Biochar from Biomass Slow Pyrolysis

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Abstract. Pyrolysis is widely used in the chemical industry to produce e.g. carbon black from heavy fuel oil (HFO) and coke from coal, to convert post-consumer plastic waste into chemicals, to transform heavier hydrocarbons into lighter ones, and to thermo-chemically treat biomass. Whereas a lot of work has been presented on the fast pyrolytic production of bio-oil from biomass, the objectives of biochar and added-value chemicals are now a major focus when using biomass in a slow pyrolysis reactor. Fast pyrolysis targets mostly bio-oil (up to 60 or 70 wt%). Slow pyrolysis targets mostly biochar (up to ~60 wt%), together with 25-30 wt% of bio-oil and the balance as gas. The paper presents results from biomass pyrolysis in the slow operating mode and assesses the products formed and their application perspectives.

1. Introduction
Energy from biomass has a high potential [1,2], but this energy production is largely squandered by unsustainable exploitation and inefficient use. Novel technologies are hence needed to exploit the full potential of this energy source, pyrolysis being recognized as a leading technology.
Pyrolysis processes for ligno-cellulosic biomass are gaining interest. Fast pyrolysis occurs at moderate temperatures (~500 °C) with a high heat transfer rate to fine biomass particles (< 300 µm), a short vapor residence time in the hot reaction zone, and a fast separation of char from vapors [1]. Slow pyrolysis is less severe towards operating conditions, using lower temperatures (~350-450 °C) and long residence times of the coarser biomass (> 1 mm). Fast pyrolysis yields mostly a liquid product, including water, at about 70 - 80% of the dry biomass weight. In the slow pyrolysis mode, the main product is ~ 60% of biochar. For both fast and slow operating modes, reactors include bubbling, circulating and spouted fluidized beds and transport systems. Cyclonic and ablative reactors are typical for the fast pyrolysis application [2]. The yields and properties of the generated products depend on the feedstock, on the process type and conditions, and on the product collection efficiency.
Biomass includes all organic matter that is available on a renewable basis, e.g. energy crops and all kinds of organic wastes. Agricultural and forestry wastes are easy and cheap to collect, and will therefore dominate as a source for bio-energy, representing e.g. 94% of the EU used biomass.
Solid biomass fuels have a low energy density, which limits the commercial applications to locations close to the place of production. One way to solve this problem is the conversion of the feedstock into products with a higher energy density (table 1), easy to store and to transport.

Table 1. Bulk density, mean heating value and energy density of biomass and thermochemically derived fuels [1]
| Energy carrier     | Bulk density (kg m⁻³) | Heating value (GJ t⁻¹) | Energy density (GJ m⁻³) |
|-------------------|------------------------|------------------------|------------------------|
| Straw             | ~ 100                  | 20                     | 2                      |
| Sawdust           | ~ 400                  | 15                     | 6                      |
| pyrolysis oil     | ~ 1200                 | 17                     | 20.4                   |
| Char              | ~ 300                  | 30                     | 9                      |

Biomass can be converted by either enzymatic and bacterial bio-chemical processes, or by thermo-chemical conversion [1], where combustion, gasification and pyrolysis dominate [1,3]. The present paper considers slow pyrolysis as a conversion technology because of its efficient energy production and the important advantage that mainly liquids and solid char are formed, both easy to store and to transport [2,3]. Pyrolysis is the thermal decomposition in the absence or in a lean O₂ environment, at a relatively low temperature (623 - 823 K) compared to combustion and gasification. Main end-products of the process are vapours and a solid residue (the so-called bio-char). Due to the diversity of certain biomass components, its pyrolysis is very complex, and reaction pathways focus on the occurring primary and secondary reactions [1,2]. Product distributions and properties depend on the operational conditions of the reaction itself, operating in a slow or fast mode.

2. Pyrolysis products

Three products are produced i.e. the so-called bio-oil, biochar and non-condensable gas [1,2]. Char has a heating value of 30 MJ/kg, comparable to petroleum cokes. The non-condensable gases (mostly CO₂, CO, CH₄ and H₂) can be used as a fuel, externally or in the process. The bio-oil has a heating value about half that of conventional fuels, and has some attractive properties as fuel or as chemicals.

