Gasification Behaviour of Biomass Following Pretreatment by Hydrothermal Carbonisation

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ABSTRACT: Hydrothermal carbonisation of Willow biomass was performed at 200^0C and 250^0C with a high pressure batch reactor (Parr USA). The physical and chemical characteristics of the Willow and resulting chars were determined using ultimate and proximate analysis. Data analysed from literature in a Van-Krevelen diagram show hydrochars have better fuel quality than their initial biomass feedstock. The composition of syngas was predicted for steam gasification by stoichiometric calculations. The prediction shows that hydrochars produced from lignocellulosic biomass have better syngas quality with an increased H2/CO ratios than their raw biomasses, there is however an observed decrease in the H2/CO ratios in feedstocks with high moisture. The gasification behaviour of Willow and its hydrochars was investigated using a Mettler Toledo TGA equipment and a NETZSCH STA 449 for steam gasification at different temperatures and heating rates to evaluate the impact of the HTC process on the gasification process. Coal was used as control and compared to the behaviour of the HTC samples. Three decomposition zones were observed during the degradation of the biomasses: Dehydration, active pyrolysis, and passive pyrolysis representing moisture removal, cellulose degradation, and lignin decomposition respectively. The dehydration stage was not accompanied by significant mass loss for the HTC samples unlike the raw biomass. The decomposition rate of HTC200 Willow, and in effect, conversion to gas phase was found to be slower than the original willow sample in TGA and DTG curves using Nitrogen as a carrier gas, an even slower rate was observed for the HTC250 biomass due to increased carbonisation and lower volatile matter content with a corresponding increase in the calorific value of the biomass. Results from kinetic analysis predict the activation energy of 33.4kJ/mol, 41.7kJ/mol, and -58.0kJ/mol respectively for dehydration, active pyrolysis, and passive pyrolysis of the raw Willow. 48.9kJ/mol and -55.6kJ/mol are the calculated activation energies for zone 2 and zone 3 respectively for HTC200, while 31.1kJ/mol and -51.9kJ/mol for HTC250. Addition of steam as a gasifying agent promote water gas shift reaction that causes higher heat transfer coefficient between the biomass and the bulk gas thereby decreasing the reaction time with better syngas quality. The decomposition rate was increased by increasing the temperature while heating rate does not significantly alter the decomposition behaviour. The pyrolytic and gasification behaviour of HTC250 Willow closely resemble that of a high grade coal with reduced thermal reactivity, lower conversion rate to gas phase, and an increased calorific value.

Keywords: Hydrothermal Carbonisation, thermogravimetric analysis, gasification, kinetics, syngas, activation energy.

I.   INTRODUCTION

Biomass is readily available renewable energy source derived from all living matter and distributed all over the world, use of biomass in energy production can reduce atmospheric CO2 emissions and provide fuel security. Main sources of biomass in energy generation are crops and wastes. However, biomass is excessively moist substance with low energy density and consequently low heating value, they are difficult to transport, contain lots of volatile matter and inorganic impurities that limit their application for

use as energy sources. To cater for this, upgrading (pre-treatment) processes were developed including carbonisation or pyrolysis and torrefaction that results in increased reactivity by releasing volatile matter and altering the hygroscopic materials to hydrophobic ones. Upgraded biomass via torrefaction are called torrefied biomass while those made from carbonisation are called biocoals consisting of biochar and hydrochar for dry and wet carbonisation processes respectively (1-3).

Hydrothermal carbonisation or upgrading process involves the use of hot saturated water to thermally degrade biomass (woody, fruity, or herbaceous biomass) into a Carbon-rich, coal-like solid material, called hydrochar under mild hydrothermal condition, at temperatures of 180-260C, whose heating value resembles lignite coal. (4-8). The hydrochar produced is hydrophobic, contains low-sulphur, is non-toxic, and is easily friable with higher energy density which is achieved through the reduction of Oxygen and to Hydrogen content (O/C and H/C ratios) that destroys the colloidal structure of the fuel. The molecular level of water is altered during this process which influences the solubility, viscosity, and the polarity of biomass (9). HTC is an exothermically bound process for pure compounds and has better energy generating capacity than dry carbonisation process especially for feedstocks with high moisture contents (10).

Hydrochar is a credible alternative to coal in energy production, it is useful in Carbon sequestration, waste water pollution remediation, as activated Carbon adsorbent, nutrient conservation, in agriculture, and bio refinery, increasing Carbon stock in soil (8, 11). Hydrochar will help reduce net CO_2 emissions due to carbon cycle (12).

Gasification of biomass involves the thermochemical conversion of carbonaceous material within a reactor to produce a synthetic gas containing primarily H_2 and CO, with a lower proportion of CO_2, H_2O, CH_4, higher hydrocarbons, and N_2. Biomass is the only naturally occurring carbon resource whose energy is sufficient enough to substitute fossil fuels (13, 14). Biomass has a tendency of producing negative CO_2 emissions, it is cost effective and a sustainable energy source, and lowers greenhouse gas emissions thereby facilitating the attainment of greenhouse gas reduction targets, and produce clean and renewable energy.

