

Experimental Study on Sugarcane Bagasse Pyrolysis in a Thermochemical Processes Pilot Plant

Nahieh T. Miranda*, Lucas M. Dianin, Daniel S. Fernandes, Rubens Maciel Filho, Maria Regina Wolf Maciel

Laboratory of Optimization, Design, and Advanced Control (LOPCA)/Laboratory of Development of Separation Processes (LDPS), School of Chemical Engineering, University of Campinas, Brazil.
nahieh.tmiranda@gmail.com

This paper investigates the sugarcane bagasse pyrolysis for bio-oil and biochar production in a pilot plant that was designed to perform the gasification process. After some modifications of changing the temperature of fluidized bed reactor and the catalytic reforming reactor, the fast pyrolysis process was performed at 500–600 °C using a fluidized bed reactor (air flow rate: 20–70 L.min⁻¹) under atmospheric pressure, with sugarcane bagasse feeding (2–3.5 kg.h⁻¹) with particles size less than 1.18 mm. Fluidization tests were performed with air feed (oxidative pyrolysis), to guarantee the fluidization is occurring, finding that the minimum fluidization rate was 22 L.min⁻¹ (minimum velocity of gas: 6.3 cm.s⁻¹). The residence time was 7 seconds (ratio between empty reactor volume by fluidizing gas flow). The highest bio-oil yield of 7.43 wt. % was obtained at 500 °C, with a bagasse flow rate of 3.5 kg.h⁻¹ and 25.93 L.min⁻¹ of air flow rate, and this low yield can be explained by the inefficient heat exchanger used. On the other hand, biochar yield achieved 35.88 wt. % using a temperature of 570 °C, 3.1 kg.h⁻¹ of bagasse flow rate, and 28.26 L.min⁻¹ of air flow rate. Considering this pilot plant has never operated in a pyrolysis mode, these results demonstrate that pyrolysis can be applied to this pilot plant, being versatile for different types of processes with a great potential for biochar and bio-oil production besides the high gas production.

1. Introduction

The unceasing search for alternatives to fuels associated with environmental impacts (fossil fuels) has been facilitated by the vast availability of raw materials to be processed and transformed into biofuels/energy. Among the available raw materials, the biomass generated by the sugar-alcohol industry – sugarcane bagasse – has deserved prominence, since Brazil is the largest producer (29 million tons in 2018/2019 harvest) and exporter (20 million tons – 2018/2019 harvest) of sugar in the world, and the largest producer and consumer of ethanol (33 million m³ – 2018/2019 harvest) produced from sugarcane in the world, leading to the generation of a massive amount of bagasse; approximately 168 million tons of bagasse produced in the 2018/2019 harvest (UNICA, 2019). Although the leading destination of bagasse is as boiler fuel for energy cogeneration, the amount of bagasse that remains generates a problematic control of this residue (Islam; Parveen; Haniu, 2010). In this context, new technologies for the reuse of bagasse have been investigated. Then, the pyrolysis process has been one of the most efficient methods of biomass conversion due to its ability to produce high proportions of fuel that can be used to power multiple engines (Papari; Hawboldt, 2015), among others. Several studies have emphasized the use of sugarcane bagasse for the pyrolysis process for bio-oil and biochar production (Montoya et al., 2015); (Balasundram et al., 2019). Pyrolysis consists in decomposing organic matter using temperature in the absence of air (oxygen) or an amount that does not allow complete combustion to occur (oxidative pyrolysis) (Balat et al., 2009), but can produce both liquid (bio-oil), solid (coal – biochar), and gas products (Gollakota et al., 2016) (combustible gases, such as methane, hydrogen, carbon dioxide, carbon monoxide, ethane, ethylene, propane, propene, among others) (Asadullah et al., 2007). Thermal decomposition occurs very rapidly, in a fraction of seconds, as it is the indispensable elemental chemical reaction before combustion and gasification processes (Gollakota et al., 2016). Depending on the operating conditions of the process, such as temperature, heating rate, particle size,

and solid residence time in the pyrolysis reactor, the pyrolysis process can be conventional (slow pyrolysis), fast, and flash (Naik et al., 2010). Fast pyrolysis is the one that obtains the highest yield of the liquid product (bio-oil, the product of interest), involving high biomass heating rates (Goyal et al., 2008). Therefore, the present study aims at performing the sugarcane bagasse fast pyrolysis for bio-oil and biochar production in a pilot plant that was designed to perform the gasification process.

