establish the feasible combination of operational variables and define the technological limits.

Figure 1 shows the flowsheet for the simulation of the co-incineration of rice straw and wood pellets. In short, wood and straw pellets are firstly decomposed into their main elemental constituents (blocks: DECOMP/DECOMP2). Two streams containing the composition (DEC1/DEC2) and the heat of decomposition (QD1/QD2) exit the block and are directed to the reaction unit (GIBBS). In it, together with the humidity (H2OI) and combustor agent in stoichiometric conditions (AIR), combustion takes place assuming equilibrium. As a result, one stream containing the material balance (GASSOLID) and another stream with the produced heat of combustion (QCOMB) are obtained. Specific details on this model can be found in [23].

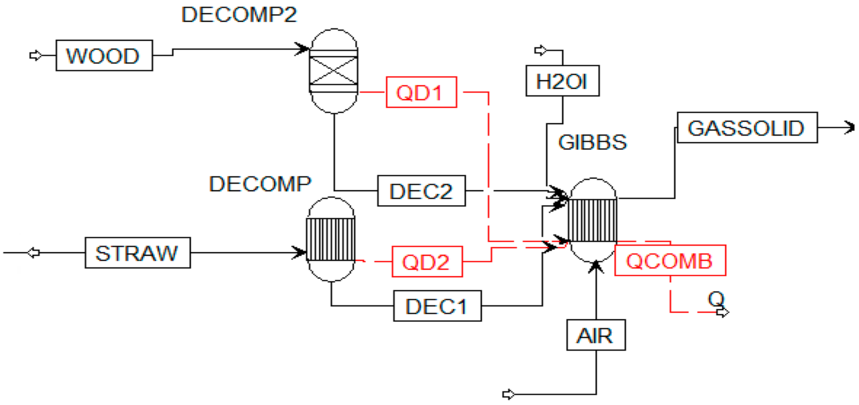


Figure 1. Flowsheet for the simulation of the co-incineration of rice straw and wood pellets.

Material (black streams) and energy (red streams) balances have been discussed. The influence on the initial feed mixture (i.e., percentage of wood pellets) and the air inflow rate has been evaluated to achieve a maximized quantity of high-quality products (gas and ashes) through an energetic self-sustained process.

2.2. Materials and Description of the Incineration Plant

2.2.1. Materials

Wood pellets and rice straw pellets were used as feedstock in the experimental activities. As it will be seen in Section 3.2, wood pellets were required to maintain a positive thermal balance to ensure self-sustained combustion. Wood pellets were commercially acquired to EN-Plus-A1 (Spain).

Rice straw pellets were produced in-site following the indications of the previous lab-scale tests [24]. Table 1 gathers their main physical and physico-chemical [13,15] properties.

Table 1. Physical and physico-chemical properties of wood and rice straw pellets

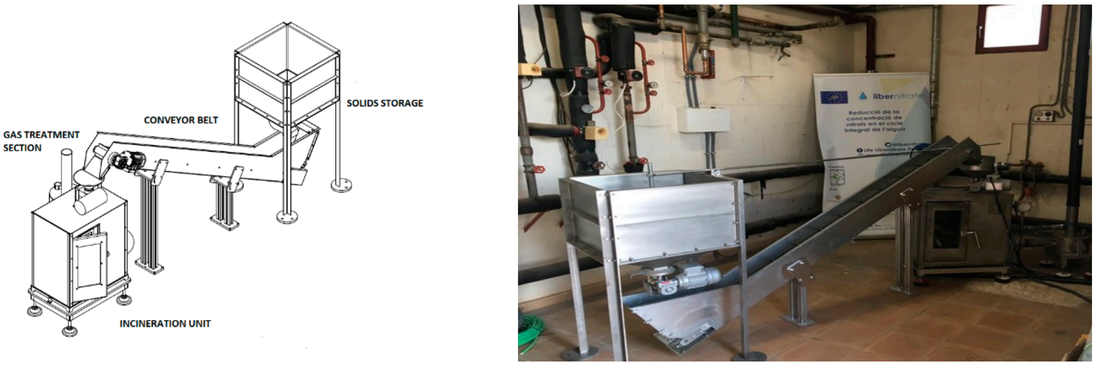
Physical Properties	**Wood Pellets**	**Rice Straw Pellets**
Length (m)	$3.0 \cdot 10^{-3}$	$3.2 \cdot 10^{-3}$
Density (kg/m^3)	600	600
Proximate Analysis (wt. %)	**Wood Pellets**	**Rice Straw Pellets**
Moisture content (MC) [a]	5.1	9.1
Fixed Carbon (FC) [b]	22.4	16.1
Volatile Matter (VM) [b]	77.3	63.3
Ash [b]	0.3	20.6
Ultimate Analysis (wt. %)	**Wood Pellets**	**Rice Straw Pellets**
Ash [b]	0.3	20.6
C [c]	50.1	35.1
H [c]	6.2	4.5
O [c]	43.4	57.8
N [c]	0.2	2.3
S [c]	0.1	0.3
HHV (MJ/kg)	19.5	11.6 [d]