2.1 Biochar and the reported characteristics

2.1.1 The production of biochar and its reported characteristics

Biochar could potentially store about 50% of the biomass carbon [4], whilst the remaining biomass carbon will simultaneously be transformed into bio-oil and/or syngas. Biochar is hence a valuable C-sequestration product. Pyrolysis has been receiving increased interests from the governmental, public and private sectors. Charcoal, produced by oxidative gasification, is commonly and traditionally considered only as fuel source. The specific yields of the pyrolysis products depend upon process conditions and these conditions can be optimized to produce biochar rather than liquid or gaseous energy carriers, although the amount of energy produced per unit energy input remains higher than obtained in e.g. the production of corn ethanol.

Several crops were tested as biochar feedstock, e.g. willow and eucalyptus [5,6], green waste [7]; rapeseed cake [8]; and Miscanthus-grass [9]. The properties of biochars produced from apricot stones, hazelnut shells, grape-seeds and chestnut shells were examined to observe the changes of the functional groups [10].

2.1.2 Biochar as carbon sink

Biochar can sequester carbon on a significant time scale [11]. The amount of time biochar will remain in the soil depends on the feedstock material, the biochar characteristics and the condition of the receiving soil. Estimates for the residence time range from 100 to 1000’s of years [12,13]. The remaining C in biochar was predicted in excess of 40% after a period of 100 years, and hence significantly more stable than non-biochar material which is decomposed progressively to below 10-20% of C after 5-10 years already. This C-retaining capacity of biochar is recognized as very important.
2.1.3 Effect of biochar on the soil properties
Biochar, as charred organic matter, can be applied to the soil in a deliberate manner to improve soil properties: it is known as a fine grained and porous material, visually similar to charcoal [14,15], and useable as soil amendment for improving soil quality. The response of vegetation to biochar is varied depending on its effect on nutrients supply, retention of pollutants, and improvement of soil physical and biological properties [11]. Biochar addition significantly improved biological nitrogen fixation in common beans [16], and there is also evidence of a significant reduction of N\textsubscript{2}O and CH\textsubscript{4} emissions after biochar application [4]. The yield of wheat and Miscanthus has moreover been shown to increase by biochar addition [7]. Biochar can prevent the leaching of soil nutrients due to its adsorbing and immobilizing properties, thereby increasing the available nutrients for plant growth, enhancing water retention and reducing the irrigation needs and amount of fertilizer required [11]. These positive qualities depend upon the properties of the biochar, and soil type, soil condition (depleted or healthy), temperature and humidity [11,17]. For maintaining soil nutrient sustainability, biochar addition must be accompanied with an additional source of nutrient (e.g. fertilizer) since a significant effect of biochar on soil nutrient availability has not been proved. Biochar can moreover adsorb heavy metals and pesticides: biochar added at 10%, reduces contaminant levels in plants by up to 80%, while reducing the total chlordane and DDX content in the plant by 68 and 79%, respectively [18,19]. The adsorbing effects are proportionally related to the specific surface area of the biochar, with a larger surface area improving its ability to capture pollutants or contaminants, although it might be feared that it could also result in an easier attack by the soil micro-organisms of the weakest carbon chain of the biochar. Clearly additional research is needed to optimize positive and possible negative effects in function of the surface area of the biochar.

2.2 Biomass pyrolysis oil and the reported characteristics
Although outside the main topic of the research, the elemental composition of bio-oil resembles that of biomass rather than that of petroleum oils and it contains a lot of oxygenated compounds. Water (15 - 30 wt%) in bio-oils results from the original moisture in the feedstock and as a product of the dehydration reactions during pyrolysis. Water affects the oil properties, lowers its heating value, and flame temperature. The oxygen content of bio-oils is high and is present in most of the more than 300 compounds that have been identified. Major groups of compounds identified are hydroxylaldehydes, hydroxyketones, sugars, carboxylic acids and phenolics, present as oligomers of molecular weight between 900 and 2500 Da. The high oxygen content results in both a low energy density (heating value), less than 50% of that for conventional fuel oils, and an immiscibility with hydrocarbon fuels. An important consequence of the organic oxygen is the instability of bio-oil, subject to polymerisation. Bio-oil also reacts with oxygen from air and is acidic (pH of 2 - 3). The oils are corrosive to common construction materials and can affect some sealing materials. The corrosiveness is especially severe at elevated temperatures and with the increase in water content. Bio-oils are combustible but not flammable. Due to the high content of non-volatile components, bio-oil requires significant energy for ignition, but once ignited, it burns with a stable self-sustaining flame. Bio-oil requires a significantly lower stoichiometric air-to-fuel ratio than common fuels (about 50%). Emissions from bio-oil combustion, in general, showed higher particulate and CO levels, but lower NOx emissions than when burning conventional fuels.