The physical properties and chemical compositions significantly affect the gasifier operations, product gas composition, and the efficiency of the biomass-based power generation (1). Biomass with high moisture content yields higher H_2 gas through the water gas shift reaction in the presence of CO, and subsequently, more CH_4 is formed by direct hydrogenation. However, the loss of energy from reduced CO leads to a lower calorific value which is not adequately compensated by the increased H_2 production. Feedstocks with high ash content severely affect the gasification process since the oxidation temperature of the mineral content is usually above the melting point of the biomass ash and this result in clinkering and slagging in the gasifiers as well as blockages. Volatile compounds also obstruct the syngas yield because tars and heavy hydrocarbons need to be destructed in the pyrolysis stage prior to gasification. Particle size is another crucial factor in the gasification process; large particles hinder the movement of feeds unlike small particles because of high pressure drop by clogging air voidages (15). Hydrochars are expected to cater for these shortcomings with reduced moisture content, low ash, and a higher energy density.

Many studies have focussed on the impact of process conditions on hydrochar characteristics using ultimate analysis, proximate analysis, and examining the H/C and O/C ratios through the Van-Krevelen diagram (5, 16-19). Others discussed pyrolysis characteristics of the hydrochars (20-22). Fate of inorganic materials extracted during the hydrochar production process as well as their impacts on the combustion behaviour of hydrochars (9), hydrochar combustion (21), and thermodynamics in addition to the pyrolytic behaviour of the hydrochars (20). Meanwhile, previous works that examined the gasification of hydrochars concentrated on steam gasification of hydrochar in sewage sludge (22-24). Some experimented on hydrothermal gasification processes (25, 26), others on supercritical water gasification Castello, D. et al. (4), (27, 28). The present study is unique because it examines gasification behaviour and kinetics of hydrochars produced from an energy crop, Willow, evaluate the syngas composition and yield, and how these characteristics differ from that of its raw feedstocks and their similarity to coal, as well its potential in replacing coal as an energy source. This, to the best of my knowledge, has not been carried out previously.

II. METHODOLOGY
2.1 Materials and Preparation
24g of Willow biomass was loaded with 220ml biomass into a 600ml high pressure (Parr USA) bench top reactor in energy research laboratory, University of Leeds, given it 10% solid loading. The mixture was heated at a rate of

8^0C/min up to 200^0C when it was held for 1 hour and at an isobaric pressure of 16bar. It was allowed to air cool and the gaseous products released to the atmosphere while the liquid and solid substances were filtered. The same procedure was repeated for 250^0C.

Samples of these hydrothermally carbonised Willow hydrochars and their raw biomass was used in investigating the gasification experiment. Sample of high rank coal also was also obtained in the institute for the experiment. Results from the ultimate and proximate analysis of these samples are given in Table 1. Raw and HTC Willows are also available in literature (9).

Table 1 Characteristics of the feedstocks used.

Sample	C %	H%	N%	O%	Ash (wt.%) db	S%	Gross Calorific value (MJ/kg)
Raw Willow	45.3	6.2	0.5	43.8	4.1	0.1	16.4
Willow HTC200	58.9	7.2	1.4	29.0	3.5	0.2	25.0
Willow HTC250	70.4	5.3	1.3	20.2	2.7	0.1	27.8
Coal	45.54	3.71	0.99	42.6	33.15	7.16	

Raw and HTC biomass feedstocks with 5-10cm sizes were grounded with a retched grinder to obtain a homogenised fine powder with an improved surface area that will facilitate the gasification potential of raw and HTC biomass feedstocks while minimising diffusion resistance, small sized-particles prevents clogging and air voidages that would otherwise occur when larger particles are used due to high pressure drop (15). Mass and heat transfer limitations often affect the result of the pyrolytic process when varying weight of samples are analysed, delaying the dehydration step and given higher residues when using large sample quantity (32) (33), thus, for uniformity, all the samples used were weighed to a range of 10-13mg to overcome these effects.

2.2 Gasification Procedure

Three samples each for raw willow, HTC200, and HTC250, were appropriately weighed and inserted in the crucibles of Mettler Toledo TGA equipment and was run at different heating rates of 10K/min, 15K/min, and 20K/min. The temperature profiles for the different runs began at ambient temperature, ramped at a heating rate of 15K/min up to 105C temperature, it was then held for 10 minutes, then heated continuously at 10K/min until it reaches 900C where it was held for 15 minutes to fully gasify. Nitrogen was used as a carrier gas in the experiment flowing at 50ml/min from the ambient temperature up to the gasification temperature. At the 900C temperature, the flow of nitrogen was replaced with air also at flow rate of 50ml/min. The procedure was repeated for the three samples and the heating rate from 105C to 900C was changed for 15C/min and 20C/min.

2.3 Steam Gasification Procedure

The water vapour furnace was chosen for NETZSCH STA 449 analysis. About 10mg was loaded to crucible and ran according to temperature profile in Table 2.

Table 2 for Thermal Anal STA 499 F3

S/No	Temperature type	Temperature (C)	K/min	Time (min)	N2 (ml/min)	N2 (ml/min)	Vapour Generator
1	Starting	110					

2	Isothermal	110		10.00	40	20	
3	Dynamic	400	15	19.19	40	20	
4	Isothermal	400		10.00	40	20	
5	Dynamic	1000	20	30.00	40	20	
6	Isothermal	1000		40.00			X
7	Emergency	1020					

The dynamic Nitrogen atmosphere was made to flow constantly at 40ml/min and at 20ml/min as protective and purge gas respectively throughout the process to provide an inert environment and avoid interference with pyrolysis products, the temperature was held for 10mins at 400^{0}C for complete moisture removal before it was raised to gasification temperatures of 800^{0}C, 900^{0}C, and 1000^{0}C analogous to literature, the choice of steam as a gasifying medium is govern by its reputation for improving the gasification yield of biomass through the provision of high transfer coefficient between solid sample and the bulk gas(33).

