PYROLYSIS BIOCHAR SYSTEMS - PILOT-SCALE PYROLYSIS PLANT FOR ‘SPECIFIED BIOCHAR’ PRODUCTION

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ABSTRACT: This paper describes the research and technology strategy of the UK Biochar Research Centre (UKBRC) in pursuing its objectives towards production of ‘specified biochar’. It outlines the research questions being tackled and describes the portfolio of process equipment developed, spanning laboratory scale, small-scale continuous and pilot-scale reactors. The range of biomass feedstocks studied is outlined and pyrolysis biochar yields are compared across scales and feedstocks. The importance of biochar stability is highlighted and test methods developed at UKBRC for biochar functional properties are introduced.

Keywords: climate change, pyrolysis, biochar, pilot plant, production, yield.

1 INTRODUCTION

Pyrolysis biochar systems offer one of the few available options for sustainable carbon-negative technology in the short-term and are the subject of increasing international research activity. Biochar is a carbon-rich solid produced by pyrolysis of organic matter where the intention is to use the product for carbon sequestration in the environment. For this end, biochar must at least be safe to use in the environment, preferably beneficial, and the carbon content must be stable over a long timescale. Potential benefits arise from use of biochar as a soil amendment in agriculture where increased crop yields, improved soil-water retention and other benefits may be realised under certain conditions. Further benefits of pyrolysis biochar systems include use of volatile co-products (pyrolysis oil and gas) as renewable fuels and provision of sustainable disposal routes for organic waste residues, as well as the benefits to climate change mitigation from carbon storage.

The properties of biochar leading to benefits for agriculture and effective carbon storage depend strongly on the production conditions employed. To date, the progress of research into pyrolysis biochar systems has been restricted by shortage of facilities for controlled slow pyrolysis of biomass at a scale that is matched to field trials. At the UK Biochar Research Centre in Edinburgh we are establishing equipment allowing production of biochar by pyrolysis under specified conditions at successive scales from laboratory to pilot plant.

2 RESEARCH OBJECTIVES

It is well known that feedstock choice and production conditions govern the physical and chemical properties of char, and that these will in turn influence stability of the carbon and behaviours in soils. They also affect the co-product yields and quality and so influence the economics of pyrolysis biochar systems.

We aim to understand how to optimise biochar production conditions with respect to the main benefit areas of biochar, ideally through understanding the cause-effect relationships involved. We aim to use that understanding and predictive capability to provide specified biochar products for particular applications.

3 TECHNOLOGY NEEDS AND STRATEGY

Biochar properties are generally determined by choice of feedstock and by production conditions. However, there are few current examples of equipment needed to make char under differing but tightly controlled conditions, appropriate to biochar and so field-trials of biochar to date have often used whatever char is available. This might be fines from traditional charcoal making or by-products of other waste treatment or energy processes.

To develop the cause-effect understanding of biochar properties required there is a need to produce many samples under well defined conditions and test their properties. To understand soil effects such tests should be representative of how chars will behave in soils and be used together with selected chemical and physical analyses for comparison. Also there is a need to make material under tight control on a scale that can be used in plot- or field-trials, and to be able to specify conditions in a way that can be scaled-up further to industrial suppliers. Additionally there is a need to study potential hazardous components of biochar, for which a smaller scale is more appropriate.

These needs lead to our technology strategy involving three successive scales of pyrolysis equipment termed Stage I, a laboratory batch reactor, Stage II, a small-scale continuous reactor and Stage III, a pilot-scale continuous reactor. These are described in the following sections.

4 EQUIPMENT PORTFOLIO

4.1 Stage I – laboratory batch pyrolysis reactor

The Stage I pyrolyser, shown in Figure 1, is a static bed reactor employing a 50 mm diameter quartz tube allowing a sample bed depth of approximately 200 mm. This is heated by a 12 kW infra-red furnace with PID control allowing a wide range of heating rates and a maximum temperature of 1300°C. Hold time at maximum temperature can be varied as desired, times between 5 and 180 min have been used so far. A nitrogen carrier flow sweeps volatile and gaseous products of pyrolysis into a series of condensers and receivers where the condensable liquid products are collected (150°C tars trap, air condenser and ambient temperature receiver, two cold traps at ca. -40°C). A volumetric flow meter measures the cleaned syngas flow and an on-line, mobile mass spectrometer measures gas composition. On-line data logging is available for the main process variables: temperature, pressure and gas volume flow. The apparatus is capable of producing about 20 g of biochar per run, depending on feedstock and conditions.

