Plantain-based Integrated Biorefinery

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Abstract

In view of the emerging research trend in bio-energy to circumvent the effects of the impending decline in world’s petroleum reserves and environmental challenges associated with the resource, there is need for African countries to exploit their huge biomass resources towards integrated biorefinery. Nigeria is an agrarian nation with enormous biomass resources that are grossly unexploited for energy generation. Therefore, this present research is investigating the viability of post-harvested plantain biomass from Nigeria for biorefinery operation. The various parts of the biomass namely: stem, leaves, flower (inflorescence) were preliminarily analyzed for their monomeric sugar using HPLC upon hydrolysis. Our preliminary work demonstrated that the various parts of the biomass can be excellent sources of C5 and C6 sugars - both in terms of selectivity and yield. The morphology and structural composition of the biomass before and after hydrolysis were studied using SEM and FTIR analyses. The remnant fiber of the biomass was subjected to torrefaction and carbonization processes to produce value-added carbon products such as biochar, carbons for water treatment, etc. BET analysis on the produced carbons showed that a surface area up to 900 m2/g can be achieved. Caloric value of over 9000 BTU/LB was recorded for Torrified post-hydrolyzed flower portion of the biomass. Therefore, this present research effort indicated that developing a plantain-based biorefinery in Nigeria is feasible and will impact positively on the economy of the nation with significant agriculture based opportunities in the rural areas.

Keywords: Bio-Energy; Plantain-Based Biorefinery; Nigeria

Introduction

The current global interest in green technology has attracted a lot of innovative concepts in bio-resources. [1-5]. The emerging streams of ideas are the deliberate response to circumvent the effects of the impending decline in world’s petroleum reserves as well as the environmental challenges associated with the resource. Biorefinery is one big concept that is currently receiving research attention globally [6-9]. To ensure the success of this concept, holistic exploitation of biomass for economic gains is crucial to sustainability of the innovation. Sugar/Starch Crops, Vegetable Oil, lignocellulosic Biomass, Jatropha and Micro-algae have been listed as the major feedstock for biorefinery operations. The first generation biorefinery used corn, wheat, cassava, barley, rye, soybean, sugarcane, sugar beet, or sweet sorghum as feedstock. However, the future challenge associated with food security and supply made this type of biorefinery non-fashionable. Hence, researchers focused on developing second generation technologies to produce fuels and chemicals from non-edible feedstock such as agricultural residue, forest residue, municipal solid waste, industrial waste, and dedicated energy crops, that will not conflict with globe’s food security [10]. However, lignocellulosic materials from agricultural and forest residues have been identified as the essence of

the second generation biorefinery due to their economic merits over other biofuel feedstocks, as it can be produced quickly and obtainable at significantly lower cost than food crops [11,12]. Lignocellulose is abundantly available all around the globe and grossly underutilized, especially in African countries, where biomass conversion technology is nascent. In view of the global needs for alternative energy sources other than fossils, there is every need to exploit the full potentials of lignocellulosic biomass as the resource seemingly holds the key to supplying society’s basic needs for sustainable production of liquid transportation fuels, chemicals, heat and power without impacting food supply [13]. Nevertheless, challenges such as feedstock availability/production, feedstock logistics, development of energy efficient technologies (pretreatment, enzyme hydrolysis, and microbial fermentation), coproducts development, establishment of biofuel and biochemical standards, biofuel distribution, societal acceptance and environmental impact minimization, [14-16] have been noted as the major drawback mitigating against the viability of lignocellulose biomass for biorefinery operation. Hence, deliberate research efforts are necessary to address these challenges to guarantee the prospect of lignocellulose biorefinery. Unlike in developed countries, where agricultural residues are intensely investigated for biofuel potency, most of the biomass available in African nations are yet to be fully explored for biorefinery operation. Most of the information available in literature about the lignocellulosic biomass from African countries generally accounted for the conversion of these agricultural residues into biofuels with little or no information on further utilization of the remnant fiber. Consequently, if the emerging biorefinery technology would be economically viable as its petrochemical refinery counterpart, there is need to focus research attention on the integrated approach of the technology wherein biomass will be maximally utilized. Therefore, this present research is investigating the potentials of post harvested plantain biomass for bio-based products. Information on this biomass as biorefinery feedstock is very scanty in literature, hence, in this study, C5 and C6 monomeric sugars of the biomass will be hydrolyzed and evaluated while the potentials of the remnant fiber will be investigated for the production of value-added carbon products such as bioccoal, biochar and activated carbon.

