

BEIS GGR Innovation Phase 1 Project
Bio-waste to Biochar (B to B) via Hydrothermal Carbonisation and Post-Carbonisation
Final Report

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Summary

The aim of this Phase 1 project was to establish the feasibility of the “Bio-waste to Biochar” (B to B) approach and optimise process design and operation for large-scale biochar production. Hydrothermal conversion (HTC) can operate successfully with AD fibre, even fibre containing high plastic contents with over 50 tonnes processed. Based on this experience, the optimal HTC plant for Phase 2 has been identified which will be fully integrated with post- carbonisation (high temperature torrefaction, HTT) of the biocoal produced by HTC of AD fibre biocoal to obtain very stable biochar at temperatures of ca. 700°C, with atomic H/C ratios <0.5 and stable polyaromatic carbon (SPAC) contents of over 90%. Further, the biochar produced from HTC AD fibre biocoal will satisfy the voluntary European Biochar Certificate (EBC) environmental standard for biochar and have good adsorptive properties for moisture and nutrient retention. A life cycle analysis and process economic study has demonstrated that the cost per tonne of CO₂ avoided is close to £100, although sensitivity analysis has shown that this estimate could deviate by up to +/- 20% due to variables in the configuration and location of a commercial plant. The integrated HTC-HTT will produce ca. 450 tonnes of biochar p.a. (1000 tonnes CO₂ equivalent) over the course of the project and this represents an “end to end” solution to a major environmental problem for the food AD industry since the biochar produced will be deployed across arable land, woodland/forestry using the extensive partner network that has been established in the UKRI GGR Biochar Demonstrator project led by the University of Nottingham.



Hydrothermal carbonisation (HTC) + High temperature torrefaction (HTT)
= Biowaste to Biochar (B to B)



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1. The B to B Technology

1.1 Background and Phase 1 project overview

Biochar can potentially make a major contribution to the UK target for Greenhouse Gas Removal (GGR) of 35M tonnes of carbon (MtC) p.a. by 2050 (Royal Society, 2018. DES5563-1, ISBN: 978-1-78252-349-9). However, there are some significant challenges to overcome, particularly the availability of feedstocks where supply of virgin wood could be limited. Biowaste or bio-residues, particularly anaerobic digestate, has significant potential to extend the range of feedstocks for biochar production. The expansion of anaerobic digestion (AD), including food waste, indicates there is potential to produce ca. 200 kt p.a. of biochar from biowaste by 2030. The Government's Environment Bill will mean the roll out of separate household food waste collections across the country by 2023 and goes one-step further by committing to eliminate food waste from landfill by 2030. To meet this ambition, it is pertinent to consider how a significant fraction of the carbon in food and other wet biowastes can be permanently sequestered in the form of biochar. From a life cycle analysis (LCA) perspective the GGR potential of using biowaste with energy recovery for biochar is greater than using virgin wood where a fraction of the carbon in a temporary store is converted into a form for permanent storage.

The fact that the majority of biowaste is wet means that it is unsuitable for direct carbonisation to produce biochar due to excessive drying costs. Hydrothermal carbonisation (HTC) is a technology that can treat wet biowaste directly where the major product is a biocoal which, for woody feedstocks, typically gives a 65% mass yield on a dry ash free basis and a carbon yield of ca. 80% (fraction of the initial carbon in the biocoal), also producing a process liquor and a small amount of CO₂-rich gas. Since HTC operates at 200°C, subsequent carbonisation (high temperature torrefaction) of the resultant biocoal is required to produce stable biochar containing low proportions of potentially degradable carbon. The process liquid is a mixture of primarily sugars and organic acids with dissolved alkali and alkaline earth metals. To minimise the biochar production costs, the feedstock needs to attract a gate fee which, in the UK for the solid residue or fibre from AD, will be considerably less than for landfilling and incineration.