3. Experimental

3.1 Feedstock and Set-up
Biochar was produced from fresh Q83 willow. The willow was chopped into 1 to 2 cm long chips with maximum thickness of about 3 to 4 mm, then air dried to below 10 wt% moisture. The pyrolysis experiments were performed in a bubbling fluidised bed reactor, as illustrated in Figure 1.
Figure 1. Schematic diagram of the pyrolysis set-up

The bubbling fluidized bed of internal diameter 0.3m, is manufactured from Incoloy steel, and externally insulated. The air flow rate was controlled by flow meter. The heat-input from the electrical heater (50 kW) was set by the bed temperature, as average of the top T1 and bottom T2 measurements. Deviations between T1 and T2 were less than 10°C because of the perfect bed mixing in a fluidized bed. Vapours, pyrolysis gases and fluidization gas were exhausted by an induced draft fan, passing a water-cooled condenser and a bio-oil collection tank. Life steam (110 °C, 5 bar) could be added in the windbox of the fluidized bed, i.e. below the sintered porous metal distributor plate. The distributor had a high pressure drop of ~ 3000 Pa at the operating flow rate and temperature.

A known weight (between 0.3 and 0.5 kg) of willow wood chips was placed into a perforated basket. The perforations enabled the fluidized bed sand to fluidised within the voidage of the willow chips. The fluidized bed consisted of about 15 kg of quartz sand (150-300 µm, 2600 kg/m³), for a total static bed height of about 35 cm.

The air flow rate was maintained below 10% of the stoichiometric air flow needed for willow combustion, and the velocity in the bed, at the operating temperature, was set at 2 to 4 times the minimum fluidisation velocity, \( U_{\text{mf}} \) (~ 2.5 cm/s). For some of the experiments, a steam dilution was also applied, reducing EF to below 5 %.

After pyrolysis, biochar was sieved from the bed material. Vapours were continuously condensed. Gas compositions (CO, CO₂, H₂ and CH₄) were measured prior to the gas discharge into the atmosphere. Biochar was produced at temperatures of 350, 440, 470, 530 and 550°C, and for different durations of treatment at 470°C, i.e. 5, 10 and 15 minutes. In additional experiments, the biomass was either soaked with de-ionized water prior to pyrolysis, or live-steam (110°C, 5 bar) was directly injected into the fluidization air flow, thus further reducing the partial pressure of O₂ being present. All experiments were repeated twice under identical operating conditions, and average results will be presented.

3.2. Product characterisation and carbon balance inventory

The full analysis of the biochar was performed using a LECO analyzer (CB-2000, LECO, USA), whereas exchangeable cations were measured using inductively coupled plasma (ICP) spectrophotometer. Before analyses, the biochar was homogenized and powdered. The geometric properties were imaged by SEM microscope (Cambridge S200 Scanning EM). The specific surface area of the different biochar samples was measured by a Micromeretics Tristar II 3020 analyser. Liquids after condensation were collected and analyzed by GC-MS 8130 (Voyager 8000 Fisons Instruments). The gas stream was analyzed for CO, CO₂, H₂ and CH₄.

4. Results and discussion
4.1 Characteristics of the produced condensable liquids
Condensate samples were collected from the condensate drum, and contained 16 to 20 wt% of water. The condensed organic fraction was analyzed by GC-MS and contained a variety of compounds, mostly of acid (e.g. acetic acid, acetic acid methyl ester, etc.), phenolic or complex oxygenated nature. The identified pyrolysis compounds all contain C, H and O in their molecular structure. As comparison, the bio-oil from other materials (e.g. rapeseed cake, hazelnut, grapeseed) consisted of asphaltens, pentane, parafinic, aromatic (toluene), and polar (methanol) components [10].

4.2 Characteristics of the non-condensables
CO, CO₂, H₂ and CH₄ were measured. Analyses are approximate only, since the compounds were diluted in a 6 m³/h gas stream. Moreover, the composition of the gas stream varies with time, and the concentration of the target gases decreased steadily. Average concentrations, converted to vol%, are 0.4 to 0.7 vol% CO₂, 0.2 to 0.5 vol% of CO, 0.1 to 0.3 vol% H₂ and maximum 0.2 vol% of CH₄.

