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Characterization of the RSU thermal potential, for the generation of Electric Energy, using Hydrothermal carbonization

Caracterización del potencial térmico RSU, para la generación de energía eléctrica, utilizando carbonización hidrotérmica

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Abstract

The zenith of oil and the greenhouse effect are the main reasons why it is necessary to use nonconventional renewable energy (NCRE) sources. Solid urban waste is one of these sources, and the main objective of this research is to determine its main features, including calorific value, as well as the use of modern hydrothermal carbonization (HTC) and hydrothermal liquefaction (HTL) procedures for the generation of energy and electrical power. For this purpose, it was used the sampling data of urban solid waste from the metropolitan Chiclayo area. A calorimetric bomb was employed for measuring its calorific value and the electrical generation potential was simulated. In addition, the main objective was fulfilled, and it was also possible to steadily generate energy and power. This will help to avoid greenhouse gas emissions, and thus contribute to meet the commitments signed by Peru to reduce greenhouse gases, and follow the path to a new sustainable energy matrix, while simultaneously providing a potential solution to the problem of managing solid urban waste, which is the main environmental problem of the city of Chiclayo Peru.

Keywords: Solid, Waste, calorific value, carbonization, liquefaction, generation

Resumen

El cenit del petróleo y el efecto invernadero son las razones que justifican la necesidad de utilizar energías renovables no convencionales (ERNC). Los residuos sólidos urbanos constituyen una de esas fuentes, por lo que la determinación de las principales características, incluido el poder calorífico, fue el primer objetivo de la presente investigación, así como la utilización de los modernos procedimientos de carbonización hidrotermal (CHT) y licuefacción hidrotermal (LHT), para la generación de energía y potencia eléctrica. Se trabajó con los datos de muestreo de los residuos sólidos urbanos del área de Chiclayo metropolitano. Se empleó una bomba calorimétrica para la medición del poder calorífico y la simulación numérica del potencial de generación eléctrica. Además, se obtuvo como resultado el cumplimiento del objetivo principal, y el hecho de que es posible obtener energía y potencia firme, que ayude a evitar las emisiones de gases efecto invernadero, contribuyendo a los compromisos firmados con tal efecto y a seguir el camino a una nueva matriz energética sostenible; a la vez se da una posible solución al problema del manejo de residuos sólidos urbanos, principal problema ambiental de la ciudad de Chiclayo, Perú.

Palabras clave: residuos, sólidos, poder calorífico, carbonización, licuefacción, generación

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1. Introduction

At present, in front of the oil crisis or zenith effect that predicts that planet Earth has reached its oil production limit, humanity is increasingly using biofuels in both traditional combustion processes and in thermochemical processes; hydrothermal carbonization (HTC) and hydrothermal liquefaction (HTL) stand out in the latter [1]. Moreover, the increase in urban solid wastes (USW) in Peru and worldwide can be observed in Figure1.

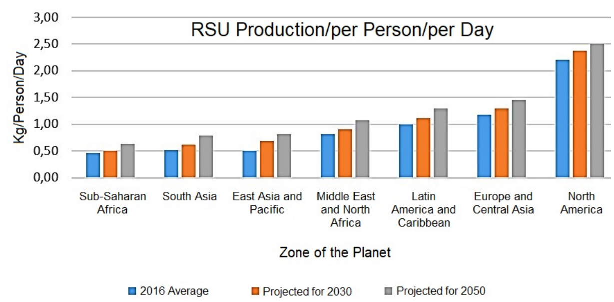

Figure 1. Projected increase in the worldwide generation of urban solid wastes [2]

It should be also highlighted that biofuels are projected as one of the main resources for "green" hydrogen production in the northern region of Peru, because its production is seasonal. Therefore, it is necessary to accumulate it in gaseous state for its further distribution through gas pipeline networks, to assure the energy horizon of northern Peru for the entire 21st century.

These solid wastes (urban solid wastes, rice husks, sugar cane bagasse, stubbles of the mechanized harvesting of sugar cane, coffee draff, among other main types of biomasses) have an energy use, through various procedures that may be classified as: biochemical processes, among which fermentation and digestion (aerobic and anaerobic in controlled reaction tanks) stand out; dry thermochemical processes, which include simple combustion, complex combustion, gasification, roasting and pyrolysis; and wet thermochemical processes, that are part of this study and include gasification, liquefaction and hydrothermal carbonization [3]. This determines that the energy coming from urban solid wastes is increasing worldwide, as well as locally in the north of Peru, as it is shown in Figure 2.