**Plantain crop**

Plantains are starchy bananas which make up one-quarter of the total world production of bananas (*Musa* spp.), it represents the world’s second largest fruit crop with an annual production of 129,906,098 metric tons [17]. They rank as the fourth most important global food commodity after rice, wheat and maize in terms of gross value of production [18]. Unlike the sweet dessert bananas, plantains are a staple food which is fried, baked, boiled (and then sometimes pounded) or roasted and consumed alone or together with other food. About 70 million people in West and Central Africa are estimated to derive more than one-quarter of their food energy requirements from plantains, making them one of the most important sources of food energy throughout the African lowland humid forest zone. In Africa, plantains are grown for home consumption, not for export. The area between the lowlands of Guinea and Liberia in West Africa and the central basin of Zaire in Central Africa produces one-half the total world output of plantains West Africa produces two-thirds and Central Africa one-fifth of the African output. In terms of cost per hectare, per ton and per unit of food energy, plantains are also the cheapest staple crop to produce.

**Morphology of plantain**

Plantain crop consists of: (a) Bunch or inflorescence. Composed of many flowers, the bunch emerges between the leaves and is attached to the plant by a rachis or fruit stalk. The many protuberances on the rachis are called glomerules. Each glomerule bears a group of flowers, also called a hand. Edible fruit (or fingers) develop from female flowers located at the first 10 glomerules of the bunch. Neutral flowers (also called hermaphrodite or intermediate flowers) appear next but do not develop into fruit as their ovaries cannot swell to form pulp. The purple bud at the end of the bunch is called the “male bud” and consists of bracts covering groups of so-called male flowers. This male bud may be absent or present when the bunch reaches maturity. (b) Pseudostem with foliage leaves. The cylindrical structure rising from the soil and carrying the foliage is not a stem in the true sense. It is a “false” stem or pseudostem because the growing tip (or meristem) of the plant remains near soil level. As the false stem consists of overlapping leaf sheaths plantains are like giant herbs and not like trees. The leaf sheaths render support to the rachis of the mother plant. Young suckers (shoots from the main plant which can
develop into bearing plants) have narrow, lanceolated leaves which are called scales and are easily distinguishable from the large foliage leaves. (c) Underground corm with suckers and roots. The corm, sometimes wrongly called a bulb, is the true stem of the plant. Numerous roots emerge from the corm, most of which grow horizontally at a depth of 0 to 15 cm. Roots are whitish if young and healthy and become brown with age. If infested by nematodes, they become brown or even black and/or show protuberances. The growing tip (or meristem) at the top of the corm continuously forms new leaves and later becomes the inflorescence. The corm produces many branches, called suckers, and the whole unit is often referred to as the “mat” or “stool”. After the plant crop has been harvested, the mother plant is cut down and the suckers are thinned. Although all suckers are followers or daughter plants, the cultivator selects one (the ratoon) to continue the next cycle of production. The second harvest from the plantain mat is called the first ratoon crop. The third harvest is the second ratoon crop, and so on [19].

Climate

Plantains, like other bananas require a hot and humid environment. Ideally, the average air temperature should be about 30°C and rainfall at least 1.00 mm per month. Rainfall should be well distributed throughout the year and dry seasons should be as short as possible. Irrigation is not suitable nor economically worthwhile for plantains grown by the family farmer. But may become necessary when larger fields are cultivated in areas with a long dry season [20].

Plantain and banana lignocellulosic biomass

Post harvested plantain biomass is one of the agricultural wastes generated annually in million tons in many parts of the world, especially, within the tropical region. In Nigeria, the climate is predominantly rainforest in the South, thus, favoring plantain and banana cultivation. This makes Nigeria ranks fourth in the production of plantain crops in the world. The agro-waste generated from post harvested plantain alone accounts for 9,450,000 tons annually [21]. Therefore, the feasibility of exploiting the biomass for bio-based fuel and other bio-products is guaranteed from the availability and economy points of view.