The above profile in Table 2 was for the evaluation of steam gasification behaviour of Raw Biomass Willow at 1000C temperature, same procedure was repeated for hydrothermally carbonised Willow at 200C temperature and at 250°C, as well as for coal sample for their steam gasification behaviours at the 1000C temperatures. The procedure was repeated for the four samples but with vapour generator unchecked which give the gasification behaviour of the sample at the temperature of 1000C without steam being generated in the process.

III. RESULTS AND DISCUSSION
3.1 Chemical characterisation of hydochars
Results from the ultimate analysis of raw and HTC biomasses obtained from literatures (4, 9, 16-18, 29, 30) was used to plot the atomic ratios of H/C against O/C to investigate the fuel quality of the biomasses and their hydrochars in figure 1
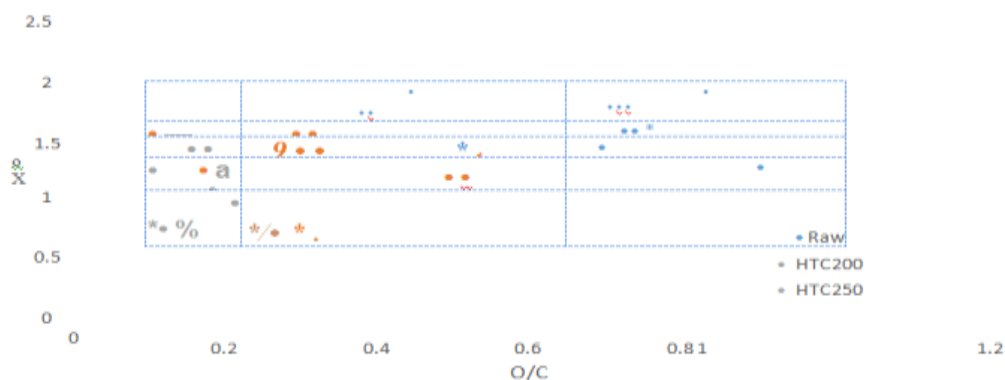
Figure 1 Van-Krevelen diagram showing the comparison of H/C and O/C atomic ratios biomass and their HTC samples

It can be observed from Figure 1 that the HTC200 biomasses have lower H/C and O/C ratios than their raw biomass counterparts, this implies more favourable fuel characteristics with decreased energy losses, reduction in water vapour and reduced smoke. The HTC250 has even lower atomic ratios than the HTC200 which implies that increasing the HTC temperature result in an improved fuel quality.

3.2 Stoichiometric Calculations
Steam gasification equation was used to predict the yield of raw and HTC biomass samples from ultimate analysis results based on data obtained from literature.

$$CnHmOk+ (n-k) H2O \qquad nCO + (n+0.5m-k) H2$$

The results from the CHNS analysis obtained from various literature was used to obtain the possible number of moles that would have been obtained in an ideal situation considering the atomic masses of the elements. The ratio of the number of moles of H_2 to that of CO was evaluated to predict the syngas quality of the raw and HTC biomass and are given in Figure 2.