[a] wet basis, [b] dry basis, [c] ash-free basis; [d] according to [25].

The ignition temperature (Ti) and burnout temperature (Tb) of rice straw pellets were also determined from thermogravimetry (TG) and derivative thermogravimetry (DTG) [15]. These two temperatures are crucial for defining the thermal regime of the system, as they indicate the minimum (Ti) and maximum (Tb) process temperatures. A minimum of Ti = 264 °C (oxidative conditions) was necessary to start yielding volatile compounds. It represents the minimum operational temperature needed to start the thermo-chemical processes and therefore, the minimum initial energy requirements of the system. Similarly, the analysis of the thermograms in oxidative conditions provided a Tb = 450 °C which indicated the minimum temperature of the system to ensure complete combustion.

2.2.2. Incineration Plant

The valorisation of rice straw was carried out in an own-designed incineration plant. The design of the unit was done in a highly personalized way considering the main quantitative objectives and the potential technical difficulties. Figure 2 shows the unit in the design stage (Figure 2a) and the final constructed plant (Figure 2b).



(**a**) (**b**)

Figure 2. Design of the incineration plant (**a**) and final constructed plant (**b**).

The quantitative initial requirements set the baseline for the plant dimensioning. The incinerator must produce 120 kg of ash in 170 days. The silo must have sufficient capacity to store enough rice straw and wood pellets for one week. The ash container must have sufficient capacity to store the quantity of ashes daily produced. Input parameters and initial design calculated variables are gathered in Table 2.

Table 2. Input parameters and initial design calculated variables.

Input Data	Value	Unit
Target silica	120	kg
Ash-silica yield [12]	0.8	-
Rice straw-ash yield [12]	0.12	-
High heating value rice straw pellet	11	MJ/kg
Ratio of mass overflow	0.4	-
Time of work	170	days
Daily working hours	8	h
Calculated design values		
Silica	150	kg
Rice straw	1227	kg
Rice straw pellets daily mass flow	10	kg/d
Rice straw pellets hourly mass flow	1.25	kg/h
Storage volume	0.0833	m^3

The plant is composed of 4 elements: storage, conveyor belt, incineration unit and gas treatment section which are explained in detail in the next paragraphs.

Solids Storage

The silo (Figure 3a) is designed to guarantee the storage of feedstock for a complete week of work. The steel unit has a volume of 0.0833 m^3 (base square length = 0.5 m) and has inclined walls to facilitate the descent of pellets. A cylindrical bar (Figure 3b) is in continuous movement creating light vibrations to prevent blocks. The feeding mass flow is controlled by a rotary valve with a diameter of 0.0486 m whose velocity is previously calibrated to meet the desired mass flow rates. A solids level sensor is located between the rotary valve and the lower part of the conveyor belt to avoid feedstock accumulation.


(**a**) (**b**)

Figure 3. Solids storage: Silo main unit (**a**) and cylindrical bar (**b**).

Conveyor Belt

The conveyor belt allows the transport of feedstock from the silo to the incineration unit. Pellets fall from the initial storage and travel upwards on the belt (materials: steel + PVC (transporting side) + TPU (bottom side)) (Figure 4a) upon the top part where they fall into a second storage unit (volume: 0.005 m^3). The belt has a length of 4.55 m and a width of 0.15 m with regularly spaced partitions every 0.175 m. This second silo (Figure 4b) permits a further control on the mass flow rates while acting as an additional security element. As in the previous storage unit, a level sensor is located inside the storage unit to avoid accumulation of feedstock.