Our analysis of combining HTC with high temperature torrefaction (HTT) has indicated that carbon sequestration costs are ca. £100 tonne/CO₂ equivalent avoided (Section 1.6), well under within the target set by BEIS. The aim of the Phase 1 project was to establish the feasibility of the "B to B" approach and optimise process design and operation for large-scale biochar production. The main achievements of the Phase 1 project providing the confidence required to proceed with Phase 2 have been:

- To demonstrate that HTC can operate successfully with AD fibre, even fibre containing high plastic contents with over 50 tonnes processed.
- Based on this experience, to improve and simplify the HTC plant for Phase 2 of the project which will be fully integrated with HTT and will produce over 600 tonnes of biochar p.a. (2000 tonnes CO₂ equivalent).
- HTT of HTC AD fibre biocoal can produce very stable biochar at temperatures of ca. 700°C, with atomic H/C ratios <0.5 and stable polyaromatic carbon (SPAC) contents of ca. 90%.
- The biochar produced from HTC AD fibre biocoal satisfies the voluntary EBC environmental standard for biochar and have good adsorptive properties.
- Providing LCA and economic evidence to show that the cost per tonne of CO₂ avoided is close to ca. £100.

1.2 Feedstocks

1.2.1. AD fibre preparation and current disposal

AD is a biological process that breaks down organic matter such as food waste to generate biofuel. The AD process also generates digestate, a nutrient-rich liquid fertiliser and soil improver, which can be used to displace traditional chemical fertilisers and provide benefits to the soil. AD operators have a duty to ensure the digestate material produced meets necessary standards on the control of plastic contamination within the BSI known as PAS110. To ensure these limits are reached, all of sites are fitted with a Boerger separator that can remove any undigested organic matter and plastics contamination over 0.5 mm. From the AD plant to land where it is spread,

digestate is typically transported a 50-mile round-trip (WRAP Cymru, *Assessing the Costs and Benefits for Production and Beneficial Application of Anaerobic Digestate to Agricultural Land in Wales*, 2014) where the average cost of transporting and spreading dewatered digestate fibre comes to £16/tonne (WRAP, *Digestate and compost use in agriculture: Good practice guidance*, 2016). There are further regulations if the digestate is to be spread to land designated as a Nitrate Vulnerable Zone (NVZ). Within NVZs, at least 5 months of storage of digestate slurry must be provided (DEFRA, *The Guide to Cross Compliance in England 2018*,). This can come at a high capital cost for the AD operator at £25-£50/m³ of digestate stored (WRAP, *Digestate distribution models*, 2013). Furthermore, with the introduction of the Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018, digestate spreading is further regulated by the Environmental Agency. In practical terms, more digestate has to be spread over a shorter period of time and over 6 month's storage is required in most situations in order to prevent hydraulic-lock at the AD plant. Additionally, new storage requirements mean that farm AD operators are having to retrofit impermeable storage covers, often coming at a cost higher than £50/m³. On top of this, there are concerns about the growing area of land designated as an NVZ. Draft legislation in Wales from April 2020 proposed to designate the whole of Wales as an NVZ, over 40 times the area currently covered (NFU Cymru, *NFU Cymru astonished at publishing of draft NVZ regulations during Covid-19 crisis*, <https://www.nfu-cymru.org.uk/news/latest-news/nfu-cymru-astonished-at-publishing-of-draft-nvz-regulations-during-covid-19-crisis/>). Although this project is primarily concerned with the fibre, this evidence suggests that it may also be economic to treat digestate along with fibre by HTC in the future.

The screenings known as 'AD fibre' or 'Boerger screenings' is the material removed from the liquid fertiliser and is the material that is subject to the trial via HTC and then pyrolysis. This material is inherently a combination of organic matter and inorganic plastics as the Boerger screenings fundamental purpose is to meet the contamination level for PAS110. This material usually has a much larger fraction of organic matter than plastics as all sites have up front de-packaging before the AD process to remove the plastics. However, there will always be a fraction that will pass through and either settle in the digesters or be removed in the Boerger screen.

Regarding AD fibre that will be used in Phase 2 of the project, STGP produces food waste digestate, as by-product of the AD process, which is recycled to land as a biofertilizer under PAS110 Quality Protocol. To achieve this protocol the pasteurized whole digestate is screened to remove particle sizes over 0.5 mm. The residual solids produced are the digestate screenings, also known as Böerger screenings, relating to the specific Börger unit used on STGPs' sites. This material is disposed of under EA and APHA regulations via landfilling or incineration, which have significant cost implications to STGP. Further, incineration and landfilling both result in significant Greenhouse Gas emissions with virtually all the carbon being recycled back to the atmosphere.



Figure 1 AD fibre samples containing relatively (a) high and (b) low contents of plastic.