Figure 1: Stage I – laboratory batch reactor

4.2 Stage II – small-scale continuous pyrolysis reactor

The Stage II pyrolyser, Figure 2, is a small continuous unit capable of making up to two kilos of biochar per hour. It can be taken through a sequence of different conditions in one run to make multiple samples of differently-produced biochar from one feedstock. It comprises an electrically heated, screw driven horizontal tubular reactor (102 mm ø x 900 mm heated length). Residence time in the hot zone can be varied between 10 and 60 minutes and the maximum temperature is 850°C. Feed rate is independent of residence time with a separate feed screw delivering up to 5 kg h^{-1} (dry weight), depending on feedstock bulk density.

Figure 2: Stage II – small-scale continuous pyrolysis unit

After pyrolysis the biochar product falls into a collection vessel while vapours and gases are swept by the nitrogen carrier gas into an afterburner chamber where a propane-fuelled pilot flame ensures complete combustion. The unit is not designed for preparative collection of condensed liquids or syngas, although a sample loop allows small representative samples to be withdrawn. The sampled liquids are condensed and collected and the syngas mixture can be analysed by an on-line mass spectrometer.

4.3 Stage III – pilot-scale continuous pyrolysis reactor

The Stage III pilot-scale unit, Figure 3, is a unique facility housed in a dedicated new building. The process flow is closely similar to the smaller Stage II unit however the reactor itself is a rotating tube with no internals.

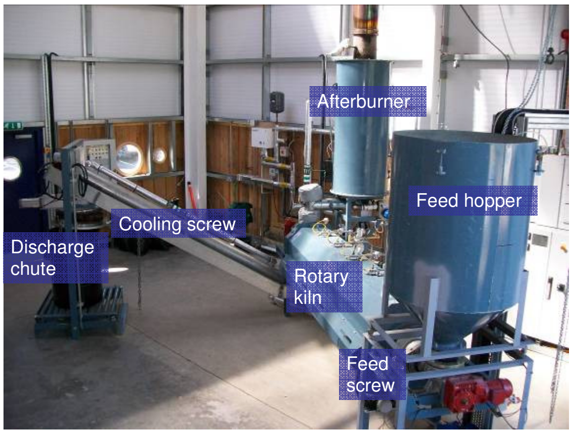

Figure 3: Stage III – pilot-scale continuous pyrolysis unit

A 600 litre feed hopper is mounted on load cells allowing control and accounting of the feed rate. Feed is delivered by screw to the reactor at up to 50 kg h^{-1} (dry, design rate) and moves through the reactor by rolling motion as fresh material is fed in. The tube is electrically heated at up to 850°C in three independent zones each with PID control. Rotation speed range of 1 to 7 rpm allows variable residence times in the hot zone. The equipment operation is PLC controlled.

At present, as for Stage II, an afterburner disposes of the volatiles by combustion. However, there is provision for sampling the vapour/gas stream and connecting to the mass spectrometer for gas composition analysis. Also there is a branch available for a potential future gas cleaning rig.

The biochar product is conveyed from the end of the rotary kiln through a water-cooled screw to fall into a sealed product drum on a weigh-scale; production rates up to 20 kg h^{-1} are expected depending on feed and conditions.

5 MATERIALS PROCESSED

A variety of feedstocks have been processed in the three pyrolysis units described above. Initially, most have been virgin biomass in order to establish the equipment and techniques, but our focus is increasingly towards residues and wastes as biomass feeds. Commercial wood pellets have been used as a standard for comparison across scales and more limited comparisons have been made with short-rotation coppice (SRC) willow and miscanthus. Table I shows which feeds have been processed at the three scales.