(**a**) (**b**)

Figure 4. Conveyor belt: general view (**a**) and second storage unit (**b**).

Incineration Unit

The incineration unit (Figure 5a) is the core part of the system and allows the combustion and recovery of the ashes. It consists of a cast iron combustion chamber with a moving stainless-steel grill (Figure 5b) located in the inner part. This grill will be kept in controlled circular motion during the process to prevent potential slagging effects due to ash melting. In addition, a cleaning brush is placed on the inner surface of the chamber to remove any encrustations on the grill (Figure 5b).


(**a**) (**b**)

Figure 5. Incineration unit: combustion chamber (**a**) and rotary grill and cleaning brush (**b**).

Pellets enter the combustion chamber from the dosing silo through the feeding tube regulated by a rotary valve. Air is conveyed from the outside into the combustion chamber through an air conveyor. Inside this chamber, on its back surface, two ignition glow plugs (250 W each) are installed (length = 140 mm). Downstream the combustion chamber, a smoke fan is installed with a dual function:

(i) to extract the fumes from the combustion chamber towards the outside and (ii) to ensure the entry of air. A box (length = 0.19; width = 0.304 m; height = 0.094 m, for a total volume = 0.0055 m^3) is placed at the chamber's bottom to collect the ashes produced during combustion (Figure 6a). The chamber is closed with an isolated door with a glass window (Figure 6b) to observe the flame and visually control the process. Four temperature sensors are placed inside the chamber (top, gas outlet, hearth of the combustion chamber and ashes collector) whose measures are registered in the controller.

(**a**) (**b**)

Figure 6. Incineration plant: box for ash collection (**a**) and door with glass window (**b**).

Gas Treatment Section

The gas extracted from the combustion chamber is directed to the gas cleaning system (Figure 7). The steel tank (volume = 0.046 m^3) is filled with water that permits the removal of solid particles that could have been carried out in the gas flow as well as a lowering of its temperature. After flowing into the water, the gas leaves the system through the outlet tube and is discharged in the atmosphere.

Figure 7. Gas treatment section.

A portable Gas Chromatograph (GC) (ETG MCA 100 Syn, ETG Risorse e Tecnologia S.r.l, Montiglio M.to (AT)—ITALY) (Figure 8a) is used to determine the composition of the outlet gas (methane, nitrogen, oxygen, carbon dioxide, carbon monoxide and hydrogen). The calibration of the instrument with certified samples was done before the start of experiments. Before entering the GC, the gas goes through a chiller (ETG PSS 100, ETG Risorse e Tecnologia S.r.l, Montiglio M.to (AT)—ITALY) (Figure 8b) to remove tar, water, and ashes to prevent GC damages.

(**a**) (**b**)

Figure 8. Gas Chromatograph (**a**) and chiller (**b**).

Several control elements are used in the different elements of the plant: (i) temperature controllers: Inlet air, combustion chamber, outlet gas, ash container; (ii) feeding inlet flow and belt velocity; (iii) volumetric flow: Inlet air and outlet gas. All these variables are monitored through a controller which can work in an automatic mode following defined working conditions. All the elements of the system follow the fail-safe criterion in which in case of failure they remain in the most secure form.

3. Results

Theoretical results obtained with Aspen Plus© (Section 3.1) were used as the initial set up for the experimental campaign. Once the thermodynamic limits were defined, experimental activities were carried out to establish the deviations of the real unit with respect to ideality and to define the technological limits. This helped in improving the design of the valorisator as it will be explained in Section 3.2.

3.1. Simulation Results

The combustion of rice straw was initially performed considering the initial fixed design parameters and the available equipment. The first assessed variable was the percentage of wood pellet required to achieve a self-sustained thermal regime. The low value of the higher heating value HHV of rice straw pellets (11.6 MJ/kg [15] makes necessary the use of wood pellets (HHV = 19.5 MJ/kg [13]) to increase the heating value of the mixture so combustion can take place without any additional heat source. However, it is important to optimize this percentage as a high value implies lower production of rice straw ashes and lower quality of the product, potentially increasing costs and decreasing yields.