Banana by-products have been used for wrappings foods, clothes and used in various ceremonial occasions and the usage expands through cultural diversification [22]. Modern agriculture generally groups banana into fruit crop or cash crop commodities alongside with several other crops such as oil palm, sugarcane, pineapple, mangoes and rice [24]. Similarly, some of these commodities do produce huge amount of cellulosic waste termed as agricultural waste or biomass. Innovation in managing such a vast amount of agricultural waste or biomass is a continuous challenge and recent trends in biorefinery favor the utilization of this biomass for value added purposes to fulfill the need in the areas such as renewable energy, fiber composites and textiles, food alternatives and livestock feed [23,25].

A lot of research findings have been documented by the previous researchers on the use of plantain and banana lignocellulose as feedstock to meet the escalating demand of raw materials supply in various industries [26-32]. However, little information is available in literature on plantain lignocellulose biomass for bio-based products, therefore this research aimed to assess the potentials of plantain biomass for biorefinery operations.

Materials and Methods

Reagents, sample collection and preparation

Post harvested plantain biomass was collected from a Plantain plantation in Akure, Ondo State of Nigeria. The biomass was separated into three fractions: flower (inflorescence), leaf and stem. Fractions were thoroughly washed with water to get rid of the adhering soil and other dirt. The cleaned samples were sundried for 2 weeks and finally oven dried at 105°C.

The clean-dried samples were packed separately in air-tight labelled polythene bags. High purity standards of D(+)-Xylose, D(+)-Arabinose, D(+)-Glucose), furfural, 5-hydroxymethylfurfural, acetic acid, and glycerol for the HPLC analysis were supplied by the Biomass Processing Laboratory of CONN Centre for Renewable Energy and Research, University of Louisville, USA.

Pretreatment and chemical composition analysis of the plantain biomass

The dried biomass was pretreated by crushing manually and analyzed according to standard procedures for crude protein using Kjeldahl’s method (AOAC 984.13) [33], fat using Soxhlet Extraction Method (AOAC 954.02) [34], ash (method AOAC 942.05) [35], moisture (method AOAC 935.29) [36], neutral detergent fiber (NDF) (method AOAC 2002.04) [37] and acid detergent fiber (ADF) (method AOAC 973.18) [38]. The NDF and ADF results were obtained from the Central laboratory, Federal University of Technology, Akure. All samples were analyzed in triplicates and results are as given in table 1. Total carbohydrates were determined by subtracting the total percentage of fat, proteins, and ash from 100. Neutral detergent fiber was used as a measure of total cellulosic material (cellulose + hemicellulose + lignin). Acid detergent fiber was used to estimate the amount of cellulose and lignin. Hemicellulose was determined by difference between NDF and ADF values.

Hydrolysis of plantain biomass

The acid hydrolysis procedure adopted was as described by Dania, et al. [39] with a little modification. 10g of each fraction of the biomass was weighed on dry basis and packed inside a 300 mL pressure tubes and contacted with 4w/w% H$_2$SO$_4$ (aq). Acid solutions were prepared in ratio of 2:5, 1:5 and 2:15 of Fiber to Liquor (F:L). Each fraction was hydrolyzed at these ratio under same experimental conditions in a 6L M&K percolation reactor containing 300 mL of water circulating round the tubes by pump. Water was pumped through the heater to provide sufficient steam vapour in the pressure tubes. The heater was connected and controlled through a programmable controller fixed with the reactor. Sample were hydrolyzed at a temperature range of 25 - 140°C within a reaction time of 110 minutes. At the end of the reaction, heating was stopped and reactor allowed to cool with the aid of cold water jacket on the recirculation line until the reactor temperature subsided to 70°C. Hydrolyzate was carefully collected from the tubes and stored in cleaned vials for HPLC analysis. Remnant fiber was washed with water and oven dried at a temperature of 105°C, allowed to cool and kept for carbonization processes.