Most of this thermal energy is used for generation of energy and electric power, and to be sold to interconnected or isolated systems (this constitutes one of the main ways through which the use of distributed energy is extending). It is also used for the production of industrial heat, heating and air conditioning. In the 19th century, solid fuels were used for machinery and manufacturing processes [4], whereas liquid fuels were preferred in the 20th century due to their easy logistic distribution and high energy concentration; this enabled movement autonomy. However, at the end of the past century started to become evident what was predicted by engineer Hubbert and his logistic models of depletion of oil worldwide reserves.

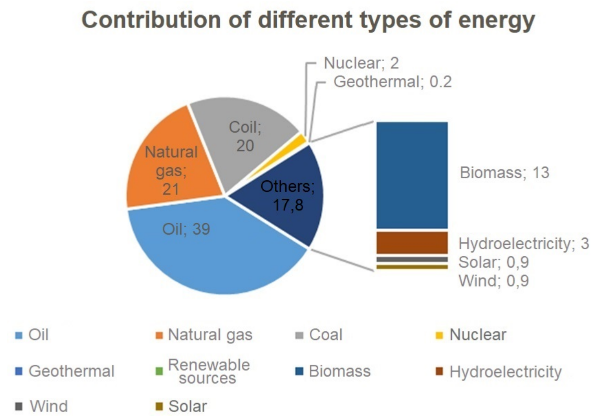

Figure 2. Global contribution of biomass in energy production [5]

Consequently, the 21st century has been devised as the era of gaseous fuels, and it is expected that the second half of this century will shift to the hydrogen as energy carrier, especially "green" hydrogen, which will not be combusted, but transformed into electricity through hydrolysis machines and fuel cells, thus avoiding the emission of greenhouse gases and their concentration in the atmosphere, which constitute the main causes of the atmospheric disturbances known as greenhouse effecto [6].

Likewise, this energy generation is classified as renewable, according to the information depicted in Figure 3, which shows its importance in the global energy matrix. It is also appreciated a decrease in the importance of fossil hydrocarbons, which are in a zenith since the discovery of new oil reserves as well as their production are slowing down, and also the places where such hydrocarbons are being produced are becoming more remote, such as the deep seas and the virgin forests, where the environmental impacts are increasingly larger and thus more difficult to remedy or mitigate. This has caused an inflationary processes in all countries of the world, especially in those that are highly dependent on hydrocarbon fuels, and thus it is important to increase the use of nonconventional renewable energy sources, such as onshore and offshore wind energy, photovoltaic energy in desert areas and in urban buildings for distributed generation, thermal solar with thermal salts, but also urban biomass and rural agricultural biomass, adding value to the products and generating employment opportunities and wealth in the rural sector [7].

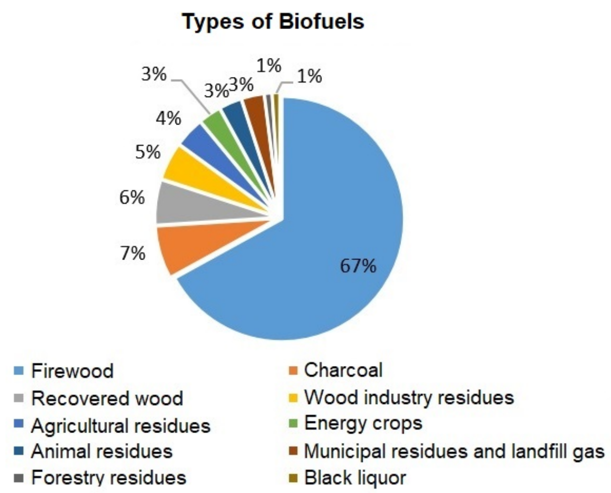

Figure 3. Breakdown of the energy produced by type of biofuel [8]

Figure 3 shows traditional biomass fuels with large environmental impact, such as wood, whose production implies the deforestation of dry woods in northern Peru.

Moreover, it systematically outlines all the possibilities for leveraging existing solid urban waste biomasses; Figure 4 shows the position occupied by hydrothermal processes.