Table 3 shows the simulation of the co-incineration of rice straw and wood pellets at 60 wt. % rice straw/40 wt. % wood pellets (50 g/min of mixture). The inflow air was varied in the range of 1–10 Nm^3/h corresponding to the available experimental characteristics of the air fun. The temperature was fixed at 450 °C defined as the optimum combustion temperature, see Section 2.2.1.

Table 3. Simulation of co-incineration of 60 wt. % rice straw/40 wt. % wood pellets (N_2-free basis).

Air Inflow (Nm^3/h)	**C (kg/h)**	**O_2 (wt. %)**	**CO (wt. %)**	**CO_2 (wt. %)**	**Other (CH_4, H_2, H_2O) (wt. %)**
1	0.60	0.00	0.02	0.60	0.38
2	0.51	0.00	0.02	0.65	0.33
3	0.41	0.00	0.02	0.68	0.29
4	0.31	0.00	0.02	0.71	0.26
5	0.21	0.00	0.03	0.74	0.24
6	0.10	0.00	0.03	0.76	0.22
7	0.00	0.00	0.03	0.77	0.20
8	0.00	0.00	0.02	0.77	0.21
9	0.00	0.00	0.01	0.76	0.24
10	0.00	0.01	0.00	0.73	0.27

These results show that solid carbon reacts with the increasing quantity of air until a value of 7 Nm^3/h when is totally consumed (hypothesis of equilibrium, therefore, ideal conditions). Combustion proceeds until a concentration of CO_2 = 0.77 wt. %, which corresponds to the maximum combustion efficiency. Excess of air is shown at an air inflow above 10 Nm^3/h. From these theoretical results it can be concluded that the studied conditions cannot be applied in the available experimental unit as the maximum capacity of the air blower is 10 Nm^3/h. These results were validated experimentally as it will be described in Section 3.2. A percentage of 50 wt. %of each type of pellet in the mixture was taken as valid to fulfill the material and energy requirements.

Once the optimal feeding mixture was set, efforts were devoted to maximise the inlet mass flow to optimize the amount of produced ash. The simulation of three scenarios were done using the model described in Section 2.1.

Simulation #1: 40 g mixture/min: 20 g wood/min + 20 g rice straw/min

Figure 9a shows the mass composition of the produced gas (left side) and the remaining solid carbon mass flow (right side) at varying air inflow. As expected, the carbon content (red dots) decreased with the increasing air flow because of combustion reactions, whereas O_2 remained equal to 0 until a value equal to 7.5 Nm^3/h (stoichiometric air). Above it, carbon was completely burnt and O_2 was in excess.

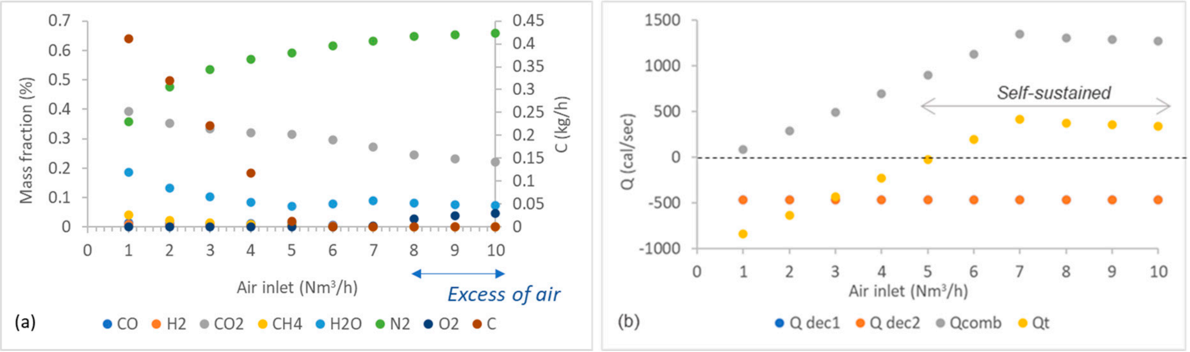


Figure 9. Mass; and (**a**) energy; (**b**) balances for the co-incineration of 40 g mixture/min.

In addition, the energy balance is shown in Figure 9b. The heat of decomposition of both materials (Q dec1 and Q dec2, coinciding blue and orange dots) is removed from the produced heat of combustion (Qcomb, grey dots) to obtain the total produced heat (Qt, yellow dots). The process is thermally self-sustained when Qt is higher than 0, which corresponds to an air flow above 5 Nm^3/h.