Determination of sugars and degradation products in the hydrolyzate

Concentrations of C5 and C6 sugars and their degradation products (Furfural and hydroxymethyl furfural) in the hydrolyzate were analyzed using a Waters 600E HPLC system (Waters Corporation, Milford, MA) configured with an Agilent 1260 Infinity refractive index detector and an Agilent Hi-Plex H column (300 mm x 7.7 mm, 8 mm). The Column temperature was set to 60°C with a refractive index detector temperature of 55°C. A solution of 5 moldm$^{-3}$ sulfuric acid was used as the mobile phase. The flow rate of the mobile phase was maintained at 700 mm$^3$ min$^{-1}$. Prior to the analysis, samples of the hydrolyzate were filtered through a 0.45 mL syringe filter and 20µL of each standard solution and the samples were injected in Triplicate runs. The analysis was monitored over a period of 45 minutes during which all the hydrolyzate were analyzed for monomeric sugars (glucose, xylose, arabinose), as well as furfural and hydroxymethylfurfural.

Characterization of plantain biomass fibers and carbonized biomass by scanning electron microscopy (SEM)

The morphology of the plantain biomass fibers before and after hydrolysis was studied using TESCAN SEM 600 scanning electron microscope (FEI Company; Hillsboro, OR). The samples were prior air-blown to remove loose particles from sample surface before attached onto a carbon tape. Samples were positioned on holders and gently tightened on sample stage. Resolution and magnification were carefully selected to bring sample images to focus. The same procedure was repeated for the carbonized products of the biomass. Elemental composition of the Biomass was equally investigated with EDAX coupled with the SEM.

Carbonization of the residual fiber of plantain biomass

Remnants fiber of the biomass after hydrolysis was subjected to graphite tube carbonization processes at different temperatures in the presence of Nitrogen flow to obtain various carbonized products, namely torrefied carbon and activated carbon.
Plantain-based Integrated Biorefinery

Activation process

The activation process adopted was a graphite-tube furnace process as described by Zachary Dean Herde [40]. The dried sample of the remnant fiber was pulverized, screened through a 3.50 mm mesh and treated with KOH (aq) in ratio 1:1 and 2:1. The alkali-treated sample was thoroughly mixed until a thick paste was formed and dried in an oven at a temperature of 105°C. 3.0g of the dried alkali-treated sample was weighed inside a rectangular ceramic boat and activated in a tube-furnace programmed to ramp to a maximum temperature of 950°C, within a pressure range of 4 - 5 Pascal. Carbonization was performed in the absence of oxygen with continuous flow of Nitrogen gas for 2h. After which the temperature of the furnace started to subside until 50°C. Yields and percentage loss on carbonization were calculated.

Torrefaction process

3.0g of the remnant fiber was torrefied in a graphite tube furnace (MTI, GSL1500X) at a temperature of 300°C with constant flow of Nitrogen gas. Heating was programmed to attain this temperature within a reaction time of 1h. After which the furnace was allowed to cool down to 50°C. Yields and percentage loss on Torrefaction were calculated.

Fourier transform infrared (FTIR) analysis

The functional groups present in the biomass (Pre-hydrolyzed, post-hydrolyzed and torrefied samples) were detected with Fourier Transform Infrared (PerkinElmer-Spectrum 100). The respective biomass samples were pulverized and screened through a 250 µm analytical sieve. 2 mg portion of each sample was put on sample crystal and compressed at a force gauge of 72 before scanning. Spectra were recorded and analyzed.

Brunauer-Emmett-Teller (BET) analysis

About 0.5g of the activated carbon of each sample of the biomass was weighed in a pre-weighed sample tube and degassed for 3 hours. After which the weight difference was noted. The sample was analysed in the BET equipment in the pressure of Nitrogen gas overnight and BET surface area and Adsorption isotherms were calculated thereafter.

Results and Discussion

Pretreatment and chemical composition of plantain fiber

The chemical compositions of the untreated and pretreated biomass of the plantain fiber are given in table 1. The effect of size reduction, which was the only pretreatment method performed on the biomass showed a significant improvement on the yields of the composition of the fiber. For instance, a fractional increase of 18.87% was noticed in the protein content of the pretreated fiber and similarly, a noticeable fractional increase of 11.96% occurred in the fiber content (NDF) of the biomass. The percentage composition of the hemicellulose of the biomass increased appreciably upon reducing the size of the biomass prior the hydrolysis process, about 23% increase was observed.