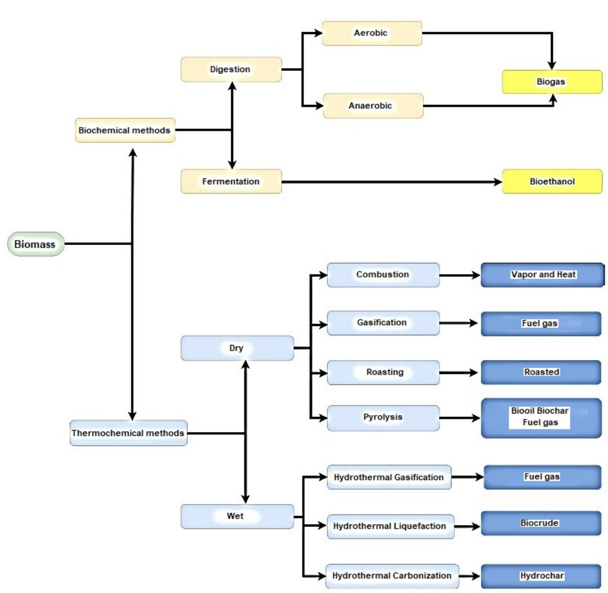

Figure 4. Different methods for leveraging biofuels

In other words, the northern region of Peru has a long history of biomass usage (especially sugar cane bagasse) in combustion processes in bagasse cauldron furnaces in sugar agricultural companies, gasification of rice husk in over a hundred of big rice mills existing in the region, as well as in anaerobic pyrolysis prototype processes for generating electric power and heat in industrial processes. This enables achieving costs savings in production and mitigation of the environmental impacts on the air quality in the concentration at the receiving body as well as at the emitting points (chimneys and others), and in turn end up with the problem of disposing the rice husk excess, which are discharged in dumps that pollute air, the water of lake ecosystems and the soil itself, which losses its superior agricultural properties [9].

In addition, it should be taken into account that hydrothermal carbonization (HTC) is a process that occurs in the temperature range from 200 a 300 ºC, at the corresponding vapor pressure, with reaction times that go from two to several hours. The main objective of hydrothermal carbonization (HTC) is to produce a carbon-rich solid known as hydrochar [10].

In general, during this process, carbohydrates are hydrolyzed and completely dissolved in the liquid phase and then repolymerized, giving rise to hydrochar and some subproducts such as organic acids and water [11].

All these works were conducted under the control and supervision of the environmental entities responsible for processing organic solid wastes in the city of Chiclayo, with the perspective of using the residues from agricultural activities, such as sugar cane bagasse, which has had an energy use in the zone for more than 140 years due to the industrial sugarcane activity.

2. Materials and methods

The lower heating value of the USWs was determined. The equipment and instruments used to determine the calorific value of the solid wastes sampled are described below.

Constant volume calorimetric bomb. It consists of a stainless-steel cylinder which is put in an isothermal bucket with a capacity of more than two liters of water. It also has a mixer, driven by a squirrel cage electric motor, that evens the temperatures [12], to prevent heat from leaking to the exterior by conduction, convection or radiation. Errors when adjusting the jacket temperature should be avoided during the tests, to maintain a high precision in the measurements. The bomb is sealed by a precision machined screw cap that is closed manually and seals automatically, to enable the pressure increase [13].

Regarding the assembly, it will be carried out in stages in the following sequence:

The bucket should have a minimum volume of two liters, and it should be verified that the initial temperature is 25 ºC, according to the ASTM D240 – 09 standard. In the case of the city of metropolitan Chiclayo it is not necessary a preliminary heating, because that is the annual average temperature. Afterwards, the USW pellet is prepared through a pressure compacting process in special machines manufactured by the university; then, the calorific value is calculated and the thermal wire that will be connected to the electrical electrodes is installed. Once the bomb is closed, it is filled with oxygen at 99% under the appropriate supervision, due to the risks associated to the transfer; then, it is connected to the electric source, causing the complete combustion of the test material.

A precision thermometer, with a resolution of 0.01 ºC, and an OHAUS electronic precision scale, with a resolution of 0.00001 grams, were also used.

The fuel mass is between 0.9 grams and 1.1 grams, at an operating pressure of 380 psi that is obtained pumping oxygen.

The data should be collected every five minutes, and after the fuel is ignited it should be collected at 15, 30, 45, 60, 75, 90 and 115 seconds.

All pertinent safety measures should be taken, as expressed in the corresponding IPERC matrices; such measures include the presence of fire extinguishers, ventilation systems to prevent the concentration of explosive gases and control of biological risks.

As a method to characterize the calorific value of the organic solid wastes of metropolitan Chiclayo during the 2016-2020 period, it was made a sampling to obtain 100 kg of solid wastes in the proportion shown in Table 1, which coincides with what was determined by Rodríguez [14].

