Investigation of carbonization process parameters to manage Japanese knotweed (Fallopia japonica) in the UK

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Abstract. Japanese knotweed (Fallopia japonica) is an invasive and destructive floral species in the UK. It causes a significant problem to natural and built environments. Stems and/or rhizomes need to be burned before disposal in order to prevent further propagation [1]. This process has a high carbon footprint and a decrease is favored. Hence, carbonization of Japanese knotweed into char, bio-oil and syngas has been proposed. In this paper, carbonization has been demonstrated to be possible. Japanese knotweed can be separated into 2 main parts: stems and rhizomes. Both parts were characterized for their chemical, physical & thermal properties and subsequently carbonized between 300 to 800°C with the duration held for 1h and 2h. It was found that stable carbonization parameters occurred at 600°C with duration of 1h. At higher temperatures, no further formation of char, oil or gas occurred. The calorific values for Japanese knotweed stem char and bio-oil were 31.2 MJ kg⁻¹ and 13.7 MJ kg⁻¹, respectively, whereas those for Japanese knotweed rhizomes char and bio-oil were 31.7 MJ kg⁻¹ and 23.3 MJ kg⁻¹, respectively. Carbonization may therefore, be a viable bio-fuel option for the management of Japanese knotweed.

1. Introduction
The growing recognition that global resources and materials are being consumed at a rate that is unsustainable for the long-term stability of society has resulted in the acceptance that better resource management is needed. In the developed world, the generation and management of waste biomass from horticulture, agriculture and food processing is an increasing problem and consequently, it has been identified as a material with potential for significant energy recovery and resource reuse. Alongside these societal wastes, the long history of global trade by the UK has resulted in many non-indigenous plant species being brought to the British Isles with their widespread adoption for decorative and landscaping purposes. Most of these species are innocuous but certain invasive flora species in the UK have caused significant damage to the natural and built environment. One of the most publicized and problematic species is Japanese knotweed (JKW, Fallopia japonica).

JKW was introduced to the UK as an ornamental plant and cattle fodder in the 1850s and has since colonized nearly all of the British Isles [1]. It has been reported to cause a decline in the biodiversity of local flora by restricting neighboring native plants’ access to sunlight because of its high growth rate [2]. It damages the man-made environment, e.g., JKW shoots have been reported to break through pavements and asphalt, and the rhizomes can perforate foundations, walls and flood defense structures [3, 4]. The control of JKW spread requires physical methods such as regular cutting of stems or chemical methods such as herbicides. The cut stems and/or excavated rhizomes are disposed of by burning or burial, which was recommended as this prevents plant material from spreading [4], with disposal to landfill being discouraged as a result of the 2002 (England and Wales) Landfill Regulations.
Furthermore, there is no evidence that landfill disposal neutralizes the rhizome viability. An opportunity exists to recover energy and resources from this problematic biomass in the form of biofuels and char i.e., using JKW as a second generation bio-fuel to avoid competition with food crops [5]. This can be accomplished by carbonizing the JKW plant and thereby rendering it incapable of propagation. In carbonization, organic materials are degraded thermally under inert atmosphere. This process is also described as pyrolysis, especially when the process temperatures are < 500°C [6]. The fundamental chemistry of the two processes is similar, with the main products being char, oil and gas. However, the key objectives are different; carbonization is used to produce a carbon-rich char whereas pyrolysis is used to produce oil.

Another form of carbonization, termed hydrothermal carbonization (HTC), involves heating organic matter (biomass) using water under pressure. HTC produces a solid char product and a liquid by-product that contains sugar monomers and their decomposition products, organic acids and carbon dioxide gas [5]. HTC is often used to increase the fuel quality of raw biomass with the resulting char possessing a similar fuel quality to lignite [7]. During JKW carbonization, lignocellulosic components are decomposed into bio-oils, syngas and char. Most of the hydrogen, nitrogen, oxygen and sulfur atoms are removed in gaseous form because of the pyrolytic decomposition of the feedstock (in a process known as devolatilization). The ‘freed’ carbon atoms re-arrange into crystalline structures known as elementary graphitic crystallites, which results in a relatively ‘purer’ carbon form [8]. The arrangement of crystalline structure is irregular and as such, tarry substances produced during carbonization fill and block interstitial spaces between carbon atoms in the char.