<table>
<thead>
<tr>
<th>Component</th>
<th>Untreated Plantain Fiber (%)</th>
<th>Pretreated Plantain Fiber (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude protein (%)</td>
<td>15.52</td>
<td>18.45</td>
</tr>
<tr>
<td>Crude fat (%)</td>
<td>1.50</td>
<td>0.95</td>
</tr>
<tr>
<td>Ash (%)</td>
<td>12.50</td>
<td>9.96</td>
</tr>
<tr>
<td>Neutral detergent fiber (%)</td>
<td>52.32</td>
<td>58.58</td>
</tr>
<tr>
<td>Acid detergent fiber (%)</td>
<td>29.45</td>
<td>30.45</td>
</tr>
<tr>
<td>Total Carbohydrate (%)</td>
<td>67.48</td>
<td>73.64</td>
</tr>
<tr>
<td>Hemicellulose (%)</td>
<td>22.87</td>
<td>28.13</td>
</tr>
</tbody>
</table>

Table 1: Chemical composition of the untreated and pretreated plantain fiber.

a: Mass fraction of the total cellulosic material.
b: Mass fraction of the total cellulose and lignin.

Hydrolysis of biomass and yields of sugars

Table 2 shows the concentration of sugars and their respective degradation products during the hydrolysis process. The concentration of the sugars varied with the concentration of the acid at different fiber/liquor ratio (Table 3). The hydrolysis condition was optimized by hydrolyzing each part of the biomass at three different Fiber:liquor ratio (different acid concentration). Figure 1a-1c show the concentrations of monomeric sugars (C5 and C6) in the three part of the plantain biomass investigated. F/L of 2:5 gave the best yields of these sugars in the biomass fractions, i.e. at high acid concentration more sugars were released during hydrolysis. However, the yields and selectivity of arabinose were comparatively higher at lower acid concentration, that is higher than glucose and xylose. Figure 2 shows variation of sugar concentration in biomass parts at different fiber to liquor ratio. The sugars were noticed to be hydrolyzed more at 2:5 fiber/liquor in all the parts of the biomass, followed by 1:5, while concentration of the sugars were at lowest values at 2:15. This implies that high acid concentration with low dilution favours hydrolysis of hemicellulose portion of the biomass at low fiber:liquor ratio. The total concentration of C5 and C6 sugars was higher in plantain leaf than any other parts under the hydrolysis condition employed. Figure 3 shows that a total of 24.69 g/L was recorded in the leaf part, while 21.25 g/L and 19.27 g/L were recorded in the stem and flower parts of the biomass respectively. Selectivity of sugars is depicted in figure 4. Selectivity was high for glucose and xylose in plantain stem at F/L of 2:5 and 1:5 than what obtained in 2:15. This implies that higher acid concentration (lower F/L) favored the release and selectivity of xylose and glucose than arabinose in the biomass. Conversely, arabinose shows a remarkable selectivity at high fiber/liquor i.e. at lower acid concentration than glucose and xylose.