2. Methodology

2.1 Pilot Plant – Pyrolysis

Figure 1 shows the medium-sized pilot plant (3 meters length x 3 meters wide x 5 meters height) modified to operate pyrolysis. Before all modifications to operate pyrolysis, this pilot plant was used to perform gasification (Figueroa et al., 2017). Some modifications were made so that the gasification pilot plant was able to perform the pyrolysis process, but it did not lose the possibility of performing gasification, seeking the versatility of this pilot plant of thermochemical processes. The pyrolysis is possible since these thermochemical processes present similarity and versatility in the types of reactors that can be used, besides the pyrolysis process is present at the beginning of the gasification process, being the first reactions that occur when the material is submitted at elevated temperatures. No equipment was modified or removed from the pilot plant. The modifications were restricted to operational conditions concerning the process that was already done in this plant by Figueroa et al. (2017). The catalytic reforming reactor was used by Figueroa et al. (2017) at 800 °C, aiming to achieve a higher gas yield. However, as this would be unfeasible for the pyrolysis process since there would be a loss of liquid yield, the temperature of this reactor was lowered to 400 °C. The plant was divided into 08 operating areas to facilitate understanding the location and operation of each equipment, which was guided by Turton et al. (2012): 100 (Sugarcane bagasse feeding), 200 (Gas feeding), 300 (Thermochemical Process – Pyrolysis), 400 (Solids separation), 500 (Steam catalytic reform), 600 (Bio-oil recovery), 700 (Gas cleaning), and 800 (Gas combustion). The characterization of sugarcane bagasse that was fed into this pilot plant can be seen elsewhere (Miranda et al., 2019).

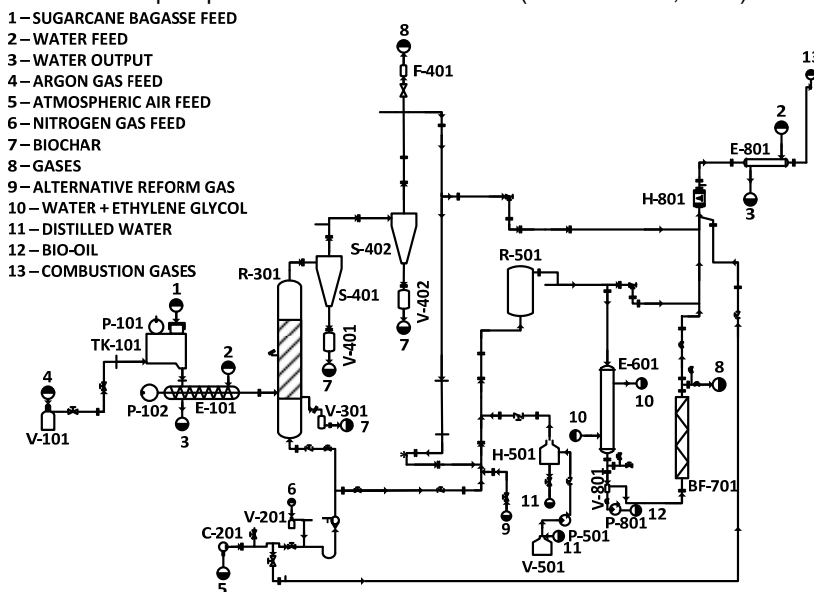


Figure 1: Pyrolysis pilot plant flowchart (Translated from Miranda et al. (2018))

In area 100, sugarcane bagasse is fed into the feeding unit – tank (TK-101), equipped with a pump (P-101) to move the stirring blade and keep the bagasse agitating. The feeding unit is sealed with Argon gas (V-101) to prevent gases produced in section 300 (reactor – R-301) from returning to the tank. Below this unit, there is a conveyor thread coupled with a condenser (E-101) and a pump (P-102) to feed the bagasse into the fluidized bed reactor (R-301). The condenser of this thread was fed with tap water. Area 300 covers the gas supply: atmospheric air from the compressor (C-201). Area 300 can be considered the most important area of the pilot plant as it is where the pyrolysis process takes place in the fluidized bed reactor (R-301). Just below the reactor is the first biochar vessel (V-301). The gases and vapors produced in the reactor are sent to two cyclones (Area 400): S-401 and S-402. The solids charged with gases and vapors are collected in vessels V-