(c)
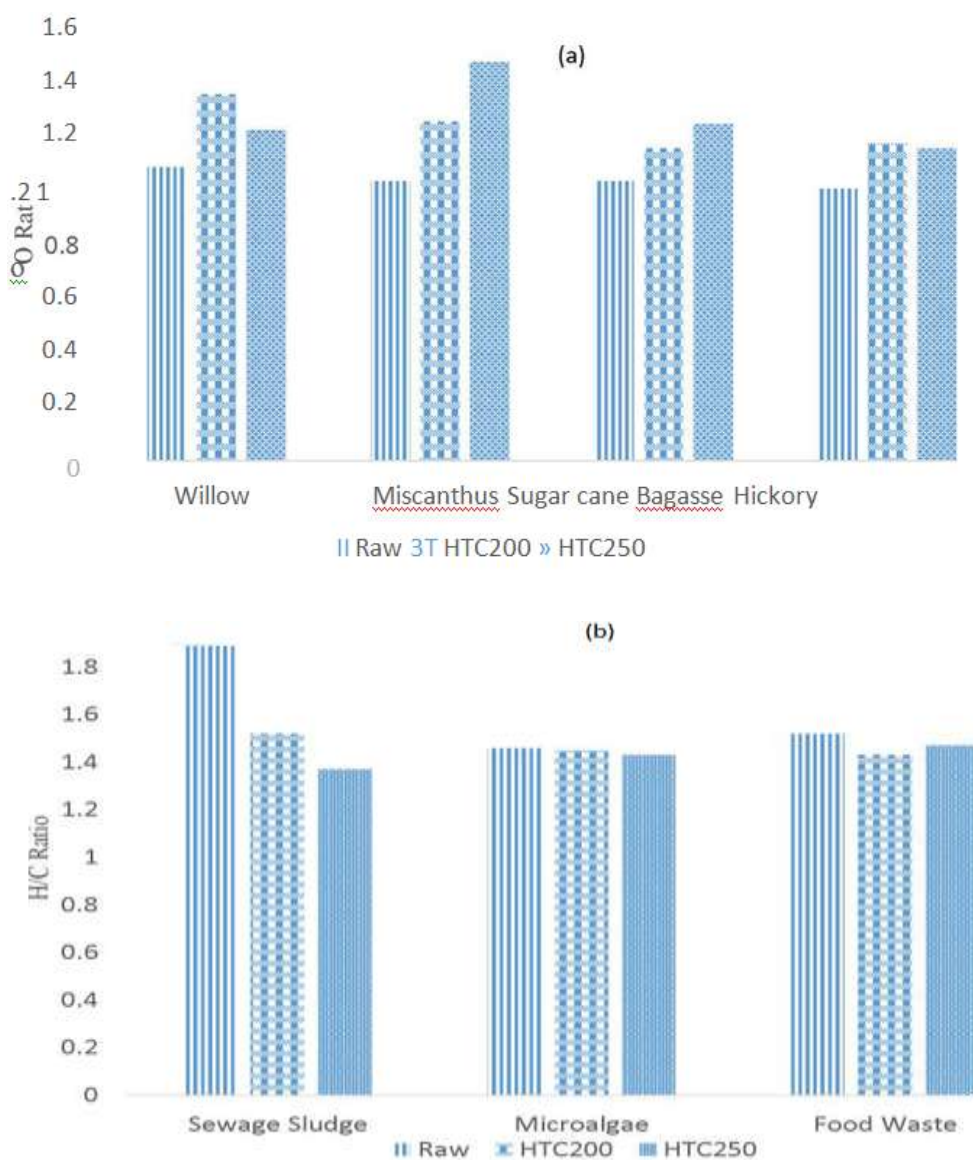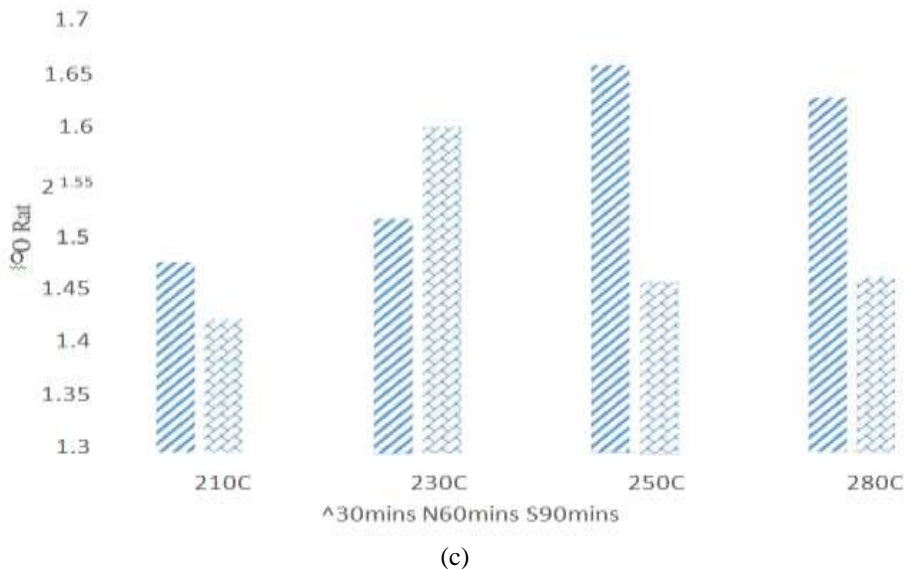
Figure 2 Stoichiometric prediction of syngas quality for (a) Woody biomass, (b) Nitrogenous biomass, and (c) Reaction time effect of HTC from MSW.

Figure 2 (a) shows the predicted quality of syngas yield in woody biomass which clearly shows the significance of the HTC process on the expected syngas yield, the ratios of H to CO in Willow, for example, shows an improvement in the syngas quality from the raw Willow sample to the HTC200 biomass, signifying an increased hydrogen yield, there is however small reduction of the H_2/CO ratio from HTC200 to HTC250 but still higher than that of the raw feedstock, this might because of the degradation of cellulose 250^0C that can be accompanied by loss of hydrogen. Sugar cane bagasse and Miscanthus however, show a consistent increase in the H_2/CO ratio from raw to the HTC200 to HTC250. The trend is however different in figure 2 (b) when highly nitrogenous compounds are considered, sewage sludge shows reduced H_2/CO ratio from raw sample to HTC200, similarly, HTC250 has lower ratio than HTC200 due to decreased H_2 content during hydrothermal carbonisation from the degradation of organic fractions and removal of inorganics. More so, experiment on sewage sludge reveals that the raw biomass has a higher calorific value than the resulting hydrochars [9]. No clear correlation can be deducted from the effect of time on the expected syngas quality from MSW HTC process in figure 2(c), it can however be said that the optimisation of the temperature and reaction time is needed to predict this behaviour, for example, the highest ratio observed is at 250^0C with 30minutes residence time, a different result may be obtained when different feed is investigated especially because MSW does not have a distinct composition.