<table>
<thead>
<tr>
<th>Part of Biomass</th>
<th>[H+]</th>
<th>F:L</th>
<th>[Glu]</th>
<th>[Xyl]</th>
<th>[Ara]</th>
<th>[HMF]</th>
<th>[Ff]</th>
<th>Total Conc. of sugars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flower (fluorescence)</td>
<td>16.0</td>
<td>2:5</td>
<td>0.38 ± 0.03</td>
<td>4.45 ± 0.27</td>
<td>4.76 ± 0.25</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>9.59 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>1:5</td>
<td>0.20 ± 0.01</td>
<td>2.00 ± 0.10</td>
<td>3.76 ± 0.15</td>
<td>0.001 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>5.97 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>2:15</td>
<td>0.00 ± 0.00</td>
<td>0.27 ± 0.20</td>
<td>3.43 ± 0.14</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>3.71 ± 0.10</td>
</tr>
<tr>
<td>Stem</td>
<td>16.0</td>
<td>2:5</td>
<td>0.82 ± 0.06</td>
<td>5.93 ± 0.46</td>
<td>4.06 ± 0.35</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>10.83 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>1:5</td>
<td>0.41 ± 0.10</td>
<td>4.79 ± 0.30</td>
<td>3.27 ± 0.31</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>8.48 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>2:15</td>
<td>0.00 ± 0.00</td>
<td>0.43 ± 0.04</td>
<td>1.50 ± 0.06</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>1.94 ± 0.03</td>
</tr>
<tr>
<td>Leaf</td>
<td>16.0</td>
<td>2:5</td>
<td>0.27 ± 0.08</td>
<td>5.05 ± 0.16</td>
<td>4.79 ± 0.18</td>
<td>0.002 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>10.12 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>1:5</td>
<td>0.22 ± 0.00</td>
<td>3.49 ± 0.10</td>
<td>4.79 ± 0.20</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>8.49 ± 0.10</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>2:15</td>
<td>0.05 ± 0.04</td>
<td>2.09 ± 0.35</td>
<td>3.94 ± 0.5</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>6.08 ± 0.22</td>
</tr>
</tbody>
</table>

Table 2: Variation in the concentration of the hydrolyzate components at different acid concentrations and fiber/liquor ratio.

<table>
<thead>
<tr>
<th>Part of Biomass</th>
<th>[H+]</th>
<th>F:L</th>
<th>Glu</th>
<th>Xyl</th>
<th>Ara</th>
<th>Glu</th>
<th>Xyl</th>
<th>Ara</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flower (fluorescence)</td>
<td>16.0</td>
<td>2:5</td>
<td>3.98</td>
<td>46.39</td>
<td>49.62</td>
<td>0.10</td>
<td>1.11</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>1:5</td>
<td>3.49</td>
<td>33.51</td>
<td>62.99</td>
<td>0.10</td>
<td>1.00</td>
<td>1.88</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>2:15</td>
<td>0.00</td>
<td>7.31</td>
<td>92.68</td>
<td>0.00</td>
<td>0.20</td>
<td>2.58</td>
</tr>
<tr>
<td>Stem</td>
<td>16.0</td>
<td>2:5</td>
<td>7.66</td>
<td>54.78</td>
<td>37.55</td>
<td>0.21</td>
<td>1.48</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>1:5</td>
<td>4.92</td>
<td>56.53</td>
<td>38.54</td>
<td>0.21</td>
<td>2.40</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>2:15</td>
<td>0.00</td>
<td>22.50</td>
<td>77.49</td>
<td>0.00</td>
<td>0.33</td>
<td>1.13</td>
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<tr>
<td>Leaf</td>
<td>16.0</td>
<td>2:5</td>
<td>2.73</td>
<td>49.94</td>
<td>47.32</td>
<td>0.07</td>
<td>1.26</td>
<td>1.20</td>
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<tr>
<td></td>
<td>8.0</td>
<td>1:5</td>
<td>2.58</td>
<td>41.02</td>
<td>56.40</td>
<td>0.11</td>
<td>1.74</td>
<td>2.40</td>
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<tr>
<td></td>
<td>5.3</td>
<td>2:15</td>
<td>0.77</td>
<td>34.47</td>
<td>64.75</td>
<td>0.04</td>
<td>1.57</td>
<td>2.96</td>
</tr>
</tbody>
</table>

Table 3: Selectivity and yields of sugars at different acid concentrations and fiber/liquor ratio.

Figure 1: Concentration of sugar in the plantain biomass at different Fiber/Liquor ratio.

Figure 2: Variation of sugar concentration in biomass fractions at different fiber to liquor ratio.

Figure 3: Total concentration of sugars in different parts of the biomass.
Figure 4: Selectivity of sugars at different fiber/liquor ratio.

Scanning electron microscopic analysis of the plantain biomass

SEM micrographs (Figure 5a-5f) depict the changes observed in the fiber surface morphology of the plantain biomass after the hydrolysis at a reaction temperature of 140°C and sulfuric acid Concentration of 4%. The increased number of pores on the post-hydrolyzed sample confirmed the effectiveness of the hydrolysis process adopted.