Table 1. Percentage production of solid wastes

Item	City	Percentage
1	Chiclayo	52,85%
2	José Leonardo Ortiz	22,93%
3	La Victoria	9,27%
4	Pimentel	2,93%
5	Reque	1,71%
6	Pomalca	3,46%
7	Monsefú y Eten	6,85%
	Total	100,00%

The second objective of this research work was to demonstrate the technical feasibility to experimentally carbonize moist biomass, and make combustion with mineral coal to produce energy. It should be taken into account that hydrothermal carbonization is the process through which a material is subject to high temperatures, immersed in a moist environment, without allowing that boiling occurs. It has been detected that this type of reaction enables carbonizing solid lignocellulosic materials, but also polysaccharides dissolved in water, obtaining as products nanostructured carbonaceous materials [15].

The particular requirement of an aqueous medium is very useful for the application of this method to residues that, precisely, have a high content of water. In fact, without this method such residues would require various drying steps to be able to carbonize them in dry conditions and directly.

Similarly, it should be pointed out that the development of the hydrothermal carbonization (HTC) technology and its application at an industrial level, was initially possible thanks to the scientific work conducted by Friedrich Bergius approximately one hundred years ago, which was complemented by subsequent developments conducted by Max Planck [16], among others; it should be indicated that it is also an objective the design and construction of a biomass hydrothermal carbonization plant at an industrial scale, as part of the R + D activities of the process.

The great strength and opportunity posed by the HTC process is that it occurs in an aqueous medium, and thus the moist of the source biomass is not a problem. Therefore, it is possible to add the calorific value of the source biomass in a biofuel solid and, conversely, be able to generate fertilized water that may be reused in watering activities [17].

For the ideal case of biochar production, it will be followed the procedures carried out with various alternatives of solid wastes processed in the city of Chiclayo, which will be plotted and used to measure the efficiency of the hydrochar production process. The moist biomass was weighted at the inlet of the process, after the autoclave and runoff process, and finally after it is passed through the furnace.

The precision scale that will be used for weighting the biomass was cleaned; the calorific value of such biomass will be further measured.

A biomass pellet with urban solid wastes was obtained through compaction, based on the samples collected.

The calorimetric bomb was purged with oxygen, its electrodes were cleaned and the calibrated ignition wire was installed.

The biomass pellet was placed inside the calorimetric bomb, and the electric electrodes were connected to the power source to produce the spark and the corresponding combustion.

The isothermal jacket was filled with water, and the mixer was activated to even the temperatures.

The bomb was placed in the isothermal jacket, and the thermometer that will measure the temperature increase in the water was connected.

The calorimetric bomb was filled with oxygen, at a pressure of 20 bars, and the excess was eliminated.

The electrodes were electrically connected to the corresponding combustion and periodical measurements of temperatures, which were recorded.

The electrodes were disconnected, the oxygen remains were purged, the electrodes were disassembled, and the calorimetric bomb was cleaned.

3. Results and discussion

3.1. Results

Four subsamples were collected, two from Chiclayo, one from José Leonardo Ortiz and another from La Victoria. Five calorimetric tests were conducted per sample. Table 2 shows the arithmetic mean and standard deviation of the results obtained for each of the tests conducted, at normal conditions (temperature: 20 ºC, pressure: 1 atm).

Table 2. Descriptive statistics of the lower heating values – KJ/Kg

Placer	N.° of Sample – Dry					Mean	Standard
	Lower calorific value						
	1	2	3	4	5		
Chiclayo 1	7,150	6,970	7,210	7,145	7,110	7,117	0,090
Chiclayo 2	7,230	7,150	7,190	7,230	7,240	7,208	0,038
JLO 1	6,970	6,890	7,050	7,040	7,050	7,000	0,070
Victoria 1	7,070	7,030	7,050	6,950	6,940	7,008	0,059

The question here is if the composition and, hence, the calorific value of the samples is the same. Then, it is formulated the hypothesis that the USW populations of the different centers have the same calorific value; for this purpose, it is considered the hypothesis $\mu_x = \mu_y$, with five degrees of freedom (n = 5), which according to the tables and a confidence margin of 95% determines a significance level $\alpha = 1,8595$ (equation (**??**)).

$$t = \frac{\left(\overline{X} - \overline{Y}\right) - (\mu_X - \mu_Y)}{\sqrt{\frac{S_X^2 + S_Y^2}{n}}} \quad (1)$$

Was used, which yields 0.9315 < 1.8595 after substituting the values; thus, the hypothesis is rejected. Hence, it is determined that the different USW populations have different calorific value.

