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Production of Hydrochar from Domestic Kitchen Waste using Hydrothermal Carbonization

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Abstract:

Organic waste from household at present is converted to biogas and manure through anaerobic digestion process. Often the digestion process is slow and the obtained products need additional processing further delaying utilization of waste. Hydrothermal carbonization (HTC) is a novel thermochemical process that converts domestic wet waste to useful solid fuel called hydrochar. HTC is a fast process needing only few hours and the products are sterile. This means, the produced hydrochar can be handled safely by waste handlers (paurakarmikas). HTC process involves processing the wet waste in a reactor at temperatures exceeding 180 °C for several hours in the presence of water.

The present work involves application of HTC technique to convert the household wet waste to hydrochar. A batch reactor was designed and fabricated to withstand temperatures above 250 °C, and pressure of about 1.5 MPa. The experiment involves heating the reactor and its contents to temperatures of 200 °C for up to 2.5 hours in an oven. The hydrochar thus obtained was checked for its microstructure and composition using SEM and XEDS analyses. The results from the microstructure analysis shows that the food fibres are not completely broken down at the experimental conditions. Overall, the hydrochar had porous structure with pore diameters in the range of 10 - 100 µm. The XEDS analysis shows the presence of Nitrogen and Oxygen along with Carbon, which indicates hydrochar as an alternative fuel and can lead to safe disposal of wet waste.

***Keywords:** Hydrothermal Carbonization, hydrochar, Waste to energy*

I. INTRODUCTION

The conversion, emission and sequestration of the element carbon is all part of carbon cycle in nature. Carbon cycle on Earth has been altered due to human activities in ways that natural processes cannot restore carbon cycle to pre-industrial revolution state. (Huang, 2016), (Davis. Jackson. W., 2017) Nations are evaluated and compared based on the use of energy in the form of fossil fuel usage and foreign oil dependency. Major geopolitical events are partly rooted in the crude oil prices and availability. (Aurelio F. Bariviera, 2017)

Urbanization in developing countries have contributed to increased household waste generation. The wet and dry waste is a consequence of higher standards of living that produces mixed municipal solid waste that is difficult to process. Further the current methods of waste disposal and recycling needs technologies that create better waste management practices. Biochemical and thermochemical methods are routinely used in waste management. Biochemical reactions such as composting is time consuming and will produce carbon dioxide sludge along with methane in the form of biogas. The sludge that is produced in this process needs to be disposed or managed. Typically, the sludge based manure is produced, which may have harmful chemicals that prohibit the direct use in fields. The sludge can be combusted in co-combustion process in industries including cement production and energy sector. However, co-combustion of dried sewage sludge with coal releases gaseous mercury emissions higher than combustion of medium quality coal. (Sang-sup Lee, 2017)

There are other wet thermochemical processes that are well suited for these kinds of waste including low temperature hydrothermal carbonization (HTC), subcritical hydrothermal liquefaction (HTL) and supercritical hydrothermal gasification (HTG). HTG, also known as super critical water gasification operates above the critical point of water to produce gaseous product known as syngas with typical constituents predominantly including methane and hydrogen. HTL process involves the production of bio-oil by processing the waste with the use of steam above 250 ^{o}C but below critical point of water. HTC process produces hydrochar at low temperature range of 150 to 250 ^{o}C. The low temperature requirement makes the process energy efficient, the produced hydrochar is sterile as the temperature range is well above autoclave temperature of 120 ^{o}C. These processes and their steam requirements is discussed in literature and are graphically illustrated in figure 1. As can be observed, the near saturated steam in the reactor denatures proteins, dehydrates the biomass and carbonizes the carbohydrates, sugars and fibers in food. The steam will be in the saturation region as there is no superheating of steam.

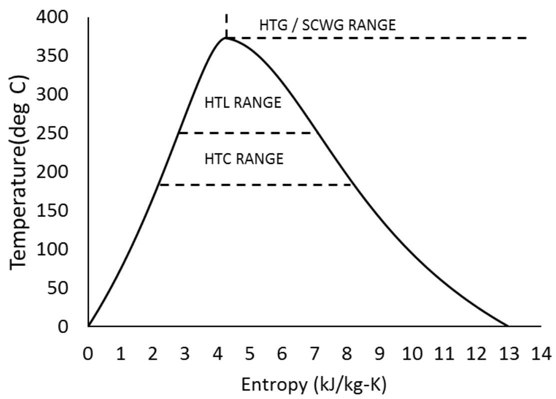

Figure 1: HTC, HTL and HTG process operation region in a Temperature – Entropy chart for steam