3.3 Thermogravimetry and Derivative Thermogravimetry

The selection of the temperature profile involving alternate isothermal and dynamic temperatures above was inspired by similar experiment on Steam-Nitrogen gasification of biomass (33). To ensure complete moisture removal the temperature was kept at 110^0C for 10 minutes before ramping especially since the process could not begin from an ambient temperature, similarly, the temperature was held at 400^0C to ensure complete pyrolysis of the biomass, and then ramping to the gasification temperature were it was held for 20 minutes to be able to extract any possible gas that might evolve from the samples.

For the raw Willow sample, noticeable degradation is observed from 33^0C temperature which continues up to around 120^0C representing the drying phase of devolatilisation of the biomass characterised by removal of moisture from the Willow as seen in figure 3(a) with about 9% weight loss, the trend is followed by somewhat negligible weight loss from the 120^0C up to 250^0C, which might represents removal of light volatile compounds before the pyrolysis stage which goes on rapidly with high heating rate from 270^0C to about 370^0C temperatures losing more than 65% of its weight while given off pyrolysis product, this rapid weight loss can be seen in the DTG curve of the raw willow with the appearance of its highest peak at a temperature of 370^0C in figure 3.1 (b) of

the dm/dt versus temperature plot, a lower weight loss rate was then noticed immediately after the pyrolysis stage up to the 900^0C when the biomass sample was fully gasified. Different trend was however observed in the TGA curve of both HTC200 and HTC250 biomass from the beginning: For the HTC200 Willow, it can be observed that moisture removal (drying phase) of devolatilisation phase in the curve is not accompanied by significant mass loss, this is because the HTC is already a char having undergone this phase during the hydrothermal carbonisation process, there is also unlikely evolution of gases in the phase, hence its decomposition goes on steadily, losing only a small proportion of its mass, when the pyrolysis stage takes up at around 320^0C temperature with

higher decomposition rate and the greater degradation as it losses about 53% of its initial weight as pyrolysis gases are evolved in the process, the steep decline was replaced by a steady decomposition from the temperature of 430^0C up to the gasification temperature. HTC250 decomposes via a similar terrain as the HTC200 but with a lower decomposition rate leaving up to about 43% of the initial mass of char to be gasified at the 900^0C gasification temperature. The low decomposition of the HTC250 sample implies that it has higher energy density than HTC200 and the raw Willow meaning that the product gas from the process will have an increased useful gas composition (less H2O and CO2), better energy yield, and higher calorific value(33).
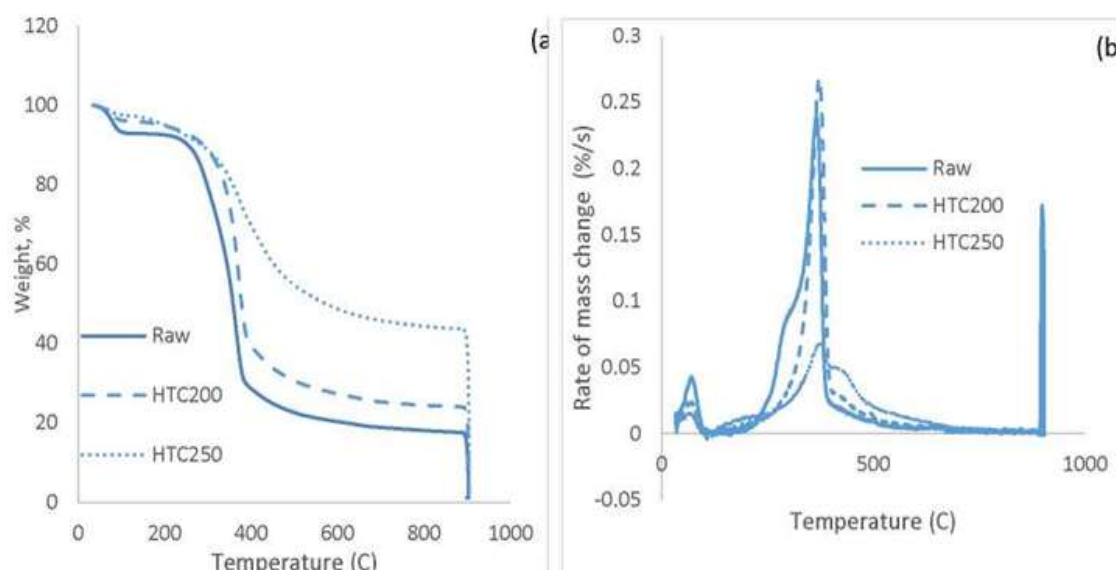