Regarding the technical feasibility of experimentally carbonizing moist biomass and make combustion with mineral coal to produce energy, according to the results verified in the literature it has been obtained energetically densified biomass, specifically biochar (homogeneous black powder), having as raw material biomass from urban solid wastes, with energy performance above 40%. The biochar obtained has a calorific value larger than the calorific value of the original biomass (> 15%), and a moisture of 3% after filtering. The hygroscopicity decrease is visible (a reduction of up to 50%), which agrees with what was stated by Peng [18].

It should be added that the combustion tests with mineral coal that were carried out in the laboratory, evidenced interesting reductions of 10% and 30% in the emissions of NO_x and SO_2, respectively. The results obtained are described in Table 3.

Table 3. Conversion factors of moist USW by stages of the process

Stage/Sample	1 (kg)	2 (kg)	3 (kg)	4 (kg)	5 (kg)
Initial weight	8	8	8	8	8
Weight after autoclave and pressing	0,6	0,62	0,59	0,6	0,61
Weight after drying in the furnace	0,56	0,57	0,56	0,57	0,57

Average calorific value of the material dried in the furnace:

The lower heating value (LHV) of biochar is 29,200 KJ/kg, from which the energy potential of the city of metropolitan Chiclayo may be estimated using the following equation (2). This is summarized in Table 4.

$$PC\ Biochar\ (TJ/dia) = P\ RSU\ (Tm/Dia) \cdot PCIBiochar \quad (2)$$

Table 4. Biochar production per zone of metropolitan Chiclayo

Item	City	Production of RSU Tm/Día	Calorific potential of the Biochar TJ/Día
1	Chiclayo	211,40	6172,88
2	José Leonardo Ortiz	91,72	2678,22
3	La Victoria	37,08	1082,74
4	Pimentel	11,72	342,23
5	Reque	6,84	199,73
6	Pomalca	13,84	404,13
7	Monsefú y Eten	27,40	800,08
	Total	400,00	11 688,01

By means of a Rankine thermodynamic cycle with an average efficiency of 40% (a combustion efficiency of about 30% was obtained previously), this biochar enables to obtain the averages of usable energy and power specified below.

Energy: 16,23 Gwhr, for a plant factor 0,90
Power: 591 Mw base
1,000 Mw peak

Since this is the power delivered to the electric generation system, totally scalable, it is prioritized the delivery of power at peak hours because they have a greater selling price both as energy and as power, in order to maximize the income and profitability of the entrepreneurships to be carried out.

This energy is produced with minimum emission of greenhouse gases, sulfur and dangerous and toxic compounds, such as furans, etc., and helps to eliminate practices that are dangerous from the environmental point of view, such as the burning of urban solid wastes outdoors, in the current municipal dump, where the existing hills known as seven roofs save the city of Chiclayo from environmental pollution; the purpose is to eliminate such municipal outdoor dump existing in the Reque pampas, in the southern area of the city of metropolitan Chiclayo.

Table 5 shows the projections in time of energy production due to biochar, which implicitly includes the variations of vegetal growth and USW composition in the different areas of the metropolitan Chiclayo.

Table 5. Projection of biochar production at the different places of metropolitan Chiclayo

	Production of Biochar in the medium term TJ/day						
Year	Chiclayo	JL Ortiz	LA Victoria	Pimentel	Reque	Pomalca	Monsefu
2023	6172,88	2678,22	1082,74	342,23	199,73	404,13	800,08
2024	6271,65	2671,52	1100,06	347,71	202,93	410,60	812,88
2025	6371,99	2664,85	1117,66	353,27	206,17	417,17	825,89
2026	6473,94	2658,18	1135,55	358,92	209,47	423,84	839,10
2027	6577,53	2651,54	1153,72	364,66	212,82	430,62	852,53
2028	6682,77	2644,91	1172,18	370,50	216,23	437,51	866,17
2029	6789,69	2638,30	1190,93	376,43	219,69	444,51	880,03
2030	6898,33	2631,70	1209,99	382,45	223,20	451,62	894,11
2031	7008,70	2625,12	1229,35	388,57	226,77	458,85	908,41
2032	7120,84	2618,56	1249,01	394,79	230,40	466,19	922,95

It should be noted the continuous growth of the projection in the Chiclayo district, the reduction in the José Leonardo Ortiz district and the plateau in La Victoria district. These trends may be also visualized in Figure 5.