Table I: Biomass feeds processed at the different scales

Feed	Stage I	Stage II	Stage III
Softwood pellets	✓	✓	✓
Softwood chip	✓		
Sugar cane bagasse	✓		
SRC Willow chip	✓	✓	✓
Rice husk	✓		
AD digestate	✓		
Miscanthus	✓	✓	✓
‘Treibsel’ (flotsam)		✓	

6 BIOCHAR YIELDS

The following charts, Figures 4, 5, 6, show selected yields from pyrolysis runs on the three successive scales of reactor. Data are for percent weight recovered yields on a dry feed basis. The numerals in the legends for these and later charts refer to the scale of production – Stage I, II or III.

The Stage I results, Figure 4, are for runs under similar conditions (heating rate 5°C min^{-1}, hold time at peak temperature 40 min) with two exceptions: willow chip (hold time 30 min) and miscanthus (heating rate 100°C min^{-1}, hold time 10 min – aiming to mimic conditions of a continuous reactor). The results show the expected trend of decreasing yield with increased temperature and also the expected degree of variation between different feedstocks, depending on their composition.

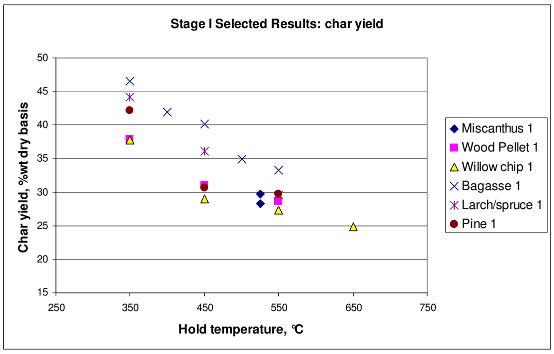

Figure 4: Stage I – selected biochar yield results

Stage II yield results, Figure 5, follow a similar pattern with the exception of the ‘Treibsel’ which forms an outlier with high yield. This material, flotsam collected from canals and sea-walls in northern Germany, is fairly heterogeneous and is believed to have a high mineral content which may explain the higher yield. The runs all used a hot-zone residence time of 16 min.

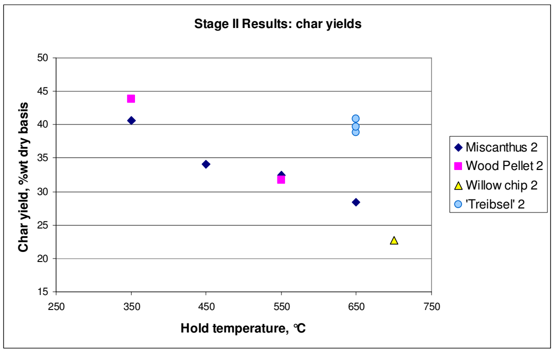

Figure 5: Stage II – biochar yield results

Fewer data have been acquired for Stage III yields, Figure 6, and most of these are from commissioning runs at 500°C with hot-zone residence times around 30 min. The apparent variability of yield relates to difference in material accounting methods in early runs and more experience is needed to firm-up these values. However, yields fall in the expected general range.

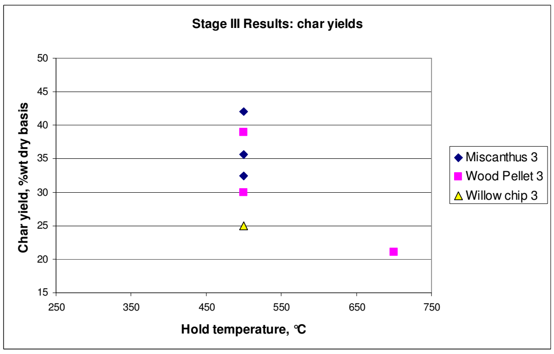

Figure 6: Stage III – biochar yield results

Comparisons of yields between the three production scales has been made for three feedstocks: wood pellets, miscanthus and willow. Direct comparisons at the same pyrolysis temperatures are so-far limited to wood pellets, as shown in Figure 7. At 350° and 550°C the yields in the continuous Stage II reactor were 6% and 3% respectively higher than the Stage I yields. This is likely to relate to the shorter residence time at peak temperature experienced in the continuous reactor.