Figure 3 (a) TGA behaviour of Raw and HTC biomass (b) DTG in air gasification

Figure 3.1 (b) shows the rate of decomposition of Raw, HTC200, and HTC250 Willow biomass gasified under same condition of 900C and the ramp rate of 15K/min up to the gasification temperature. High reactivity of raw willow can be observed from the beginning of the experiment rising up to 0.05% of its percentage weight per second at about 70^0C temperature, this stage corresponds to the drying stage of the biomass, as the inherent moisture present in the raw Willow was removed, a lower rate is observed for the HTC200 willow biomass and the least for the HTC250, this may be because some volatile compound especially CO2 is lost by decarboxylation during the hydrothermal carbonisation process as stated in the literature discussing the chemistry of the HTC process(11). The raw biomass has shown clear difference with

the HTC samples with the appearance of shoulder at 280C before reaching its highest peak which is true for lignocellulosic biomass stated in previous work(35), this might be as a result of the decomposition of hemicellulose. The stage where the highest peak was observed from the curve is the temperature of 370^0C for all the three samples which is consistent with literature for the lignocellulosic biomass (36), characterised by decomposition of cellulose(35), there is however, huge difference in the rate of decomposition of HTC250 and others: about 0.27%/s for the raw and HTC200 and 0.07%/s for HTC250, this might be because the HTC250 has achieved greater level of carbonisation and tends to behave more like coal than being a biomass as it can be seen in relating the gasification behaviour of the HTC biomass to that of coal under the presence of steam in later

stages of this work. The HTC250 also differs with HTC200 and the raw biomass TGA as the latter 2 showed a wide tail attributed to lignin decomposition followed by char formation(35) immediately after the reaching the highest peak. HTC250 on the other hand showed a shoulder at around 400C before the tail, meaning that it has

lost part of its lignocellulosic characteristics.

3.4 Kinetic Analysis

The modified form of Arrhenius equation obtained from literature (12) was used in determining the activation energies at various devolatilisation phases in the TG curve

Substituting for conversion, $X = \dfrac{W-Wf}{Wo-Wf}$ (6)

$-\ln\left[\dfrac{1}{Wo-Wf}\dfrac{dt}\right] = \ln A - \dfrac{E}{RT} + n\ln\left[\dfrac{W}{Wo-Wf}\right]$ (7)

Assuming n = 1, equation 6 becomes

$\left[\dfrac{1}{Wo-Wf}\dfrac{dw}{dt}\right]$ $\dfrac{W-Wf}{Wo-Wf}$ $\ln A - \dfrac{E}{RT}$ (8)

$-\dfrac{dX}{dt} = KX^{n}$ (2)

Substituting the Arrhenius equation

$\dfrac{dX}{dt} = (Ae^{-E/RT}) X^{n}$ $K = Ae^{-E/RT}$ (3)

Taking ln on both sides

$-\ln\dfrac{dX}{dt} = \ln A - \dfrac{E}{RT} + n\ln X$ RT (4)

(5)

The left hand side of the equation was then plotted against ■ ■ the activation energy, E was determined K! as the slope of the graph and the intercept used to obtain the pre exponential factor.
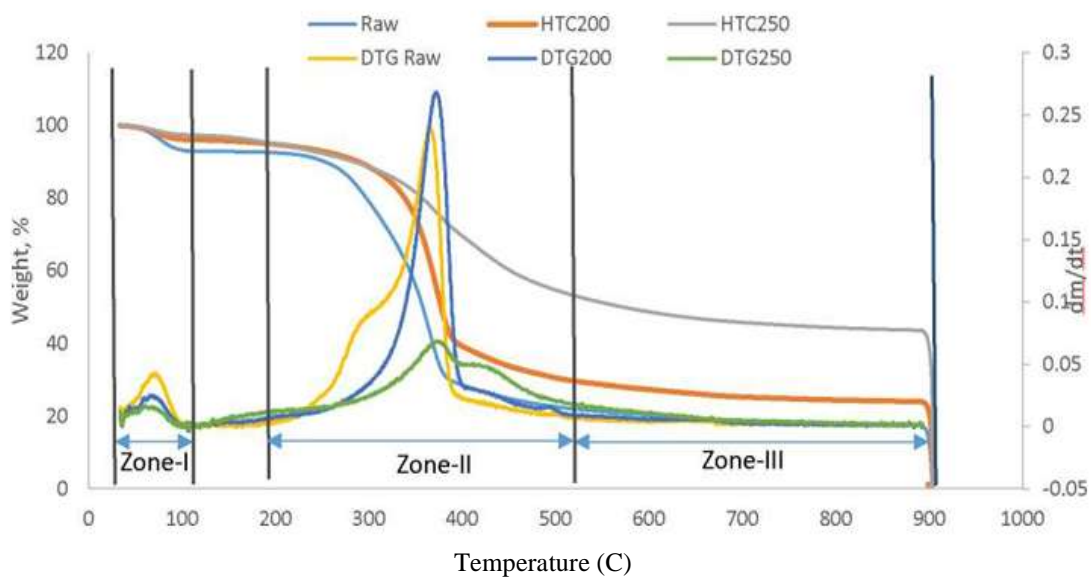

Figure 4 The TGA and DTG behaviour of raw and HTC Willow

Three distinguished zones can be identified from the figure: Zone I represent moisture removal or dehydration, Zone II represent hemicellulose-cellulose degradation, while Zone III is the lignin decomposition as discussed earlier in the relationship between temperature and percentage decomposition. The plots of the LHS of equation 8 against $1/RT$ for the different zones give relevant equations for each zone as shown in Table 3. Zone I is only applicable for the raw Willow as can be observed from the TG curves of the HTC biomasses

Table 3 Equations of the regression line at various decomposition zones

Feedstocks	Zones	Equation	Correlation coefficient, R^2
Raw Willow	Zone I	y = 33355x - 3.4866	0.7234
	Zone II	y = 41665x - 1.0062	0.7231
	Zone III	y = -57790x + 19.702	0.8681
HTC200	Zone II	y = 48884x - 2.2411	0.7665
	Zone III	y = -55622x + 18.843	0.9872
HTC250	Zone II	y = 31110x + 2.1356	0.8713
	Zone III	y = -51886x + 17.102	0.9873