Figure 5: SEM images of plantain fibers (a) before and (b) after hydrolysis at 140°C, 4w/w% of H2SO4.
FTIR analysis

Effect of hydrolysis and torrefaction on biomass

Figure 6a-6c show the variation in the functional groups present in the three parts of plantain biomass upon torrefaction process.

Figure 6a: Variation in the functional groups in Plantain Leaf upon Torrefaction.

Figure 6b: Variation in the functional groups in Plantain Stem upon Torrefaction.

Figure 6c: Variation in the functional groups in Plantain Flower upon Torrefaction.
The peaks were normalized to Aromatic C=C absorption wavelength. In all the figures, the peak height of the OH and C=O groups in the prehydrolyzed and posthydrolyzed samples were observed to reduce upon torrefaction compared to their respective peaks in the prehydrolyzed torrefied samples. The decrease in the peak heights of these functional groups showed the effectiveness of the torrefaction processes conducted on the biomass.

BET analysis

Figure 7 shows the isotherm linear plot of the activated carbons produced from the post hydrolysed fiber of the plantain biomass. The figure depicts that the activated carbon derived from plantain flower has the highest quantity of the absorbed gas. Equally in table 4, the BET surface Area report showed that plantain flower has $942.2303 \pm 16.7136 \text{ m}^2/\text{g}$, which is relatively higher than $11.7103 \pm 0.0820 \text{ m}^2/\text{g}$ recorded for Plantain Stem and $159.3058 \pm 4.1108 \text{ m}^2/\text{g}$ for Plantain leaf.

![Figure 7: Isotherm linear plot. PF: Plantain Flower; Pl: Plantain Leaf; PS: Plantain Stem.](image)

<table>
<thead>
<tr>
<th>Biomass</th>
<th>BET surface area</th>
<th>Pore size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plantain Flower</td>
<td>942.2303 m$^2$/g</td>
<td>2.74463 nm</td>
</tr>
<tr>
<td>Plantain Leaf</td>
<td>159.3058 m$^2$/g</td>
<td>3.20004 nm</td>
</tr>
<tr>
<td>Plantain Stem</td>
<td>11.7103 m$^2$/g</td>
<td>13.01368 nm</td>
</tr>
</tbody>
</table>

*Table 4: BET data for post-hydrolyzed plantain biomass.*

Calorific value of plantain biomass

Table 5 shows the energy content value of the torrefied samples of the three parts of the plantain biomass. The pre and posthydrolyzed samples of the biomass torrefied at 300°C show remarkable increase in their energy value compared to their respective counterparts torrefied at lower temperature of 250°C. The implies that the energy content of the biomass was enhanced upon hydrolysis and torrefaction processes.

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Torrefied Prehydrolyzed @ 250°C</th>
<th>Torrefied Posthydrolyzed @ 250°C</th>
<th>Torrefied Prehydrolyzed @ 300°C</th>
<th>Torrefied Post-hydrolyzed @ 300°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plantain Flower</td>
<td>8102</td>
<td>8871</td>
<td>8341</td>
<td>9444</td>
</tr>
<tr>
<td>Plantain Leaf</td>
<td>7742</td>
<td>8110</td>
<td>8652</td>
<td>8487</td>
</tr>
<tr>
<td>Plantain Stem</td>
<td>7491</td>
<td>8122</td>
<td>8030</td>
<td>8290</td>
</tr>
</tbody>
</table>

*Table 5: Calorific values of torrefied plantain biomass.*

_Citation:_ Ogunsuyi Helen, _et al._ “Plantain-based Integrated Biorefinery”. _EC Agriculture_ 6.5 (2020): 66-78.
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Conclusion

In this study, it is being established that plantain biomass contains significant quantity of monomeric sugar which are recoverable quantitatively under optimum experimental conditions of the hydrolysis process. The morphology of the post hydrolysed sample showed the effectiveness of the hydrolysis process. The yields of the monomeric sugar obtained showed that plantain biomass is a potential feedstock for biofuel and bio-products generation. However, better yields could still be obtained if more favorable experimental conditions are established for the hydrolysis. The carbon generated both from torrefaction and carbonization processes are potentially suitable for green coal and activated carbons for water purification respectively.

Bibliography


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