4.3. Biochar yield
The yields of the biochar for different pyrolysis temperatures are given in Figure 2, illustrating that an increasing treatment temperature decreases the yield. The decomposition reaction was however incomplete at 350°C, with raw willow chips still visible in the product. At higher temperatures, a carbonaceous residue was completely formed: the average yield at 440°C and 470°C was 407 g/kg and 273 g/kg respectively. In a second series of experiments, the effect of the duration of the thermal decomposition on the biochar yield was studied at a single selected temperature of 470°C. The pyrolysis time was varied from 5 to 10 and 15 minutes. Results are presented in Figure 3. Increasing the heating time from 5 minutes to 15 minutes considerably reduces the biochar yield. For a 5 minutes treatment, the biochar yield was close to 60%, comparable with the 60.6% value obtained from Eucalyptus grandis [10]. The lowest biochar yield (27%) was obtained for a treatment at 15 minutes. Experiments were also conducted on wood chips, pre-soaked with water, and when live steam was directly added to the fluidized bed. The yield at 475°C and 15 minutes was about 50%, nearly twice the yield of biochar production without water vapour being present. It is thus evident that steam pyrolysis enhances the biochar yield. Further experiments are however needed to confirm these initial findings. These experiments are ongoing, and will be reported in a further paper.

Figure 2. Biomass yield (wt% of dry biomass) in function of operating temperature.
Figure 3. Relationship between time of pyrolysis and biochar yield (average of 2 experiments)

Figure 3 also adds literature data for rapeseed stalk treated at 800 °C, or grapeseed and chestnut shell at 450°C. The different contents of hemi-cellulose, cellulose and lignin explain this different behavior.

4.3.1 Biochar characteristics

The difference in structure of the willow wood chip, and of the biochar produced at different temperatures was imaged by SEM: whereas the willow feedstock has large pores and contains some debris, the produced biochar has a higher porosity, with significantly smaller pore sizes for high temperature biochar, thus offering a high potential for adsorption of organic or mineral soil compounds. The increased porosity and reduced pore sizes was also reflected in the specific surface area, measured as BET-value, and between 62 and 84.4 m²/g for 530°C-biochar, or even in excess of 142 m²/g for steam-assisted pyrolysis at 530°C, a nearly double surface area than for non-steamed biochar. These BET values exceed reported values for biochar from apricot stone, hazelnut shell and grape seed at 11.24, 14.68 and 14.47 m²/g respectively [10], and values of biochar from sugarcane bagasse between 14.07 to 17.66 m²/g. BET of 500°C biochar from pine needles was reported as 236.4 m²/g. Steam pyrolysis appears to have the highest potential, for its high biochar yields, and high BET-values. Further research is ongoing.

4.3.2 Biochar elemental analysis

The analyses of 13 elements in biochar, produced by thermal treatment during 15 minutes but different temperatures, are given in table 2, together with the reference analysis of the willow chips. Data accuracies are 0.1 wt% for C, and 0.01 wt% for other elements. The same experimental error applies for Table 3.

The pH of a biochar-water suspension significantly increases with increasing pyrolysis temperature, changing from 5.8 for the wood chips to 10 for 530 °C-biochar as a result of the concentration of alkaline elements. Also, the concentration of other elements (except C and N) increases with temperature from 440°C to 530°C, of course due to an increased release of volatiles at increasing temperature. A maximum enrichment is noticed in 470°C-biochar, in-line with literature data [20]. The results show that carbon (C) was the predominant element followed by Ca, itself almost twice the concentration of K. The carbon content of the willow and of its biochar is about 45 to 55%, lower than the values reported for other materials, such as beech trunk, rapeseed, wood bark, cotton stalk and hazelnut shell, at 88%, 67%, 85%, 72% and 96% respectively [8,27], or about 76 % from several tree species (Acacia mangium, Eucalyptus grandis, Eucalyptus camaldulensis, Pinus sylestris and Robinia pseudoacacia) as given by Lehmann et al. [10].
Table 2. Elemental composition of dry willow feedstock and biochar produced at different temperatures, in wt%, or ppm* (Na, B, Cu, Fe, Mn and Zn)