In summary, the simulation indicates that a minimum of 7.5 Nm^3/h of air should be fed to the reactor to completely burn all the carbon in the biomass in self-sustained conditions.

Simulation #2: 30 g mixture/min: 15 g wood/min + 15 g rice straw/min

Similarly, Figure 10a shows the mass composition of the produced gas and the remaining carbon mass flow at different air inflow values and Figure 10b shows the corresponding energy balance. In this case, the stoichiometric air flow was found at nearly 6.5 Nm^3/h, whereas the air inflow ensuring a thermally self-sustained reaction was found above 5 Nm^3/h. A minimum of 6.5 Nm^3/h of air should be fed to the reactor to completely burn all the carbon in the biomass through a self-sustained combustion.

Simulation #3: 20 g mixture/min: 10 g wood/min + 10 g rice straw/min

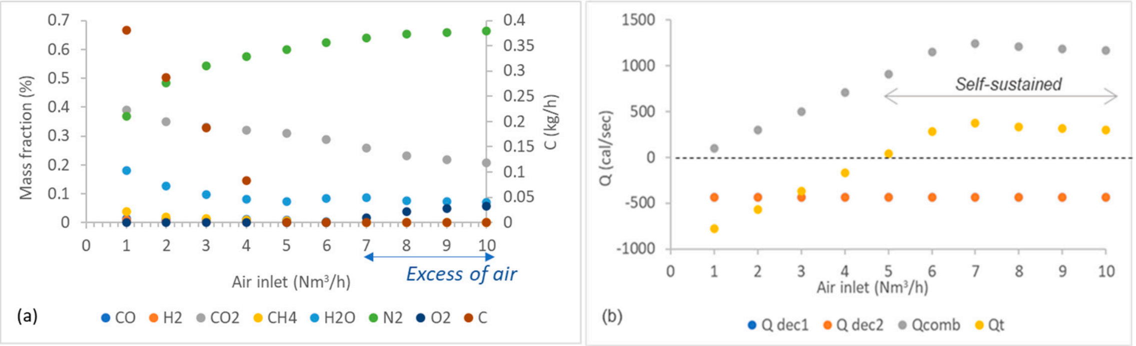


Figure 10. Mass (**a**) and energy (**b**) balances for the co-incineration of 30 g mixture/min.

Lastly, a total quantity of 20 g of mixture/min was simulated. Figure 11a shows the mass composition of the produced gas and the remaining carbon mass flow at different air inflow values and Figure 11b shows the corresponding energy balance. In this case, 5 Nm^3/h was the stoichiometric air flow for complete combustion and 3.5 Nm^3/h was calculated as the air inflow ensuring a thermally self-sustained reaction. The simulation indicates that a minimum of 5 Nm^3/h of air should be fed to the reactor to completely burn all the carbon in the biomass through a self-sustained combustion.

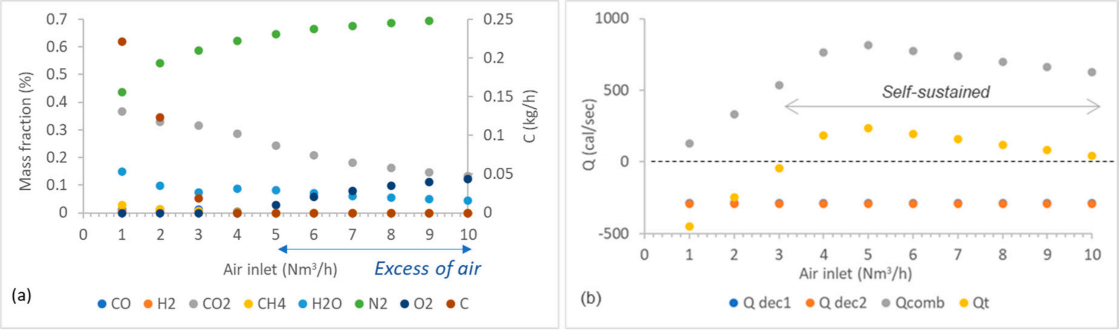


Figure 11. Mass (**a**) and energy (**b**) balances for the co-incineration of 20 g mixture/min.

