Título: ASSESSMENT OF DIFFERENT PATHWAYS FOR THE CONVERSION OF BANANA AGRICULTURAL WASTES TO BIOENERGY

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Resumen: The 2030 Agenda for Sustainable Development of the United Nations aims to ensure affordable energy for all and to diminish greenhouse gas emissions in order to mitigate the effects of climate change in 2030. A way to achieve these goals is by the substitution of fossil fuels with biofuels. Bioethanol is the most used biofuel in the transport sector and some countries have encouraged the use of blended gasoline with ethanol to mitigate the greenhouse gas emissions from the transport sector. This study aims to analyze some conversion pathways of banana agricultural wastes (rachis, pseudostem, leaves and discarded banana) for bioenergy purposes, covering the whole productive chain and considering sustainability criteria. This study encompasses: (i) analysis of the biofuel legal framework of some countries, (ii) study of the production of the residue in one of the most banana productive provinces of Ecuador and a tentative plant location, (iii) optimization of the operation conditions for second generation ethanol production (pretreatment, enzymatic hydrolysis and fermentation) and (iv) a life cycle assessment of the bioethanol with a well to wheel approach of its production and consumption in different blending percentages.

The legal framework of biofuels analysis considered three Andean countries for its comparison. Colombia, Ecuador and Peru are neighboring countries located in the tropics, which share some characteristics like extensive land areas with similar climate conditions, crops and in consequence similar agricultural residues. Banana is one of these crops, and in fact, it is the most important fruit crop in the world. The plant bears one bunch in its life, leaving behind a large amount of agricultural residues, which could be starchy (discarded fruit) and lignocellulosic (rachis, pseudostem and leaves). This biomass could be used for different purposes such as bioenergy. Ecuador is the world¿s largest exporter of banana fruit. Therefore, the analysis of different transformation pathways of the agricultural residues is focused on this country.

As a result of the analysis of the status of bioethanol in each country studied from the Andean Region, Colombia demonstrated to be near to reach its blending target (E5-E10 depending on the region); Ecuador (E5 blending mandate) recorded a bioethanol deficit estimated at 75% in 2015; and regarding Peru (E7.8), in the last years they have achieved their national target. In addition, a social network analysis was developed to compare the current regulations that each country has established to promote the use of biofuels. Besides the blending mandates, the countries appear not to rely on a sustainability policy for the development of first or second generation bioethanol. These Andean countries are planning to increase their blending targets in the next years. In order to achieve this, political efforts must be focused on feedstock availability and guidelines related to sustainability and the technology to be applied, in their own context.

To analyze the banana agricultural waste production, the assessment of the supply chain was developed considering El Oro (Ecuador) province area, and using Geographic Information Systems (ArcGIS® 10 software). The methodology included the assessment of biomass distribution, facility location, transport optimization and a novel virtual land parcel that allows carrying out this type of studies in areas with lack of geo-referenced information. According to our approach, El Oro province has an available biomass potential of 190,102 t fm.y-1 of starchy residual biomass and 198,602 t dm.y-1 of lignocellulosic residual biomass. Two candidate points located at 79°51'12"W 3°11'21"S and 79°52'49"W 3°17'49"S were identified for the installment of energy conversion facilities supplied with residual biomass. From the available potential of starchy biomass, it would be possible to obtain up to 19 million liters of bioethanol per year assuming an average yield of 101.2 l.t-1 in fresh matter basis. Meanwhile, the available lignocellulosic biomass, which energy content (Lower Heating Value, moisture free biomass) was determined at 12.9 MJ.kg-1 on average, could be used for power generation with an installed capacity of 18 MW. Chemical characterization of the lignocellulosic biomass suggested that further studies should be undertaken regarding the potential application of lignocellulosic residues for second generation bioethanol.