Bio-oil is a dark brown liquid with approximately half the calorific value of transport fuels [9]. It can be modified for use as a fuel substitute for transport, boilers, furnaces and turbines or as a precursor in chemical production [6]. Syngas is the non-condensible fraction of carbonization products and can be combusted for heat generation or for carbonization [10]. There is precedence of using biomass to manufacture char and its subsequent use as a precursor for activated carbons [11], a fuel source [12] or for sequestering anthropogenic carbon [13]. JKW carbonization is governed by its lignocellulosic structure, which consists of lignin, cellulose and hemicellulose contents. During thermal degradation, hemicelluloses decompose first (220–315°C), followed by cellulose (315–400°C). Lignin is relatively thermally stable and decomposes between 160–900°C [14]. Differences in thermal stability are attributed to their different inherent structures and chemical nature. Hemicellulose contains more carbonyl groups (C=O) and cellulose has more alcohol groups (C-OH) and ether groups (C-O-C), whereas lignin is composed of more methoxyl (C-O-CH₃) groups [14].

The thermal decomposition of JKW biomass samples was studied by thermogravimetric analysis (TGA), which also allows for proximate analysis. The proximate analysis characterizes the sample volatile matter, fixed carbon contents and moisture and ash contents. The volatile matter content is that portion that is driven off as a gas (including moisture) by heating to 950°C, and the fixed carbon content is the mass remaining after release of volatiles, excluding the ash content [15]. Bomb calorimetry was used to determine the caloric value (CV) of JKW-derived biomass samples, bio-oil and char. The material CV is an expression of energy content or heat value released when burnt in air and is measured in MJ/kg and can be expressed as a gross or net value. The gross CV is the total energy content released when the sample is burnt in air and includes the latent heat of vaporization of water. The net CV is corrected for the latent heat and is therefore an appropriate indicator of energy available for subsequent use [15]. The focus of this paper is on characterizing JKW biomass, which is considered an invasive species and a waste biomass in the UK. The characterization includes the physical, chemical and thermal properties of both JKW stem and rhizome. Carbonization was chosen as a method to valorize JKW by turning the waste biomass into a value-added by-product. The by-products of JKW carbonization are then characterized for CV, alkalai and alkali earth metals (AAEM) content, morphology and yields.

2. Materials and methodology

2.1. Materials

JKW samples were obtained from Redruth in Cornwall, UK. The as-received JKW was segregated into stems (JKWS) and rhizomes (JKWR). The moisture content was determined in triplicate using ASTM...
Method D444-07. Stem samples were broken by hand and rhizome samples were cut using a band-saw to 30–50 mm to enable them to fit into the carbonization reactor and for characterization. These were then crushed using a Glen Creston CBM-20 cross beater mill (Glen Creston Ltd., London, UK) to ≤ 10 mm particles.

2.2. Ash analysis
The sample ash content was determined in triplicate using ASTM Method D1102-84 (2007). The ash content is the amount left unreacted after combustion in air and results from the presence of minerals in the original plant biomass. The amount of ash present in the biomass is important to determine further use of the bio-char produced.

2.3. Lignocellulosic content
The lignocellulosic content of JKWS and JKWR was determined in triplicate according to ASTM Methods D1106-96 (2007) for the determination of lignin content and D1109-84 (2007) for the determination of hemicellulose content. The cellulose content is determined by subtraction of the lignin, hemicellulose and ash contents of the samples. Carbon, hydrogen, nitrogen and sulfur contents were determined by MEDAC Ltd, Cobham UK.

2.4. Sample digestion
Samples for elemental analysis were prepared by microwave digestion. An Anton Paar Multiwave 3000 microwave reaction system (Anton Paar GmbH, Graz, Austria) with a MF100 pressure vessel in a 16 position rotor was used to acid digest the samples according to USEPA Method 3051a. Elemental concentrations were determined using inductively-coupled plasma-optical emission spectroscopy (ICP-OES, Perkin Elmer 7300DV) by triplicate analysis. A JEOL 5610LV scanning electron microscope (JEOL Ltd., Tokyo, Japan) was used to generate images to examine the morphology. The JKW-derived bio-oil water content was determined using a Dean–Stark apparatus [16].