In summary, Table 4 gathers the results from all the simulations. As expected, higher biomass mass flows need more air to completely burn the mixture and therefore, self-sustained reactions occurred at higher air flows. These values will be reference for the initial settings during the experimental campaign. In addition, it is important to highlight that they represent the ideal conditions and so indicate the thermodynamic limits in the process.

Table 4. Air requirements for the tested mixtures

Biomass Flow Rates	40 g/min	30 g/min	20 g/min
Stoichiometric air (Nm^3/h)	7.5	6.5	5.0
Air for self-sustained combustion (Nm^3/h)	5.0	5.0	3.5

3.2. Experimental Results

The first set of experimental activities were devoted to the investigation of the start-up procedures for the pilot plant and the adequate running of all its elements. Once the procedure was optimized and the correct behaviour of the plant was confirmed, tests were run using the operational parameters from the previous simulation activities (Section 3.1) to assess the deviation of the model with respect to the actual unit. These comparisons allowed to identify potential improvements in the plant to achieve maximised efficiencies.

3.2.1. Start-Up Procedure

An initial quantity of 500 g of wood pellets were used due to its lower ignition temperature and its higher heating value. Shorter times were required for the start-up and, at the same time, higher temperatures were achieved to heat the inner part of the combustor. Ignition of wood pellets occurred after 4 min of heating with the glow plugs. Once the flame appeared, they were shut down and replaced by continuous inflow air. Wood pellets were burnt with air at a mass rate of 10 g/min until a constant temperature of 500 °C was achieved inside the combustion chamber. After 30 min, the feeding was switched to the mixture wood/rice straw pellets.

3.2.2. Testing and Adjusting of the Single Elements

The single elements were individually tested and connected to detect potential malfunctions on the system. Three of the elements required an initial calibration; the two feeding systems and the velocity of the inner grid. The feeding valves were set to meet the required mass flows and the velocity of rotation for the grid was binary adjusted (time ON/time OFF).

3.2.3. Start-Up Tests on the Pilot Plant

Initial start-up tests were performed to evaluate the correct behavior of the whole plant. First, tests using only rice straw pellets were performed, but combustion was not able to be carried out without providing external heat. Then, an initial mixture of 60 wt. % rice straw/40 wt. % wood pellets was tested. As expected from Section 3.1, the system was not able to achieve an auto-thermal regime and after some minutes the flame was extinguished. This experimental validation confirmed that mixtures containing less than 50 wt. % of wood pellets are not appropriate for a successful combustion. After some testing, 50 wt. % of wood pellets was indicated as the minimum value to establish an adequate thermal regime.

Once the percentage of the components of the mixture was set, tests were devoted to evaluating the behaviour of the plant at different feed mass flows and stoichiometric air inflows. In these tests, the comparison between the observed experimental behaviour and the expected theoretical results identified some design and constructional failures. Firstly, certain quantity of pellets remained non-combusted inside the combustion chamber. A closer observation of this fact indicated that some pellets fell inside the chamber but, after some minutes of accumulation, moved out of the inner part of the chamber. For this reason, an extra piece was introduced to prevent the accumulation of pellets outside the chamber (Figure 12a). In addition, ashes tended to accumulate at the bottom of the chamber instead of flying out with the flame. A controlled opening window was done to help ashes falling towards the collecting box (circle in Figure 12a). The calculated stoichiometric air (Table 4) was considerably lower than that observed experimentally and it was decided to introduce an extra isolating layer in the inner part of the chamber and reinforce the junctions with silicone (Figure 12b).


(**a**) (**b**)

Figure 12. Improvements on the furnace cover (**a**) and extra isolating layer (**b**).

After these improvements, the plant finally behaved as expected and experimental activities were then focused to the maximization of the biomass inflow to maximise the produced quantity of ashes. With this purpose, three different mass flows (at 50 wt. % wood/rice straw) were tested: 40 g/min, 30 g/min and 20 g/min.

Test #1: 40 g of mixture/min: 20 g wood/min + 20 g rice straw/min

After one hour of the start-up procedure, the system was thermally stable and the initial wood flow was replaced by the mixture. The chamber contained accumulated unburnt fuel after only 30 min. The flame was not stable, and it abruptly scattered every 5 min disappearing immediately afterwards. The velocity of the wheel was increased to favour the combustion reaction, but the system was even more unstable.