After analyzing the possibility to use lignocellulosic residues for the production of cellulosic ethanol, the first step was to optimize the operational conditions of the pretreatment (steam explosion) of the two main banana lignocellulosic residues, rachis and pseudostem, in order to achieve high overall sugar yields. A response surface statistical model (22+star points with triplicate at central point) was used for the optimization, considering the enzymatic hydrolysis yield and the overall yield of glucose and xylose as main criteria. The optimal conditions of steam explosion pretreatment for pseudostem were established at 177 °C, 5 minutes and 2.2% H2SO4 (v/v), presenting a high overall glucose yield of 91.0%. For rachis, the optimal conditions were 198 °C, 5 minutes and 1.5% H2SO4 (v/v) with an overall glucose yield of 87.1%. An acid-catalyzed pretreatment was needed due to the low presence of acetyl groups in both feedstocks. After rachis pretreatment, extractives, soluble ashes and hemicellulose were solubilized causing an enrichment of cellulose in the insoluble fraction. However, due to the high amount of starch in pseudostem, a significant amount of glucose was recovered in the liquid fraction.

Subsequently, the enzymatic hydrolysis (saccharification) and fermentation stage of the bioethanol production

process was optimized considering conditions transferable to industry. Rachis and pseudostem were previously pretreated with steam explosion optimized conditions. Enzymatic hydrolysis was routed to obtain glucose concentrations ¿100 g.L-1, using factorial statistical models. Later, for fermentation stage, three different configurations of saccharification and fermentation processes were analyzed searching for an ethanol concentration ¿40g.L-1. For pseudostem, the selected conditions were simultaneous saccharification and fermentation configuration with 15.1% of solid loading and 14.9 FPU.g glucan-1 of enzyme dosage, attaining an ethanol concentration of 40.1 g.L-1, which means 112 L of ethanol per each dry tonne of pseudostem. Meanwhile, rachis selected conditions were pre-saccharification of 8 hours and simultaneous saccharification and fermentation at 17.6% of solid loading and 16.0 FPU g glucan-1 of enzyme dosage. With these conditions, rachis is able to attain 48.3 g.L-1 of ethanol concentration, which means 103 L of ethanol per each dry tonne of rachis. These conditions led to achieve ethanol production process with high solids loading, low enzyme dosage, low yeast inoculum, no mineral salts supplementation and maximum ethanol productivities.
Finally, to ensure environmental sustainability of second generation bioethanol derived from banana agricultural wastes and demonstrate that it can fulfill its primary purpose (reduce GHG emissions), a life cycle assessment was developed. The methodological approach was conducted in a Well-to-Wheel perspective, using as functional unit 1 MJ of energy released in the combustion of different ethanol/gasoline blends in a passenger car. For the assessment, sources of primary and secondary information were used. Mass balance and ethanol yield data were obtained from laboratory experimentation. The environmental assessment was carried out using SimaPro 8.0.4.30 software and the impact assessment methodology used was ReCiPe midpoint (H). The impact categories quantified were climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), photochemical oxidant formation (PO), particulate matter formation (PM), water depletion (WD), and fossil depletion (FD). In addition, net energy value and energy ratio (ER) were analyzed to ensure a positive energy balance. The studied biofuel presented positive and negative impacts in different categories. The use of blended gasoline reduces the impact in CC, PO, PM and FD, in comparison to the use of full gasoline. Meanwhile, the impacts in FE, TA and WD increased. The energy balance obtained was positive, obtaining an ER of 2.68 MJ/MJ. With the use of life cycle assessment methodology, it can be determined hotspots of the production process. Therefore, wastewater treatment is the process that stands out with greater energy consumption. Due to the fact that Ecuador is the major exporter of banana, and a great amount of agricultural waste is available, a case study in this country was analyzed, resulting that Ecuador could use this residue for ethanol production, considering the positive and negative impacts that it entails. In conclusion, second generation ethanol derived from banana agricultural waste reduces greenhouse gas emissions and fossil depletion, and have a positive energy balance.