2.5. Thermal analysis
Thermogravimetric analysis (TGA) was conducted using a Rheometric Scientific STA 1500. Approximately 15 mg of ≤ 10 mm stem or rhizome sample ground to ≤ 500 µm particle size was placed in a 4.5-mm-diameter alumina crucible. Nitrogen gas was used as inert atmosphere during TGA, whereas air was used as reactive atmosphere during proximate analysis. TGA proximate analysis was by a modified ASTM method E870-82 [17]. Approximately 15 mg of ground sample was placed in an alumina crucible and heated in the TG analyzer to 105°C at 50°C/min using a nitrogen flow rate of 50 ml/min and held for 5 min to allow entrained moisture to evaporate. The volatile matter was determined by heating the sample to 950°C at 50°C/min in a nitrogen atmosphere and then held at 950°C for 20 min. The sample was allowed to cool to 600°C, at which point the nitrogen atmosphere was substituted for air and was held at 600°C for 10 min in an air atmosphere to determine the fixed carbon content.

2.6. Experimental setup
The experimental system consists of a quartz reactor with oil condensation system that is heated inside a Carbolite HTR 11/75 rotary furnace (Carbolite Ltd., Derbyshire, UK) as shown in Figure 1. A JKW sample of between 25 and 30 g was placed inside the reactor, depending on the respective bulk densities. A nitrogen flow rate of 100 ml/min was used to maintain inert reactor conditions. The carbonization temperature, heating rate and residence times were controlled by a Eurotherm Model 3204 controller (Invensys Eurotherm, Worthing, UK). The outlet arm of the reactor was connected to an oil trap to assist with vapor condensation and oil collection at room temperature. Non-condensable gases were vented into a fume hood. Prior to each run, the reactor and all connections were purged with nitrogen. At the end of the run, the sample was left to cool to room temperature under flowing nitrogen. Product yields were determined by differential weighing of glassware.
Figure 1. A schematic diagram of the laboratory-scale carbonization setup.

The gross calorific value (CV) was determined in triplicate for each sample using a Parr 6100 oxygen bomb calorimeter with a Parr 1108 oxygen bomb (Parr Instrument Company, Illinois, USA). Samples were ignited in 99% pure oxygen. All CV determinations were carried out on a dry/moisture-free basis.

3. Results and discussion

3.1. Physical and chemical characteristics of JKW

The moisture content of biomass naturally varies due to the environment it is grown in and the species [18]. This will affect the way the biomass is stored and used [19, 20]. Biomass that contains high moisture levels requires increased energy to vaporize the water during carbonization. The moisture content and ultimate analysis of JKWS and JKWR are shown in Table 1. The carbon, hydrogen, nitrogen and sulfur contents of JKWS and JKWR are similar; however, the sulfur content is unusually high for plant biomass. The sulfur content of JKWR is comparable to that of bituminous coal [15]. In its native habitat of Japan, JKW can be found growing on volcanic slopes and is able to tolerate high atmospheric sulfur dioxide concentrations [4]. The high sulfur content of the JKW samples occurs most likely because the samples were harvested close to closed tin mines and smelters near Redruth in the UK, where high sulfur content in soils occur because of sulfur release into surrounding areas from tin smelting.

The ability of JKW to tolerate and absorb elevated sulfur in soils illustrates a potential beneficial application of JKW in phytoremediation. Rather than trying to eliminate JKW, it could be cultivated deliberately on brownfield or contaminated sites polluted with heavy metals, as previously suggested [21]. Once fully grown, stems could be harvested for carbonization. The biomass could be excavated and carbonized in mobile pyrolysis units placed at infestation or agriculture sites and equipped with flue gas scrubbers to remove heavy metals volatilized during combustion. Once carbonized, the calorific products can be transported and used off-site without the risk of spreading JKW.