Chemical composition of hydrochar is highly influenced by the raw materials used in HTC process. This indicates that the is used in a variety of applications including co-generation in power sector, soil conditioner in agro industries, activated carbon as adsorbents, Lithium ion battery electrodes. (Simsir, 2018) and hydrochar chemical catalyst from glucose HTC. (Román, 2018)

Hydrochar as fuel:

The hydro-char produced contains particles in the range of few microns to nanometers can be de-watered easily, as the particles tend to agglomerate and settle. The sewage sludge and biogas digested slurry typically have heating values of 7 to 15 MJ/kg. (Escala, 2015) At present there is conflicting reports about the increase in heating value of uncompressed hydro-char compared to the feedstock. (Kambo & Dutta, 2015) (Reza, 2013) (Malatak, 2015) But the combustion of hydro-char is expected to be easier with less tar production and more stable compared to the combustion of sludge or digested slurry. (He, 2013) Co-firing hydro-char with fossil fuels like lignite is reported to improve the combustion characteristics. (Liu, 2012) (Kambo & Dutta, 2015)

HTC breaks down the hemicellulose that has branched structure. This breakdown is associated with removal of inorganic elements and resulting in reduction of ash and tar during the hydro-char combustion. It is reported up to 90% of calcium, magnesium, sulphur, phosphorus, and potassium were removed along with some structural silicon. The slagging and fouling indices are reduced due to removal of these inorganic elements. (Reza, 2013) Since the hydro-char contains particles in the micro and nanoscale with porous carbonaceous materials, the mass density of compacted pellets is higher compared to biomass digested slurry or sewage sludge pellets. (Titirici, 2007) The volumetric energy density of such a compacted hydro-char is much higher compared to dried sludge or biomass digested slurry. (Kambo H. S., 2014)

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II. Modeling the hydrochar yield from HTC:

The wet waste produced in kitchen predominantly consists of sugars, starch, cellulose and types of lignin. The carbonization process of these food consists of removal of inorganics, oxygen and hydrolysis of glycosidic bonds. The HTC method of carbonization involves multiple reactions and is dependent on the type of feedstock used. This carbonization reaction is modelled as a two-step process to produce hydrochar. (Kladisios, 2018) (Basso. D., 2014) The initial biomass is converted to an intermediate compound and volatiles, volatiles are again produced due to conversion of the intermediate compound to the final hydrochar. The steps are shown in figure 2 below.

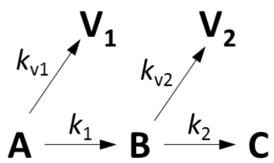

Figure 2: A two-stage reaction kinetics representation for HTC

The HTC reaction is assumed to be happening at constant temperature, and the reactions are modelled as first order reaction. The reaction rate dependence on temperature is given by the Arrhenius equation. (Basso. D., 2014)

$$k = -k_0 e^{E_a/RT} \quad (1)$$

where, k_0 is the proportionality factor, E_a is the activation energy (J/mol), R is the universal gas constant (J/mol K) and T is the temperature (K). Equations (2) to (6) describe the two step model for the HTC reaction.

$$\frac{dm_A}{dt} = -k_1 m_A - k_{v1} m_A \quad (2)$$

$$\frac{dm_B}{dt} = k_1 m_A - k_{v2} m_B - k_2 m_B \quad (3)$$

$$\frac{dm_C}{dt} = -k_2 m_B \quad (4)$$

$$\frac{dm_{v1}}{dt} = k_{v1} m_A \quad (5)$$

$$\frac{dm_{v2}}{dt} = k_{v2} m_B \quad (6)$$

where, m_A, m_B and m_C are the masses of feedstock, intermediate product and hydrochar respectively. m_{v1} and m_{v2} are the masses of produced volatiles. The individual reaction rates for the yield of intermediate compound, and hydrochar is k_1 and k_2 and that for the production of volatiles are k_{v1} and k_{v2} respectively. The reaction rates for a variety of feedstock are presented in literature. (Román, 2018), (Basso. D., 2014), (Kladisios, 2018) The experimental parameters for high hydrochar yields was 190 to 200 ^oC and a residence time of 3 hours. The initial heating time and the time for cooling the reactor is not included.

The mechanism of carbonization is assumed to be following spherical shrinking core model. (Iryani. D. A., 2016) The model is able to predict the decomposition and hydrolysis of sugarcane bagasse that yields the intermediate products. These intermediate products include arabinose and xylose from hemicellulose, phenolic compounds from lignin, and decomposed cellulose. The temperature ranges for these reactions are reported to be 200 – 240 ^oC for hemicellulose, 240 – 270 ^oC for cellulose and 200 – 300 ^oC for lignin.