During the Phase 1 trials, a suboptimal load of Boerger screenings had been identified. The reason for this load is that a mixer had failed on the tank where the liquid digesters filters through the

Boerger separator. The mixer had been working sub-optimally for some time and was replaced. While the new mixers worked much better, they also lifted the very old material with high plastic content from the bottom of the digestors that could have been there for years, even before the upfront de-packaging unit was installed on the Coleshill site. The plastic material has likely been settled over an extended period and likely happened before the site had a de-packaging unit installed upfront of the digester system, given the size of the plastic pieces. This meant the plastics in the feedstock was significantly higher than would normally be the case (Figure 1a, approximately 15% (dry mass) compared to typically ca. 5% by weight). However, 40 tonnes of this sample was successfully processed by HTC. Fibre from one of STGP's other AD plants was identified (Figure 1b) and over 10 tonnes of this second sample has been processed.

This however has been a good lesson for a potential future plant. Organic residue from a food waste plant will contain plastics until all packaging is plastic free and bio-digestible which is not currently available on the market for food manufactures. Therefore, it should be expected that the Boerger screenings will always have varying plastics levels, which has been taken into consideration for a full-scale plant. We have demonstrated that the HTC plant can cope with such variable plastic contents.

1.2.2 AD Fibre availability for biochar production

Table A1.1 in Appendix 1 summarises the breakdown of AD in the UK. In 2019, 12.5 million tonnes of feedstock were processed by 486 AD plants resulting in over 500,000 dry tonnes of digestate (fibre) production (NNFCC, *The Anaerobic Digestion (AD) Portal - Biogas Map*, <http://www.biogas-info.co.uk/resources/biogas-map/>). Although there are delays in construction, as of April 2020 this number of plants rose to 579 with a further 331 under development (NNFCC, *Anaerobic digestion deployment in the United Kingdom Seventh Annual Report*, 2020). Digestate composition depends on the feedstock used, but it has been estimated that there are between 130,000 and 240,000 tonnes of carbon contained in digestate annually (Table A1.2) (J. Liu *et al.*, *Bioresour. Technol.*, 2020, **302**, 122841).

AD capacity in the UK has increased over the last 15 years, supported by feed-in tariffs and renewable heat incentives. Looking ahead, it is expected that AD of food waste in particular will increase. Currently, 17% of AD plants process food waste, whether that is as a mono-substrate or co-digested with a variety of different feedstocks. WRAP estimated that in 2018, 9.5 million tonnes of food waste was generated within UK households, hospitality & food service, food manufacture, retail and wholesale sectors WRAP, *Food Surplus and Waste in the UK – key facts*, 2020). This had a value of over £19 billion and would be associated with more than 25 million tonnes of greenhouse gas emissions. This value does not include food waste arising from primary food production, with a central estimate of 1.6 million tonnes annual production. Of the 9.5 million confirmed tonnes of waste, an estimate of 1.3 million tonnes were directed to AD (Which?, *Three food waste facts everyone needs to know*, <https://www.which.co.uk/news/2019/06/three-food-waste-facts-everyone-needs-to-know/>). The AD Biogas Map reports that 2 million tonnes of food waste were processed by AD in 2019 and so it is assumed that the difference is made up of a fraction of the food waste arising from primary food production.

There are governmental targets to reduce food waste generation over the next 10 years. If the Courtauld 2025 and SDG12.3 targets on UK food waste are met, overall food waste is projected to fall to 8.4 million tonnes in 2025 and 7.7 million tonnes in 2030 (WRAP, *Food Surplus and Waste in the UK – key facts*, 2020). The UK government have identified that AD with digestate as a fertiliser material is environmentally better for treating unavoidable food waste than composting or other recovery options (Department for Business Innovation & Skills, *Building a high value bioeconomy: opportunities from waste*, 2015). Assuming that 80% of food waste is directed to AD by this point, 6.8 million tonnes of food waste would be treated (Figure A1/1). Ignoring the increase in AD treatment of other feedstocks, this would be over a 50% increase in AD capacity in the next 10 years.

To conclude, by 2030, the quantities of food waste processed by AD are projected to increase by approximately three-fold, representing over 2M tonnes of CO₂ equivalent with mandatory food waste collections coming into effect in England in 2023. The amount of food waste collected is projected to increase by 1.35 million tonnes by 2029. Clearly, this represents a major resource for

the BtoB approach. Therefore, our analysis indicates that there is sufficient AD fibre nationally to support plants producing combined savings of over 500,000 tonnes of CO₂ equivalent p.a. by 2030. Other biowastes including green waste and oversize compost can also be processed by HTC. However, these will attract a lower or no gate fees which will increase the cost of CO₂ avoided in biochar as discussed in Section 1.6.