The ash content of JKWR is relatively high compared with that of JKWS because of the minerals and metals that have been absorbed by the growing biomass. The ash content is an important characteristic because the residual material reduces the calorific value of produced chars and bio-oil and causes slag formation during combustion [15]. The holocellulose content is the sum of hemicellulose and cellulose contents and represents the amount of volatiles that can be released during thermal degradation. The hardy structure of JKWR is determined by the higher cellulose content when compared with JKWS.

Table 1 also shows that the JKWR samples have a higher CV (gross and net) than JKWS as a result of the higher lignin content. This observation has been reported [22] for different gross CVs of several biomass fuels. The same report also mentioned that there was no correlation between holocellulose content and gross CV, which is also observed here. The dry calorific values of cellulose, hemicellulose
and lignin are 16.5 MJ/kg, 13.9 MJ/kg and 20.4 MJ/kg, respectively [23]. This claim proves that the calorific value of biomass is determined by lignin content because of the nearly identical calorific values of cellulose and hemicellulose.

Table 1. Moisture content and ultimate analysis of Japanese knotweed stem (JKWS) and rhizome (JKWR).

| Properties                  | JKWS          | JKWR          |
|-----------------------------|---------------|---------------|
| As-received moisture content (%) | 60.4 ± 2.9    | 8.1 ± 0.3     |
| C (%)                       | 45.70         | 46.30         |
| H (%)                       | 5.68          | 5.36          |
| N (%)                       | 0.63          | 1.62          |
| S (%)                       | 0.37          | 1.12          |
| Ash content (%)             | 1.56          | 4.43          |
| Lignin (%)                  | 19.9 ± 0.9    | 21.2 ± 0.8    |
| Hemicellulose (%)           | 46.7 ± 2.1    | 24.9 ± 0.9    |
| Cellulose (%)               | 31.8 ± 1.2    | 52.4 ± 1.6    |
| Holocellulose (%)           | 78.5          | 77.3          |
| Gross CV (MJ/kg)            | 18.3 ± 0.10   | 19.2 ± 0.05   |
| Net CV (MJ/kg)              | 17.1 ± 0.10   | 18.0 ± 0.05   |

3.2. Thermal characteristics and proximate analysis of JKW

The thermal degradation of the JKW samples by TGA in nitrogen is shown in Figure 2. A low heating rate of 1°C/min was selected to ensure a high resolution of mass loss data during thermal degradation in nitrogen. The initial mass loss can be attributed to water evaporation, with JKWS containing 6.1% moisture and JKWR containing 1.2% moisture. The onset of thermal decomposition commences between 150°C and 200°C with a main thermal degradation step at 310°C, where major devolatilisation occurs. At these temperatures, the holocellulose content, and especially the hemicellulosic element, is reduced significantly. The devolatilisation of hemicellulose is the main contributor to the bio-oil and non-condensable gases by-product, and as such, we are able to relate the approximate amount of volatiles produced using TGA.

The main mass loss is completed by 380°C and further temperature increase results in minimal mass losses, which indicates the completion of significant decomposition (carbonization) reactions and the commencement of graphitization reactions to form char. The char yields determined from Figure 2 were 35% for JKWR and 22% for JKWS at 600°C. The stem produced marginally less char than the rhizome. This can be attributed to the lower cellulose content of the stem (cellulose is more thermally stable than hemicellulose) and the lower ash content of JKWS compared with JKWR.

The lower temperature differential thermogravimetric peak of JKWS and JKWR, which starts at 200°C and ends at 250°C (seen as a shoulder) is a result of the onset of hemicellulose decomposition in nitrogen and the main higher temperature peak at 300°C occurred because of the decomposition of cellulose and any remaining hemicellulose. Lignin decomposes over a wide range of temperatures and is indiscernible as a peak in the differential thermogravimetric plots. Observations in literature and in this work concur with regards to temperatures observed for decomposition. Pure cellulose and hemicellulose decomposes at lower temperatures and other inhibiting factors exist in the complex biomass matrix [24].
Figure 2. Thermogravimetric analysis (TGA) and differential thermogravimetric (DTG) plot of Japanese knotweed stem (JKWS) and rhizome (JKWR) samples at 1°C/min to 1000°C.