401 (2nd vessel) and V-402 (3rd vessel), which are located below the cyclones. Above the second cyclone, there is a place to produce a flame (F-401) for testing gas production, but it has always been kept closed to prevent accidents. After this second cyclone, there are two more alternative streams: 1st) sending the gases directly to combustion (H-801); and, 2nd) sending to the catalytic reforming reactor (R-501) and bio-oil condenser (E-601). As the objective was the pyrolysis process, the second alternative was always chosen. Thus, the stream passes through the catalytic reforming reactor (R-501 – area 500), which has the alternative of receiving water vapor from the vaporizer (H-501), coming from the water vessel (V-501) and a pump (P-501). In this reactor, steam reforming and water-gas-shift reactions occur when the reactor operates at high temperatures (> 800 °C) in the gasification process. Since the objective was the pyrolysis process, the catalytic reforming reactor was maintained at 400 °C to avoid those reactions. The next area (600) considers the bio-oil condensation process containing a condenser (E-601) coupled to an ultra-thermostatic bath with ethylene glycol and distilled water mixture feed. The V-601 vessel holds the stored bio-oil, which was pumped to another vessel by a peristaltic pump (P-601), upon opening the valve. Then, there is a bag filter (BF-701 – area 700) for cleaning the gases and the combustor (H-801 – area 800) for combustion of the unrecovered gases. These gases pass through a condenser (E-801) to cool them to be disposed of in the atmosphere. This pilot plant also consists of hydraulic, electrical, and gas installations for the heat exchangers, power of the pilot plant from an electrical panel, and gas supply and outlet, respectively (Figuerola et al., 2017).

2.1.1 Hydraulic installation

There are 3 heat exchangers in the pilot plant. They were kept in the same way as Figuerola et al. (2017).

- In the conveyor thread, which decreases the temperature that can be raised by the friction that occurs between the conveyor thread and the bagasse being fed.
- In the bio-oil condenser, which is responsible for obtaining bio-oil, where the bio-oil is transformed from steam into liquid. In this part, it was noted the need to use an ultra-thermostatic bath instead of using tap water, with temperature control, since the heat exchange should be efficient for the bio-oil condensation. The bath was programmed to remain around -5 °C using a mixture of distilled water (20 %) and ethylene glycol (80 %).
- In the exit of gases to the atmosphere, which is essential for the cooling of gases that are eliminated into the atmosphere.

2.1.2 Electrical installation

There is an electrical cabinet external to the laboratory that provides power for the pilot plant control panel, which is the equipment that powers the rest of the plant. The purpose of this control panel is to control all heat supply resistances, thermocouples for temperature checking, stirring blade in the feeding tank, conveyor thread, pumps, and air compressor. Electrical resistances, which are in the form of shrouded cables and are placed around the plant pipes, are used to heat the pilot plant. Equipment requiring heating (air heater, pyrolyzer and cyclones, the tubing between cyclones and catalytic reforming reactor, catalytic reforming reactor, catalytic combustor, and vaporizer) were wrapped in thermal insulation glass wool, avoiding significant heat loss due to thermal exchange with the environment. All the equipment previously mentioned has 6 external thermocouples plus 4 thermocouples, which check the internal temperatures of the pyrolyzer, catalytic reforming reactor, catalytic combustor, and vaporizer.

2.1.3 Gas installation

Argon is used to seal the feeding unit at a low flow rate for a few minutes before activating the conveyor thread, preventing reactor gases from returning to the tank. Nitrogen gas was also considered to be used as a fluidizing gas (Miranda et al., 2018), but the atmospheric air demonstrated better results of fluidization.

2.1.4 Exhaust gases

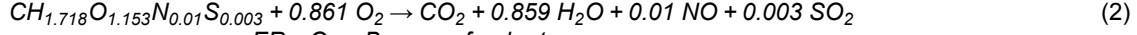
Among the gas production, there is the presence of undesirable gases, which must, therefore, be eliminated from the plant in some way. For this, the plant has a catalytic combustor, which performs the complete combustion of them. Therefore, there is a safe outlet for the atmosphere in the catalytic combustor.