|            | Willow chips | Biochar 440°C | Biochar 475°C | Biochar 530°C |
|------------|--------------|---------------|---------------|---------------|
| pH         | 5.8          | 6.5           | 9.1           | 10            |
| C          | 51.52        | 51.3          | 54.68         | 43.76         |
| N          | 1.53         | 1.09          | 1.07          | 0.82          |
| Ca         | 2.47         | 1.03          | 2.32          | 1.96          |
| K          | 0.15         | 0.8           | 1.58          | 1.18          |
| Mg         | 0.24         | 0.21          | 0.46          | 0.4           |
| P          | 0.12         | 0.24          | 0.62          | 0.56          |
| S          | 0.17         | 0.11          | 0.13          | 0.06          |
| Na*        | 0.07         | 0.07          | 0.09          | 0.1           |
| B*         | 39.3         | 24.2          | 48            | 35.4          |
| Cu*        | 9.98         | 11.6          | 24.79         | 27.81         |
| Fe*        | 366.3        | 242.1         | 439.9         | 601.7         |
| Mn*        | 445.3        | 173.8         | 397.7         | 320.5         |
| Zn*        | 345.1        | 212.7         | 476.8         | 438.5         |

The total N present in biochar decreases considerably with increasing production temperature. The P content increased more than 2 times at higher temperature, indicating that this element was mostly associated with the inorganic fraction in the willow chips. In contrast, the amount of S consistently decreases with increasing temperature, indicating that some S is volatile and released with the gases and vapors. As illustrated in Table 3, the effect of increasing the treatment duration from 5 to 15 minutes affected neither pH, nor the amount of P, S and alkaline cations such as Ca, K, Mg. The concentration of Fe, Mn and Zn increased slightly.

Table 3. Elemental composition of biochar produced at 470°C for different durations, in wt%, or ppm* (Na, B, Cu, Fe, Mn and Zn)

|                  | Bio char 470°C, 5 minutes | Bio char 475°C, 10 minutes | Bio char 475°C, 10 minutes, soaked with water | Bio char 475°C, 15 minutes |
|------------------|---------------------------|-----------------------------|-----------------------------------------------|---------------------------|
| pH               | 5.9                       | 6.2                         | 6.9                                           | 9.1                       |
| C                | 49.82                     | 48.58                       | 53.18                                         | 54.68                     |
| N                | 0.93                      | 0.88                        | 0.86                                          | 1.07                      |
| Ca               | 0.6                       | 0.72                        | 0.66                                          | 2.32                      |
| K                | 0.5                       | 0.59                        | 0.7                                           | 1.58                      |
| Mg               | 0.13                      | 0.16                        | 0.17                                          | 0.46                      |
| P                | 0.14                      | 0.2                         | 0.12                                          | 0.62                      |
| S                | 0.08                      | 0.08                        | 0.09                                          | 0.13                      |
| Na*              | 0.09                      | 0.08                        | 0.13                                          | 0.09                      |
| B*               | 13.8                      | 16.5                        | 14.9                                          | 48                        |
| Cu*              | 9.69                      | 11.03                       | 9.87                                          | 24.79                     |
| Fe*              | 1243                      | 270.4                       | 138.3                                         | 439.9                     |
| Mn*              | 104.1                     | 114.2                       | 93.4                                          | 397.7                     |
| Zn*              | 134.2                     | 145.5                       | 134.3                                         | 476.8                     |

4.3.3 Overall carbon balance

The total carbon balance can be determined, the C in the liquids being accounted for as difference between C available in the willow, and the sum of the biochar and gas C. This is presented on a 1 kg willow-basis for the selected results at 440°C, 475 °C and 550°C (Tables 4). The carbon balance clearly illustrates the C partition between the three products streams obtained from pyrolysis.
Table 4-a. Calculated Carbon Inventory in the gaseous products

| Compound | 440 °C, 15 minutes | 475 °C, 15 minutes | 530 °C, 15 minutes |
|----------|---------------------|---------------------|---------------------|
|          | kg/ kg willow | kgC/kg willow | kg/ kg willow | kgC/kg willow | kg/ kg willow | kgC/kg willow |
| CO₂      | 0.132      | 0.036      | 0.192      | 0.0523     | 0.233      | 0.063      |
| CO       | 0.042      | 0.012      | 0.080      | 0.0343     | 0.104      | 0.045      |
| H₂       | 0.0013     | -          | 0.0033     | -          | 0.0040     | -          |
| CH₄      | 0.013      | 0.0035     | 0.0171     | 0.0128     | 0.0217     | 0.016      |
| N₂O or NO₂ | <<        | <<         | <<         | <<         | <<         | <<         |
| Total Gas | 0.052      | 0.0994     | 0.124      | 0.124      | 0.124      | 0.124      |