3.3. Proximate analysis
A proximate analysis of JKWS and JKWR shows that carbonization of JKWR is a more promising source of carbon sequestration than JKWS carbonization, using the fixed carbon content shown in Table 2 as an indicator of the carbon in the char product. The lignin content of the JKW in Table 1 relates positively with the fixed carbon content as determined by proximate analysis using TGA, which infers that the fixed carbon content is related to the lignin content of the biomass sample. This observation was also reported with different biomass samples [25].

Table 2. Proximate analysis of Japanese knotweed stem (JKWS) and rhizome (JKWR) biomass.

| Properties                        | JKWS       | JKWR       |
|-----------------------------------|------------|------------|
| Moisture content (after air drying) (%) | 6.1 ± 0.2  | 1.9 ± 0.1  |
| Volatile matter (%)               | 74.9 ± 2.9 | 70.5 ± 3.9 |
| Fixed carbon matter (%)           | 16.3 ± 0.8 | 21.2 ± 1.0 |

JKWS and JKWR contained (74.9 ± 2.9) % and (70.5 ± 3.9) % volatile matter, respectively, which compares closely with the holocellulosic contents of the two waste biomass samples reported in Table 1. This confirms the assertion by [24], that thermal degradation of cellulose and hemicellulose releases volatiles in gaseous form. Rhizome and stem samples were carbonized at 5°C/min from 300°C to 800°C and held for 1 h at each respective temperature in the Carbolite HTR 11/75 rotary furnace. The residence time was included to ensure complete carbonization of samples, which is evidenced by minimal emissions of volatiles during proximate analysis of produced chars, as shown in Figure 3. It also shows that as the carbonization temperature increases, the volatile matter content of the char decreases. This indicates an increase in stabilization of the char carbon structure, which is expected. There is no
significant difference in volatile matter content between the 1 h and 2 h residence times, especially at a higher carbonization temperature. Nevertheless, it is evident that with extended residence time, the chars tend towards a more stable structure because less volatile matter is released. The presence of volatile matter could be explained by trapped tarry substances in the porous structure of the char carbon structure [26], which is only released at high temperatures, as observed during the proximate analyses of the chars. From Figure 3, the difference in reduction of volatile matter at 600°C and different residence times was 0.9% for JKWR and 1.1% for JKWS. The residence time was set to 1 h instead of 2 h to reduce the amount of energy spent on carbonization.

Figure 3. Volatile matter content remaining in Japanese knotweed stem and rhizome chars (JKWS and JKWR) carbonized at different temperatures for 1 h and 2 h residence times.

When the proximate analysis temperature reaches 950°C, the devolatilization and carbonization reactions will proceed until all carbon in the feedstock is stabilized. To obtain a stable form of char with little volatile matter, JKWR and JKWS can either be treated at high temperature or a lower temperature can be used with long residence time. From the char yield plot in Figure 4, a temperature of 600°C for JKWS and JKWR was chosen as the compromised carbonization temperature for batch carbonization because char yields started to plateau and carbonization temperatures above 600°C do not appear to result in further increases in char yield. The extra carbonization time and energy used cannot be economically justified.

3.4. Product yields
The JKWR char yield decreased from 78.8% at 300°C to 31.1% at 800°C, whereas that of JKWS decreased from 70.3% to 23.4% in the same temperature range. As carbonization proceeds, the biomass carbon structure is rearranged to form an irregular but energetically stable char structure as the carbonization temperatures increases. Char formation can be explained by the decomposition of lignin and cellulose biomass components, which forms the bulk of the char carbon structure. The effect of thermal decomposition of hemicellulose on char yield is less pronounced. At lower temperatures, weak bonds such as the alkyl-aryl ether bond(s) in the lignin structure are cleaved and more resistant
condensed structures are formed, whereas at higher temperatures, aromatic cracking and condensation occur. This is accompanied by the cellulose dehydration to anhydrocellulose during charring [14, 27].