2.2 Operating conditions – Determination of air and bagasse feed rates

Since the fluidized gas is atmospheric air, it was necessary to study which conditions would be indicated to prevent combustion from occurring. Then, it was necessary to calculate the ER (equivalence ratio) (Eq(1)) variable. The air ratio must be worked with values very close to zero (0.01 to 0.18) to avoid gasification and combustion. First of all, to perform the ER calculation, it is necessary to determine the molecular formula of the bagasse. Therefore, the ultimate analysis of the sugarcane bagasse, reported elsewhere (Miranda et al., 2019), was used to find the molecular formula of bagasse ($CH_{1.718}O_{1.153}N_{0.01}S_{0.003}$). Secondly, the amount of oxygen required for complete combustion (Eq(2)) and the ER ratio (Eq(1)) can be determined. This calculation

is essential for defining two operating conditions: bagasse feed rate, which can be varied from 0.5 to 3.5 kg.h⁻¹, and air flow rate for bed fluidization (Eq(3)).

$$ER = \frac{\frac{\text{Air fed to the reactor (dm}^3\text{)}}{\text{Amount of bagasse (kg)}}}{\frac{\text{Stoichiometric theoretical air for complete combustion (dm}^3\text{)}}{\text{Amount of bagasse (kg)}}} \quad (1)$$



$$\text{Air flow rate (L.min}^{-1}\text{)} = \frac{ER \times O_2 \times \text{Bagasse feed rate}}{60} \quad (3)$$

After all these calculations, Table 1 brings the operating conditions used to perform sugarcane bagasse fast pyrolysis in the thermochemical processes pilot plant.

Table 1: Operating conditions of sugarcane bagasse fast pyrolysis

Run	Temperature (°C)	ER	Bagasse feed rate (kg.h ⁻¹)	Air flow rate (L.min ⁻¹)
1	500	–	2.0	40.00
2	500	–	2.0	40.00
3	600	–	2.0	70.00
4	560	–	2.0	40.00
5	600	–	2.0	40.00
6	600	0.17	2.7	26.16
7	570	0.16	3.1	28.26
8	500	0.15	3.5	29.92
9	500	0.13	3.5	25.93
10	520	0.17	3.5	33.91
11	600	0.18	2.0	20.00

Note that some tests were performed with a higher air flow rate (runs 1 to 5) to demonstrate that the plant is very versatile. However, in these runs, a higher amount of oxygen was used, which is why the ER is not demonstrated, being higher than 0.18.

2.3 Fluidization tests

Figuroa (2015) determined the average diameter of Sauter and the density of the sand used in this reactor bed. Therefore, for fluidization calculations, these data were used. To check the pressure drop, U-tubes were used, with water at room temperature as fluid. Basu (2015) and Scala (2013) recommend that the fluidization test should start at a maximum air flow rate and gradually decrease. As gas flows through the reactor solids, it exerts a drag force on the particles, causing a pressure drop in the bed. This pressure drop across the fixed bed height of uniformly sized particles can be correlated by the Ergun Equation (1952) (Eq(4)) (Basu, 2015); (Scala, 2013). However, instead of solving the Ergun Equation and finding the theoretical bed pressure drop (ΔP), fluidization tests were performed with an air supply at 25 °C and pyrolyzer at 450 °C, considering that all reactions always exceed this temperature, maintaining the validity of the minimum fluidization velocity found.

$$\frac{\Delta P}{L} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu U}{(\phi d_p)^2} + 1.75 \frac{(1-\varepsilon) \rho_g U^2}{\varepsilon^3 \phi d_p} \quad (4)$$

Where L is the fixed bed height; ε is the bed porosity (dimensionless); μ is the dynamic viscosity of the fluid (kg/m²s); U is the surface velocity of the fluid (m/s); ϕ is the sphericity of the solid particles of the bed (dimensionless); d_p is the average diameter of the solid particles of the bed (m); and, ρ_g is the density of the fluidizing gas (kg/m³).

3. Results and Discussion

3.1 Determination of minimum fluidization velocity

Preliminary tests showed that the compressor allowed a maximum air flow of 90 L.min⁻¹. However, under high temperatures, the maximum flow rate dropped to approximately 50 L.min⁻¹, agreeing to the tests performed by Figuroa (2015). The minimum flow rate is 5 L.min⁻¹. It should be emphasized that the air flow rate must be higher than the minimum fluidization velocity of the sand contained in the bed. Figure 2 demonstrates the fluidization tests of the atmospheric air in the fluidized bed reactor.