The dehydration of the raw willow (Zone I) shows that the activation energy (slope) is 33.355kJ/mol and the pre exponential factor obtained by taking the exponent of the intercept is 0.0306/s while the correlation coefficient is 0.7234. Zone I was excluded from the HTC200 and HTC250 since the weight loss at this stage is insignificant. Zone II provide the activation energies for cellulose decomposition respectively for raw, HTC200, and HTC250 as 41.665kJ/mol, 48.884kJ/mol, and 31.11kJ/mol. The pre exponential factors are 0.365/s, 0.106/s, and 8.42/s respectively. Activation energies of the lignin decomposition have negative values in agreement with literature (12) since the decomposition of lignin decreases with increasing temperature and the decomposition rate is slow. Thus, the activation energies for raw, HTC200, and HTC250 are respectively -57.79kJ/mol, -55.62kJ/mol, and -51.89kJ/mol. The pre exponential factors are respectively $3.6 * 10^8$ /s, $1.25 * 10^8$ /s, and $2.67 * 10^8$/s.

3.5 Influence of process conditions
Conversion of raw, HTC200, and HTC250 Willow biomass were calculated using an equation used by Silva et al in the literature (32).

$$X = (W0 - W)/(W0 - Wf) \tag{1}$$

Where W0 is the initial weight of the biomass/char, W is the weight of the biomass/char and any instant, Wf is the final weight or the residual weight at the end of the gasification, and X is the conversion of the char/biomass at W.
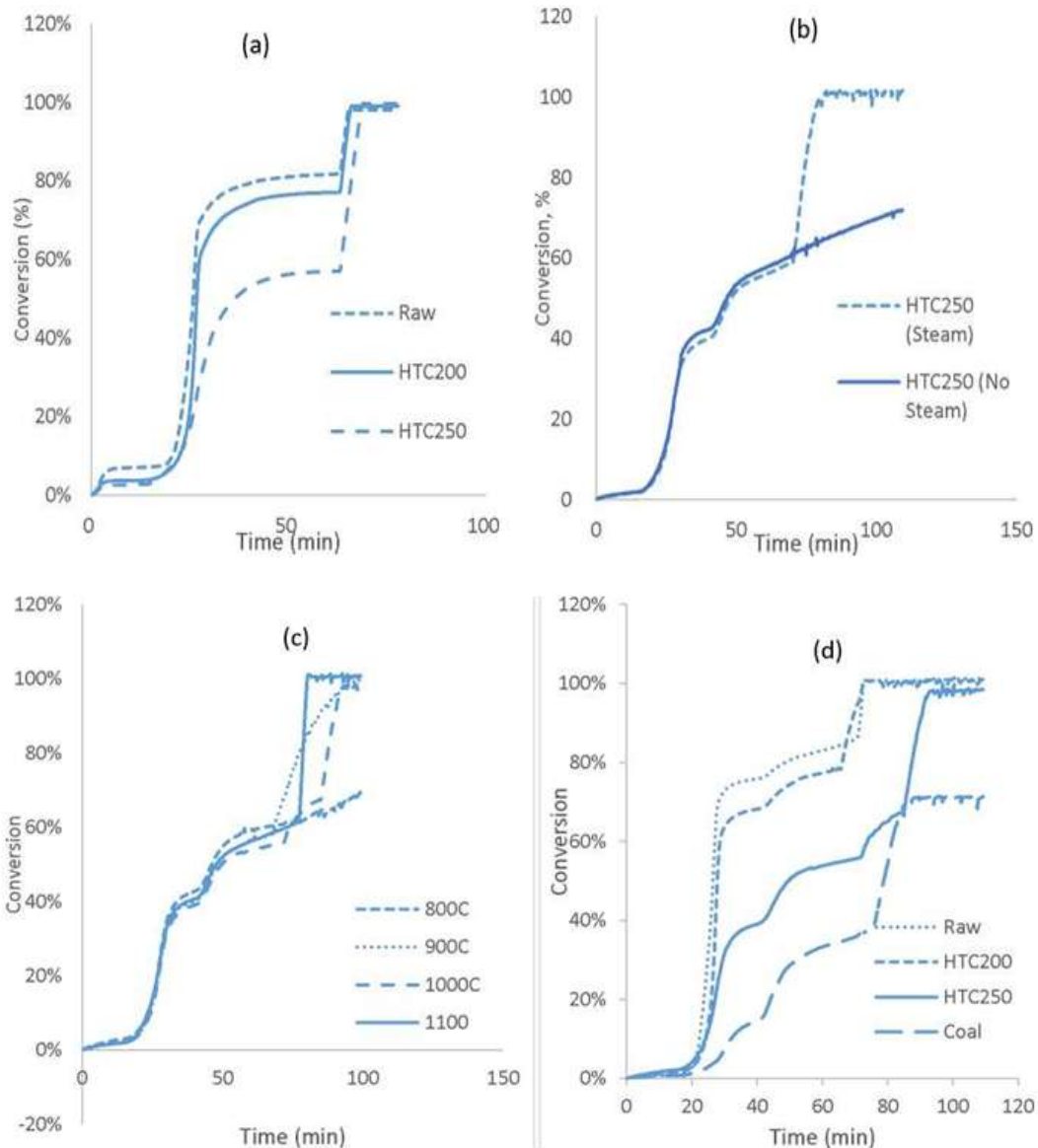
Figure 5 Plots of conversion against time (a) effect of hold time (b) Effect of steam (c) Temperature effect (d) Comparing steam gasification raw, HTC and Coal at 10000C