As a result of the higher amounts of lignin with cellulose, JKWR exhibited higher char yields at all carbonization temperatures. The difference in amount of cellulose between the two biomasses was significant in char formation, particularly at the low heating rates used. The observed decrease in char yield at higher temperatures occurs because of the devolatilization reactions that occur, which remove non-carbon atoms to form low molecular weight, volatile hydrocarbons and is typical of the carbonization process. This results in increased bio-oil and gas yields. The bio-oil yields of JKWR increased from 15.5% to 43.7% between 300°C and 800°C. In the same temperature range, JKWS oil yields increased from 20.7% to 43.5%. The gas yields from JKWR increased from 5.7% to 25.2% between 300°C and 800°C as a result of ongoing carbonization. The JKWS gas yields increased from 9% to 33.1% over the same temperature range. Hemicellulose (as opposed to cellulose and lignin content) contributes most to volatiles content (bio-oil and syngas) by forming short molecular units. It has been reported that hemicellulose decomposition resulted in high carbon dioxide yields because of its high carboxyl content and this contributes to gas yield [14]. We were unable to confirm this observation in this study.

At low carbonization temperatures, lignin degradation does not influence the char yield significantly because it is thermally stable [23]. Charring reactions are inferred as complete once the char yield stabilizes. The insignificant mass loss above 500°C indicates that the basic char structure is already formed [28].

Bio-oil yields are at minimum levels at 300°C because the main contributing reaction to bio-oil yield has just started. This reaction involves secondary degradation of cellulose above 300°C. This produces more levoglucosan and less anhydrocellulose, which contribute to bio-oil and char yields, respectively [27]. The increase in carbonization temperature encourages primary pyrolysis reactions and initiates secondary autocatalytic reactions, which, in conjunction with condensation of some volatiles, produces tar, a main component of bio-oil [6]. Therefore, bio-oil yield should increase with increase in temperature up to a point where the primary pyrolysis reactions and secondary autocatalytic reactions compete. At this point, the influence of the other biomass components, heating rate and residence times will come into effect.

The char, bio-oil and syngas yields derived from JKWS and JKWR biomass at various carbonization temperatures are shown in Figure 4. The char yield is particularly high at 300°C because of the formation of anhydrocellulose, which increases the char yield [24, 27]. However, a substantial amount of uncarbonized matter remains at 300°C, which suggests that the depolymerization and carbonization reactions have not stabilized [24]. Char yield decreased from 300°C to 500°C but at 600°C, the trend starts to plateau. This agrees with trends in literature for carbonization of other forms of biomass where plateauing was also observed at 600°C [29].

From Figure 4, JKWR and JKWS bio-oil yields are very similar in mass and follow the same trend. This is because of their similar holocellulose content (77.2% and 78.5%, respectively), which is responsible for tar production [30]. The gas yields from JKWS are higher than those from JKWR at increasing carbonization temperature. This can be attributed to the higher hemicellulose content of JKWS, because its decomposition results in less chars and tars but more volatiles than cellulose [6]. Furthermore, devolatilization reactions are favored at higher temperatures [30].
The repeatability of the Carbolite HTR 11/75 rotary furnace test is shown in Table 3. The results from batch carbonization of JKWS and JKWR were within 2% of the triplicate runs, which indicates a repeatable methodology as well as consistency and homogeneity in the feedstock.

Table 3. Average product yields of JKWS and JKWR at a carbonization temperature of 600°C for 1 h in the Carbolite HTR 11/75 rotary furnace. Standard deviation values obtained from three different measurements.

| Items                  | JKWS     | JKWR     |
|------------------------|----------|----------|
| Average (%)            | 24.09    | 31.09    |
| Standard deviation (%) | 0.10     | 0.33     |
| Relative standard deviation (%) | 1.42   | 1.07     |

* By difference

3.5. Morphology

Figure 5 (a) and (d) show the JKWS and JKWR biomass microstructure (before carbonization), respectively. Both appear morphologically similar, with JKWS having more striations than JKWR biomass. In Figure 5 (a, b, d and e), carbonization has caused perforations to form on the surfaces of the JKWR and JKWS structures. Disorganized fragments of amorphous carbon and residues are also visible as individual white specks in Figure 5 (c and f). JKWR bio-char had a relatively porous structure at 140× magnification in Figure 5 (e) whereas some external burning occurred with JKWS bio-char in Figure 5 (c). This indicates the formation of external porosity whereas the inner structural walls still remain intact.
Figure 5. Scanning electron microscope images of (a) Japanese knotweed stem (JKWS) biomass and (b) JKWS char at 140× and (c) 300× magnification. (d) Japanese knotweed rhizome (JKWR) biomass and (e) JKWR char at 140× and (f) 300× magnification. (Carbonization parameters: 600°C for 1 h at 5°C/min.)