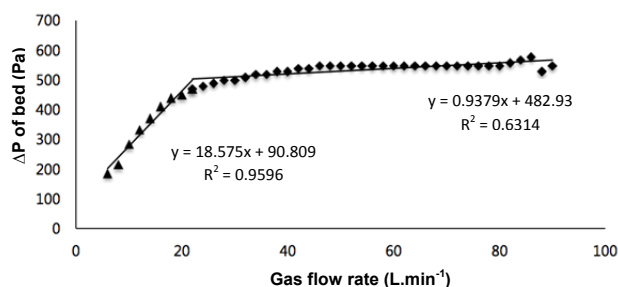


Figure 2: Fluidization test of the atmospheric air in the fluidized bed reactor

The fluidization test results provided that the minimum fluidization flow rate for this reactor bed is around 22 L.min⁻¹ (6.3 cm.s⁻¹). Thus, above this value, the particles are in a fluidized state. The bed fluidization tests demonstrated a gauge height of around 0.019 to 0.06 m, equivalent to a pressure difference of 0.002 to 0.006 atm (185.7 to 586.6 Pa), offering no danger to plant operation. After all these determinations, the possible pyrolysis operating conditions were determined (Table 1). The air flow rate was determined from the combination of bagasse feed rate and air ratio, which had several possibilities. Within these infinite possibilities, only part of them could be tested, which were those that were in the allowed range (feasible to this pilot plant), and that ensured fluidization. This last step depends on the stoichiometric oxygen determination and minimum fluidization flow calculations (section 2.2).

3.2 Fast pyrolysis process

From the operating conditions used in this pilot plant (Table 1), the results obtained are described in Table 2.

Table 2: Production of bio-oil and biochar from sugarcane bagasse fast pyrolysis in a pilot plant

Run	Bio-oil yield (wt. %)	Biochar yield (wt. %)
1	–	19.66
2	0.28	20.83
3	3.64	15.03
4	4.15	10.91
5	0.09	10.28
6	–	09.24
7	7.07	35.88
8	4.05	30.13
9	7.43	19.51
10	5.24	27.09
11	–	13.42

The bio-oil recovery was lower than expected, indicating the result of inefficient heat exchange by the heat exchanger present in the pilot plant system, which made it challenging to condensate the dense gas stream compounds. Although the bio-oil yield was low at the end of the process, there was a production of bio-oil between the cyclones and reforming reactor pipelines. Then, when this was noticed, an attempt was made to create a hose-connected external stream from the reforming reactor outlet into the inlet of the condenser pipe. This reforming reactor outlet hose is connected to a Schott flask, which remains in a vessel with ice, ethanol, and salt. This mixture could maintain the vessel temperature around -10 °C during the pyrolysis process. When performing this procedure, the recovery of bio-oil was greater (all runs that demonstrated higher bio-oil yields). However, the bio-oil yield remained lower than was expected. Another solution would be modifying the pipes of the pilot plant by aligning them, avoiding elbows that may cause a pressure drop. The run 07 had the highest yield of biochar (35.88 wt. % of biochar), while run 9 had the best option for bio-oil (7.43 wt. %). The biochar yields (9 to 35 wt. %) obtained in this work agreed with several authors in the literature that performed sugarcane bagasse pyrolysis (Montoya et al., 2015). The single shell and tube condenser was not sufficient to provide a contact and friction area that favors condensation of dense condensable gases (bio-oil). The mass balance does not close when considering the amount of sugarcane bagasse fed and the sum of products (bio-oil and biochar) (Table 2). Theoretically, pyrolysis gases would be considered as the rest of the products coming out of the process, but this cannot be asserted by the occurrence of two facts: a) some dense condensable gases were not condensed by the heat exchanger inefficiency; and b) there is bio-oil trapped in the pipes. These two facts make it difficult to close the mass balance of the process.

4. Conclusions

The results show that the pilot plant that was adapted to pyrolysis was able to produce bio-oil, biochar, and gases. The obtained bio-oil yields refer to the inefficiency of the gas stream cooling process, which is attributed to the low condenser cooling capacity, indicating that the condenser is recovering only the lightest part of the bio-oil. For this reason, it is suggested that bio-oil production is occurring, but its condensation is not efficient, causing liquid production to be underestimated. Nevertheless, the plant proves to be versatile for operating under varying operating conditions and can operate two types of thermochemical processes, being a significant result. Concerning biochar, the production was consistent with the literature data. Therefore, it was concluded that the operating conditions used were satisfactory and showed that the methodology of performing fast pyrolysis in a pilot plant that previously performed gasification was of technological importance for the area of thermochemical processes to obtain bioproducts. Significant modifications must be made to the pyrolysis pilot plant to obtain high bio-oil yields. Also, it was concluded that it would be advisable to replace the shell and single tube heat exchanger to another one, with a larger heat exchange surface.