A high quantity of ash in the form of black rice-sized grains was obtained after 2 h. The ash presented large, melted blocks confirming the not successful reaction observed during the tests. A total feed of 2.5 kg (1 kg of rice straw pellets) produced 152 g of ashes, for an efficiency of 15.2%. These results agree with the expected behaviour from the simulations. An air flow of 7.5 Nm^3/h was defined as optimal value in ideal conditions. This represents the technological barrier that must be surpassed and therefore an air flow above that value should be applied in the experimental tests. It is important to highlight that the blower maximum capacity is 10 Nm^3/h, only observed at the initial stage. The air flow remained in 7–8 Nm^3/h which, according to the simulations, was not enough to maintain combustion, as visually observed.

Test #2: 30 g of mixture/min: 15 g wood/min + 15 g rice straw/min

The burning process was more stable than the previous test although some accumulations of unburnt feedstock was sometimes observed. The optimal velocity of the moving grid created some instabilities. The air inflow remained around 6–7 Nm^3/h, just above ideal conditions. After nearly 4 h of continuous work and a total feed of 4.5 kg (2 kg of rice straw pellets), 310 g of ashes were collected, with an efficiency of 15.5%. The produced ashes were finer with respect to Test 1 and had a lighter grey colour.

Test #3: 20 g of mixture/min: 10 g wood/min + 10 g rice straw/min

The process was stable all the time with the grid in continuous light movement. Air inflow remained in 6–7 Nm^3/h and the temperature was kept at around 500 °C. After nearly 3 h of continuous work and a total feed of 3.5 kg (1.5 kg of rice straw pellets), 242 g of ashes was collected, for an efficiency of 16.1%. As expected from the simulations, this mixture was burnt in a successful way, with an increased air supply of 1–2 Nm^3/h with respect to theoretical results. This value was taken as the deviation due to the non-ideality of the experimental plant. The collected ashes were fine and grey indicating a good visual quality.

Very few units have been designed for the valorisation of rice residues with the aim of obtaining both energy and silica. The vast majority use rice husk instead of rice straw due to its higher percentage of silica and easier handling of solids. Although, high quality silica can be produced from rice husk and rice straw, most studies were performed in lab-scale muffle furnaces [26,27] and investigations at a bench scale are scarce. Only Schliermann et al. [28] used a commercial boiler to obtain ashes from pretreated rice husk samples. They showed that continuous and low emissions operations were possible be adjusting the ash handling.

In summary, this work presents one of the first units at pilot scale designed for the obtainment of silica. The feedback between simulation and experimental activities permitted to define the most adequate conditions of work for the co-incineration of rice straw and wood pellets to maximise the quality and quantity of ashes. These ashes are sent to further chemical steps (extraction and activation of silica) which showed promising results in accordance with previous lab scale tests [12] and that will be described in a further work.

4. Conclusions

The obtainment of rice straw ashes using an own-designed valorisation unit has been discussed. The methodology is based on the incineration of rice straw pellets in optimized conditions to produce a maximized quantity of ashes with high silica content. These materials will be then used to treat water polluted with nitrates in the framework of the EU-funded project LIFE LIBERNITRATE, showing an optimal example of circular economy strategy.

The valorization unit has been described, with special focus on its main constituting elements: storage unit, conveyor belt, stove and gas cleaning system. As it is an own-designed pilot scale unit, a preliminary extensive campaign for the selection of start-up and operating parameters of the plant was necessary. This selection was based on theoretical studies of the co-incineration of rice straw and wood pellets under different operating conditions. These results helped identifying potential improvements on the plant and led to the optimised combustion conditions. Successively, experimental tests using the previous theoretical inputs were performed and more improvements were applied until the obtained results were in line with the expected ones. In the end, the most adequate operational conditions were set as 10 g rice straw pellets/min + 10 g wood pellets/min, 6-7 Nm^3/h of air and T = 500 °C.

Author Contributions: Conceptualization; methodology; software; validation; formal analysis; investigation; data curation; writing—original draft preparation, C.M. and D.B.; writing—review and editing; supervision; project administration; funding acquisition, E.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by LIFE LIBERNITRATE project, grant number LIFE16 ENV/ES/000419.

Conflicts of Interest: The authors declare no conflict of interest.

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