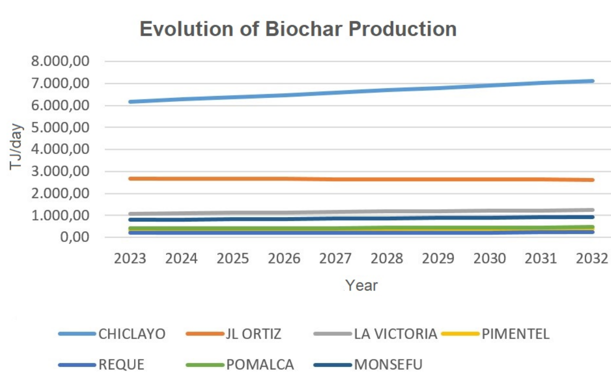

Figure 5. Evolution of Biochar production along time

The biochar production in the carbonization process depends on a series of factors, among which it can be mentioned the average temperature of the drying furnace during the different drying phases (see Figure 6).

There is also an increasing academic interest on hydrothermal processes, which is expressed in the growth in the number of works published about the topic. It is perceived that the interest on HTC has increased with the purpose of creating last generation carbonaceous materials, over the purpose of producing solid biofuels [19].

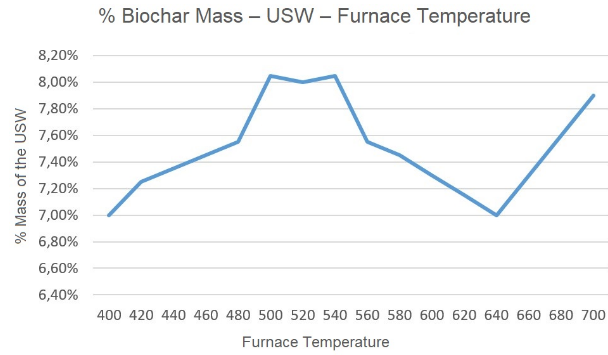

Figure 6. Biochar production from USW, as a function of the furnace temperature

3.2. Discussion

This research work enabled to determine the importance of USW in the metropolitan city of Chiclayo, as well as its energy potential. For this purpose, the urban solid wastes were thermally characterized through samples, and their lower heating value was determined as well. It was also reviewed the production of coal through the hydrothermal carbonization process, with production ranges of 0.56 kg of biochar for every 8 kg of USW, concentrating its calorific value from 7100 KJ/kg to 29 200 KJ/kg, preventing the emission of greenhouse gases, and furans and other poisonous gases, as well as generating job opportunities directly and indirectly, coinciding with what was expressed by DosSantos [20].

Also based on experiences in other areas [21] with similar results regarding the biochar production from USW through the hydrothermal carbonization method, it was observed that it depends on factors such as the furnace temperature (with variables results of increasing and decreasing production), retention time, heating velocity, solution-biomass ratio, working pressure, use of homogeneous or nonhomogeneous catalysts, velocity of combustion gases, among others. Only the first criterion, i.e., the furnace temperature, is analyzed, and it was observed that the biochar production varies with temperature, reaching its maximum production at temperatures of 520 °C and 600 °C [22].

It is important to analyze the thermal efficiency of these products and analyze residual ashes, compared to the results obtained by Trujillo [23] which indicate that the performance of poultry biochar is constant with respect to temperature. Last but not least is the energy availability, which can be summarized in approximately 16.23 Gwh per working day of the solid wastes collection system in the metropolitan area of the city of Chiclayo.

4. Conclusions

It is confirmed the need to leverage the energy capacity of USW and other residues from agricultural production for the generation of electric power, to achieve a sustainable energy matrix and a reliable and stable Peruvian electric system.

The lower heating value of moist urban solid wastes in metropolitan Chiclayo (in the districts of Chiclayo, Leonardo Ortiz, La Victoria, Pimentel, Pomalca, Reque, Monsefú and Eten ciudad y Puerto) , and it is possible to produce biochar with the assistance of a calorimetric bomb through the thermochemical process of hydrothermal carbonization; this biochar has a thermal and electricity generation potential of 16.23 GWh per day and a power between 591 and 1000 MWh, and has also different uses in the biochemical industry.

The optimal temperature to achieve the highest performance in biochar production is in the range from 520 to 700 ºC, obtaining also the entire energy potential.

The energy potential is not the same for the urban solid wastes coming from different places.

On the other hand, it is recommended to continue with the analyses, now focused on the analysis of the environmental quality of the ashes (less presence of sulfur and heavy metals), as well as to implement the design and construction of a biomass hydrothermal carbonization plant at an industrial scale.

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