Table 4-b1. Calculated carbon balance for 440°C-biochar

| Component | g C/100 g component | g C/kg willow |
|-----------|---------------------|---------------|
| Willow feed | 51.52             | 515.2         |
| Biochar (407 g/kg willow) | 51.3 | 208.79 |
| Gas       | -                   | 52.0          |
| Condensables | -                  | 254.4         |

Table 4-b2. Calculated carbon balance for 475°C-biochar

| Component | g C/100 g component | g C/kg willow |
|-----------|---------------------|---------------|
| Willow feed | 51.52             | 515.2         |
| Biochar (273 g/kg willow) | 54.68 | 149.27 |
| Gas       | -                   | 99.4          |
| Condensables | -                  | 296.3         |

Table 4-b3. Calculated carbon balance for 500°C-biochar

| Component | g C/100 g component | g C/kg willow |
|-----------|---------------------|---------------|
| Willow feed | 51.52             | 515.2         |
| Biochar (190 g/kg willow) | 43.76 | 83.144 |
| Gas       | -                   | 124.0         |
| Condensables | -                  | 287.3         |

5. Applications of bio-oil

After upgrading, bio-oil could substitute for fuel oil or diesel in many static applications including boilers, furnaces, engines and turbines for electricity generation. There is also a range of chemicals that can be extracted or derived and bio-oil can be upgraded to transportation fuels but this is currently not economic. Each of these applications was previously reviewed in literature. Most promising applications, albeit still on small-scale, are given in references [21-31]. Levoglucosan and levoglucosenone can be generated with high yields by pyrolysis [32]. Despite the initial interest in using biomass-derived fuels, the properties of bio-oils however result in several significant problems during its use as fuel in standard equipment such as boilers, engines, and gas turbines constructed for combustion of petroleum-derived fuels, but burner/boiler assemblies can operate with bio-fuel, as long as consistent characteristics are guaranteed. Emission levels are acceptable, it is economically feasible, but requires some modifications. The main concerns for operating diesel engines on bio-oils are some specific properties of these liquids such as difficult ignition (resulting from low heating value and high water content), corrosiveness (acids) and coking (thermally unstable compounds). Problems identified
include the difficulty in adjusting the injection system; wear and corrosion of injection and pump elements; high CO emissions; and the required addition of standard diesel. Although numerous tests have been carried out on the use in turbines [33], the problems associated with using pyrolytic bio-oil are the result of higher NOx, VOC, CO and SO2 emissions, the formation of deposits in the combustion chamber and on the blades, and possible polymerisation problems of the bio-oil in the feeding lines together with corrosion. When considering an upgrading of the bio-oil to transport fuels, the properties that negatively affect bio-oil fuel quality are the low heating value, incompatibility with conventional fuels, solids content, high viscosity, incomplete volatility and chemical instability. Some of those deficiencies can be improved using relatively simple physical methods while others require more complex chemical processing.

Upgrading bio-oil to a conventional transport fuel requires full deoxygenation, accomplished by hydrotreating and catalytic vapour cracking, as reviewed by Bridgwater [20]. Catalyst deactivation still raises many concerns. The processing costs are high and the products are not yet competitive with fossil fuels. Although upgrading to a liquid transport fuel does not currently look promising, bio-oil can become a source of the emerging transport fuel for the future - hydrogen. Production of hydrogen from biomass by pyrolysis and reforming has been extensively studied at NREL (USA), although the process economy was questionable.

6. Conclusions
Pyrolysis offers a considerable potential to transfer ligno-cellulosic biomass into added-value products. Biochar is currently regarded as a carbon-negative C-sequestration agent, and its applications are the subject of numerous current research programs. The liquid bio-oil product is the source of a number of valuable chemicals that offer the attraction of much higher added value than fuels. Upgrading bio-oil to a quality of transport liquid fuel still poses several technical challenges and is not currently economically attractive. There are still many challenges of technical and economic nature to overcome before bio-oil finds large-scale application as fuel.

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