3.6. Calorific value
JKWS- and JKWR-produced chars have similar CVs as can be seen in Table 4. The CV for the bio-oils differs significantly as a result of their different water contents. JKW-derived bio-oil separated into two layers: an upper, fluid layer that contains mostly water and a lower, viscous layer that consists of bio-oil. The water content was determined using the lower layer. JKWS bio-oil was not observed to separate into different layers. The carbonization products possess higher CVs because of the energy input during
carbonization. Energy was used to degrade the JKW biomass thermally into separate carbonization products. The bio-oil CVs are lower than the char CVs because of the presence of water in the bio-oils.

Table 4. Characteristics of Japanese knotweed biomass, char and bio-oil, derived at a carbonization temperature of 600°C and 1 h residence time.

| Items               | JKWS biomass | JKWS char | JKWS bio-oil | JKWR biomass | JKWR char | JKWR bio-oil |
|---------------------|--------------|-----------|--------------|--------------|-----------|--------------|
| Gross CV (MJ/kg)    | 18.3 ± 0.10  | 31.2 ± 0.63 | 13.7 ± 0.25  | 19.2 ± 0.05  | 31.7 ± 0.16 | 23.3 ± 0.30  |
| Net CV (MJ/kg)      | 17.1 ± 0.10  | 29.9 ± 0.63 | 12.4 ± 0.25  | 18.0 ± 0.05  | 30.6 ± 0.16 | 22.2 ± 0.30  |
| Water content (%)   | N/A          | N/A       | 43.9 ± 3.26  | N/A          | N/A       | 11.9 ± 0.50  |

3.7. AAEM content
JKWR and JKWS chars had higher amounts of alkali and alkaline earth metals than their respective biomasses, as seen in Figure 6. This is explained by the carbonization and devolatilization reactions, which concentrate these inorganic minerals into the char because they are not removed by the aforementioned reactions [31]. The high metal content in both JKWS and JKWR biomass shown in Figure 6 suggests that JKW can be used to remediate contaminated soils, also reported elsewhere [21]. The plant can be introduced to contaminated sites and allowed to grow. Once the soils have been remediated, the JKW biomass can then be removed and carbonized.

Figure 6. Alkali and alkaline earth metals content of Japanese knotweed (JKW) biomass and JKW-derived char produced at 600°C and 5°C/min for 1 h.
4. Conclusion

The chemical, physical and thermal characteristics of Japanese Knotweed (Fallopia japonica) have been recorded in this work. These include the ultimate, proximate and lignocellulosic analysis of JKW. The rhizome system of JKW resulted in a higher char yield after carbonization as a result of higher cellulose content than the stems. This difference also resulted in different physical attributes; JKWR being hard & woody whereas JKWS is more flexible. The proximate analysis indicated that JKWS is able to produce more bio-oil and syngas whereas JKW will be contain higher bio-char yield. Both predictions were verified using a rotary quartz reactor inside a rotary furnace. It has also been demonstrated that JKW can be carbonized and both the resulting char and bio-oil contain sufficient calorific value to be utilized as bio-fuel. Carbonization had a significant effect on the morphology of the JKW biomass; a high amount of pores was created after the carbonization process. Further work may include investigations increasing the porosity of the biochar by activating it. In addition, it may be possible to use JKW as phytoremediation for contaminated soils; after which the plant biomass can be carbonized into bio-fuels or as a precursor for activated carbons because of its high carbon and low ash content. In this scenario, this ‘waste’ biomass can then be valorized as activated carbon, a commodity.

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