From the figure 3(a), differing behaviour can be observed according to the form of biomass under consideration, the raw biomass shows a faster conversion rate with a steepest of the slopes between 2326 minutes achieving up to 68% conversion, it then rises gently to up to around 63.5 minutes to reach 82% conversion, and this is when the set 900^0C temperature was attained, the conversion of the raw biomass then rises fast to 100% in just about 1.5 minutes which is 65 minutes from the beginning the experiment. Similar trend

can be seen for the HTC200 curve, having the fastest conversion rate between 22-27 minutes reaching 60%, it then accelerates steadily up 76% conversion up to time 63.5 minutes when the temperature was held at 900C, 100% conversion was attained at 66 minutes, just a minute after that of raw biomass. For HTC250, the greatest conversion rate was achieved between times 63.5 minutes to 68 minutes, rising all the way to 100% from 56% conversion after showing far less conversion at the beginning of the process.

Table 4 Impact of holding temperature on the conversion of biomass

Sample	Conversion before hold at 900C	Conversion after hold at 900C
Raw	82%	98.1%
HTC200	76%	98.9%
HTC250	56%	99.7%

The impact of holding the temperature on the conversion and in effect the gasification process can be seen in Table 3 above. Raw Willow has 82% of its sample being converted before the hold temperature, which was further improved to 98.1% when the temperature was held at 900C, this also true for HTC200 and HTC250 whose conversion rose to 98.9% and 99.7% respectively from 76% and 56%. Therefore, the temperature of 900C can be considered as an optimum temperature for the gasification of HTC Willow samples owing to high conversion at this stage, it can also be seen that the conversion of HTC250 is higher than that of HTC200, which is also higher than Raw Willow at the gasification temperature meaning that HTC samples produce less residue, therefore less ash content than the raw samples in addition to an improve yield.

Three different behaviours can be clearly observed from conversions at temperatures of 800C, 900C, and 1000C for the same HTC250 sample in figure 3(c). The curve at temperature of 800C shows conversion of only a fraction of the HTC250 Willow as the temperature was not high enough to cause significant improvement in the conversion rate even in the presence of steam. Conversely, a dramatic rise in the conversion of the feed can be seen at 900C temperature with quite a steep slope. An even steeper slope can be observed for the experiment at 1000C showing faster conversion at a shorter reaction time, the conversion at 1100C showed almost an instant rise to complete conversion to gaseous product as higher temperature favours gaseous product yield(33)

3.4 Effect of steam on the gasification of hydrochar

It can be observed from both plots in figure 3(b) that 59.03% conversion when the temperature of 1000C was reached, however, the plot for the steam gasification has reveal dramatic increase in the conversion of biomass up to about 1after only 11 minutes at 81.25minutes according to the graph meaning complete gasification of the HTC sample was achieved. The plot without steam

on the other hand keep on a steady increase in the conversion when the temperature was held at 1000C and was only able to reach 71.95% conversion of the HTC250 biomass feedstocks even after it was held for at 1000C for 30 minutes. It can thus be seen that the steam gasification process reduces reaction time in addition to producing better yield and high quality syngas as discussed in the literature (37) as cited in this work. Thus, better yield and maximum conversion of the biomass can be reached whenever steam is used as a gasifying agent with a guaranteed increase in syngas quality as more hydrogen will be found in the product consequent of water chemistry which cannot be achieved when an inert nitrogen or air is used as the gasifying agent. Meanwhile, the presence of steam produces a higher heat transfer coefficient between char and the bulk gas(33).

3.5   Comparing HTC with coal

The relationship between the conversion of raw, HTC biomasses, and coal with time during steam gasification at 1000^0C is represented in figure 3(d), the conversion phases of raw and HTC200 behave almost the same with a characteristic conversion of lignocellulosic biomass. However, HTC250 shows a distinct conversion characteristic that mimic that of coal only that the HTC250 shows higher reactivity and faster degradation than the coal meaning lesser energy density than coal and possibly lesser calorific value, however, the not so large difference in these features implies that HTC250 can be used in place of coal in energy production as the environmental advantages of biomass and their sustainability will outweigh the little shortfall in the energy density, similarly, no sophisticated desulphurisation processes are required for the HTC gasification with very low sulphur content unlike the coal that has up to 7.16 wt. % as revealed by the results in their ultimate analysis.

IV.   CONCLUSION

Hydrothermal carbonisation process has been established as a useful biomass pre-treatment method that needs to be carried out to achieve effective gasification of biomass and produce high

quality syngas with similar energy density and calorific value as coal and at the same time avoiding the negative environmental effects of fossil fuel through the use of sustainable energy plant. It is important for the gasification process to be conducted in a pilot and commercial scale gasifiers to verify the experimental results. Detailed energy and cost analysis is also recommended in future works

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