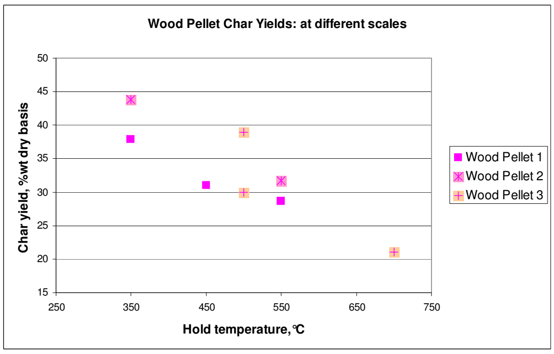

Figure 7: Comparison of biochar yields – wood pellets

The comparison for miscanthus, shown in Figure 8, is less clear but possibly also shows slightly raised yields in the continuous runs on Stage II and III units.

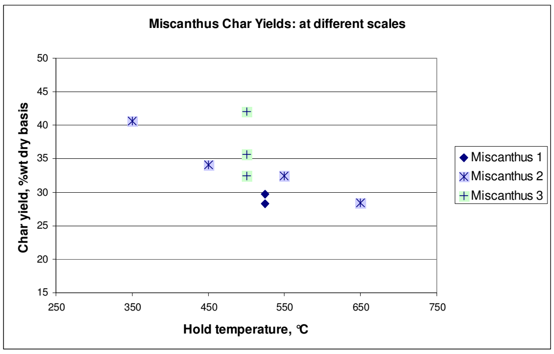

Figure 8: Comparison of biochar yields – miscanthus

However, the very limited comparative data for willow chip, Figure 9, shows, if anything, the opposite effect but this is unlikely to be significant.

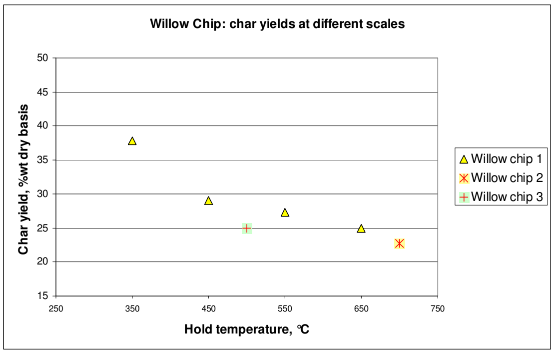

Figure 9: Comparison of biochar yields – willow chip

7 BIOCHAR STABILITY

While biochar mass yield obviously matters in a production context to maximise efficiency of use of biomass, it may not be the most important measure from the point of view of the main driver for interest in biochar. Not all char is the same, in particular the carbon content varies, increasing with production temperature. Also the chemical and physical nature, and so stability, of the carbon varies with production conditions. For carbon storage and climate change mitigation it is the yield of carbon that is stable in soil that is most important; this will be lower than total carbon yield and not necessarily the same as the fixed carbon yield as measured by traditional analysis methods. The yield of stable carbon is given by the product: (biochar mass yield) x (stable fraction in soil), a specific test is needed for the second term.

The UKBRC has developed a series of tests that mimic how biochar behaves in soils, known as the *Edinburgh Toolkit.* The tests cover: stable carbon fraction, labile carbon fraction, priming potential, nutrient value and soil structure effects. We are beginning now to apply these test to biochars produced at different temperatures and scales. This will help us to specify production conditions of biochar to give optimum stability from a given feedstock and to understand the trade-offs with other desirable properties of biochar such as nutrient value and soil structure improvement.

8 CONCLUSIONS

There are several factors which need to be understood relating biochar production conditions to its functional properties to enable the most efficient and sustainable deployment of biochar. One important factor is yield, in particular the yield of carbon in biochar that is stable in soils. The UKBRC has now developed an equipment portfolio and representative test methods to allow thorough investigation of the relationship between biochar production conditions and stable carbon yield, as well as to develop understanding of the trade-offs with other biochar properties. This will allow us to specify and produce biochar optimised for a given application and system.

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