III. HTC Method and Experimentation:

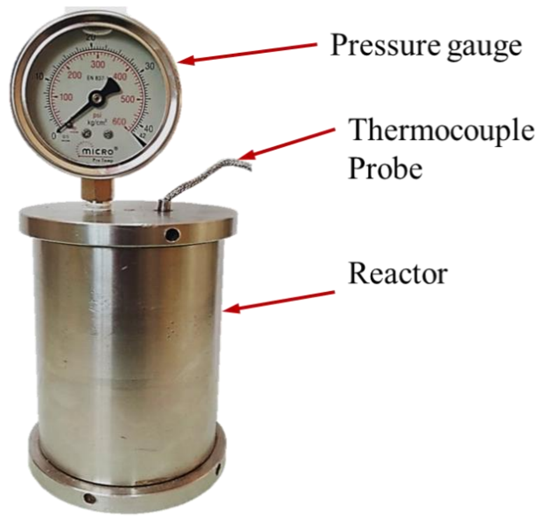

Figure 3: Hydrothermal Carbonization setup with pressure and temperature measurement

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A stainless steel reactor with a volume of 0.22 liters was used for the experiments. In total three experimental trials were conducted. The reactor was heated in an industrial oven to a temperature of 180 to 200 ^{o}C. The pressure and temperature were measured and was found to be meeting the saturated steam conditions. The feedstock contained leftover rice, cooked vegetables like tomatoes, and seasoning used in cooking. The biomass to water ratio used is 50 / 50 w/w. The residence time for carbonization is found to be 2 hours based on the calculations from equation (2) to (6) with reaction rate values reported by (Kladisios, 2018). The initial transient heating of the reactor till it reaches HTC temperature is neglected in calculating the residence time. The produced hydrochar is dried in room atmosphere for further investigation. The dried hydrochar was observed under optical and scanning microscope.

IV. Results, Discussions and Conclusions:

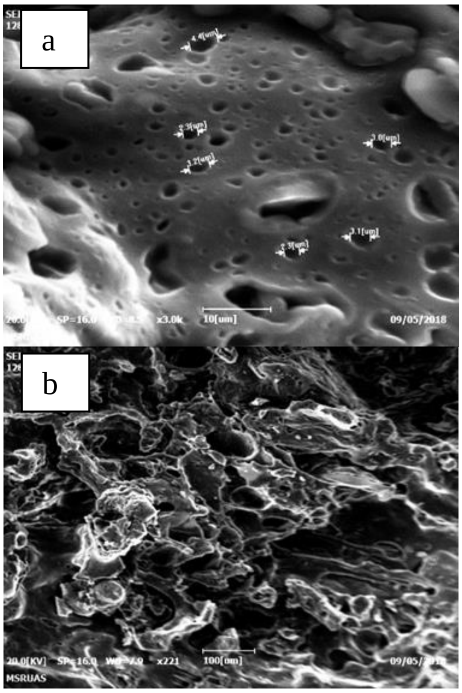

Figure 4: Scaning electron microscope images of hydrochar (a) tomato peel (b) rice

The total yield of hydrochar is calculated as shown:

$$yield = \frac{\text{dried hydrochar mass}}{\text{dried feedstock mass}}$$

The hydrochar yields for the experimental trials are in the range of 65 to 75%. Figure 4a shows the scanning electron microscope images of hydrochar containing tomato peels. These peels retained overall structure after HTC due to the presence of dietary fibres containing cellulose, resistant starch, resistant dextrins, lignins, chitins, and pectins. (Inmaculada Navarro-Gonzalez, 2011) Figure 4b shows the hydrochar produced from rice. The results of decomposition and carbonization reaction of starch can be observed. The rice shows typical core shrink behavior.

V. Conclusions:

Kitchen waste containing left over rice, vegetables, and seasoning were used processed in a HTC reactor. The produced hydrochar was analysed in a SEM and optical microscope. Following are some of the conclusions that can be drawn from the current research.

1. Particle size of the feedstock directly impact the HTC processing time, initial rough grinding process would help to reduce the particle size and complete the carbonization faster
2. Tomato peels retained overall structure after HTC due to the presence of dietary fibres.
3. Further refinement of reaction rates are needed for carbonization of domestic wet waste from kitchen
4. The range of pore size in the obtained hydrochar is from 10 to 100 micrometers conducive as lignite substitute or soil conditioner.

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