Acknowledgments

The authors thank CNPq and grants #2016/18546-8, #2015/20630-4, and #2017/18401-2, São Paulo Research Foundation (FAPESP/CAPES).

References

- Asadullah M., Rahman M.A., Ali M.M., Rahman M.S., Motin M.A., Sultan M.B., Alam M.R., 2007, Production of bio-oil from fixed bed pyrolysis of bagasse, *Fuel*, 86, 2514–2520.
- Balasundram V., Zaman K.K., Ibrahim N., Kasmani R.M., Isha R., Hamid M.K.A., Hasbullah H., Mohsin R., Ali R.R., 2019, In-situ catalytic upgrading of pyrolysis vapours from sugarcane bagasse over newly-developed Ni-Ce/HZSM-5 catalyst: Effect of catalyst to biomass mass ratio, *Chemical Engineering Transactions*, 72, 139–144.
- Balat M., Balat M., Kirtay E., Balat H., 2009, Main routes for the thermo-conversion of biomass into fuels and chemicals. Part 1: Pyrolysis systems, *Energy Conversion and Management*, 50, 3147–3157.
- Basu P., 2015, *Circulating fluidized bed boilers: Design, Operation and Maintenance*, Springer International Publishing.
- Figuerola J.E.J., 2015, *Thermochemical processes for sugarcane bagasse processing: fixed bed pyrolysis and fluidized bed gasification*, PhD Thesis, University of Campinas School of Chemical Engineering, Campinas, Brazil (In Portuguese).
- Figuerola J.E.J., Ardila Y.C., Maciel Filho R., Maciel M.R.W., 2017, Biomass gasification optimization: semi-pilot scale 2 kg/h of bagasse in fluidized bed reactor, *Chemical Engineering Transactions*, 57, 937–942.
- Gollakota A.R.K., Reddy M., Subramanyam M.D., Kishore N., 2016, A review on the upgradation techniques of pyrolysis oil, *Renewable and Sustainable Energy Reviews*, 58, 1543–1568.
- Goyal H.B., Seal D., Saxena R.C., 2008, Bio-fuels from thermochemical conversion of renewable resources: A review. *Renewable and Sustainable Energy Reviews*, 12, 504–517.
- Islam M.R., Parveen M., Haniu H., 2010, Properties of sugarcane waste-derived bio-oils obtained by fixed-bed fire-tube heating pyrolysis, *Bioresource Technology*, 101, 4162–4168.
- Miranda N.T., Motta I.L., Fernandes D.S., Dianin L.M., Maciel Filho R., Maciel M.R.W., 2018, Adaptation of a gasification pilot plant for sugarcane bagasse pyrolysis process, XXI Brazilian Congress of Chemical Engineering – COBEQ, Sao Paulo, Brazil (In Portuguese).
- Miranda N.T., Maciel Filho R., Maciel M.R.W., 2019, Sugarcane bagasse fast pyrolysis simulation: a thermodynamic equilibrium approach, *Chemical Engineering Transactions*, 74, 175–180.
- Montoya J.I., Valdés C., Chejne F., Gómez C.A., Blanco A., Marrugo G., Osorio J., Castillo E., Aristóbulo J., Acero J., 2015, Bio-oil production from Colombian bagasse by fast pyrolysis in a fluidized bed: An experimental study, *Journal of Analytical and Applied Pyrolysis*, 112, 379–387.
- Naik S.N., Goud V.V., Rout P.K., Dalai A.K., 2010, Production of first and second generation biofuels: A comprehensive review, *Renewable and Sustainable Energy Reviews*, 14, 578–597.
- Papari S., Hawboldt K., 2015, A review on the pyrolysis of woody biomass to bio-oil: Focus on kinetic models, *Renewable and Sustainable Energy Reviews*, 52, 1580–1595.
- Scala F., 2013, *Fluidized bed technologies for near-zero emission combustion and gasification*, Woodhead Publishing.
- Turton R., Bailie R.C., Whiting W.B., Shaeiwitz J.A., Bhattacharyya D., 2012, *Analysis, Synthesis, and Design of Chemical Processes*, Fourth Edition, Prentice Hall.
- UNICA, Sugarcane Industry Union <www.unica.com.br> accessed 27.11.2019.