1.3 HTC biocoal and biochar assessment

1.3.1 Biocoal and liquor production and characteristics

CPL have processed close to 50 tonnes of Severn Trent's Boerger screening waste digestate material through the HTC plant. During the testing spread over 45 days of operation. Some issues were encountered when running only one 8-hour shift per day. Once the plant is turned off and left to cool, the plastics within the feedstock that remain in the reactor re-solidify and create a binder effect with the organic material. This produces large lumps of product that has caused blockages in the reactor and, also, afterwards, in the inert separation equipment. The solution has been to run longer hours to prevent the plant from cooling down as frequently.

The particle size distribution of the biochar was determined by sieving. The results show that the HTC biocoal produced from the digestate had a bimodal particle size distribution, with approximately 65% of the material having a particle size of greater than 1 mm (Table A2.1, Appendix 2). Given the small particle size range, it has been decided to pelletise the AD HTC biocoal prior to HTT. To achieve, this in the Phase 2 pilot-plant, the sample needs to be ground to reduce the particle size to less than 1 mm.

The >4.75 mm and 2.36 mm size fractions were selected for further characterisation to assess if particle size had any impact on the properties of the biocoal. proximate and ultimate analysis results for the >4.75 mm fraction listed in Table A2.2. The moisture content of the HTC biocoal can vary due to the post-processing drying undertaken at CPL, with an initial batch containing almost 50% moisture and a later one just 10%. The data are therefore reported on an "as received", "dry" and "dry ash free" basis, with the DAF data being the most important to give an understanding of the carbon balance across the process. The biocoal was found to contain approximately 19% ash on a dry basis, and 56% carbon. Excluding the inert ash gives a carbon content of 69%, and an H/C atomic ratio of 1.19. This is consistent with the low process temperature of HTC (210°C), and indicates that as expected, due to the low extent of aromatization, the HTC biocoal would not persist in the environment (e.g. X. Xiao, *et al.*, Scientific Reports, 2016, 6, 22644).

Table A2.3 summarises the heavy metal concentrations in the AD fire and resultant HTC biocoal. All the concentrations are will within those given in the European Biochar Certificate. Although the heavy metal concentrations may increase by two-fold on subsequent high temperature torrefaction, they will still lie well within the EBC guidelines. PAH and PCB concentrations are also extremely low (Table A2.3) and well within the EBC guidelines, although subsequent high temperature torrefaction may increase the PAH levels.

Analysis of process water: Table A2.4 indicates low heavy metal analysis in the HTC liquor. The relatively low ammonia and phosphate levels means that it should meet criteria for disposal to land and can also be considered for recycling in AD.

The organic fraction of the HTC process water was subjected to liquid/liquid extraction (20 mL process water extracted 4 times in 20 mL of dichloromethane). The extract was then analysed by GC-MS following the addition of an internal standard (squalane). As shown in Figure A2.1 it is largely composed of phenolics, pyrazine, n-alkanes and fatty acid methyl esters. All the compound classes are present at very low levels, with quantification relative to the standard (assuming a response factor of 1) showed that the total phenolics (phenol, cresol, ethyl phenol) were present at ~5 mg/L. This will not limit the use of the process water as either an agricultural fertiliser, or as a co-feedstock in further anaerobic digestion.

1.4 Biochar production and characteristics

1.4.1 High temperature torrefaction

High temperature torrefaction (HTT) is being used to convert the HTC biocoal into highly stable biochar and the test programme has comprised small, medium and large-scale tests. The small

and medium-scale tests were carried out mainly on the HTC biocoal produced from the high plastic content AD fibre, which was available towards the end of the project. As already described, the particle size distribution means that the HTC biocoal with ca. 50% of the particles <1 mm means it should be pelletised prior to HTT (Figure A2.1) to avoid dust release when applied to agricultural land. Therefore, in the pilot-plant design for Phase 2, the AD fibre HTC biocoal will be first pelletised to avoid fines in the resultant biochar.

For the small, lab-scale tests 7.5 g of the AD fibre HTC biocoal (>4.75 mm) was weighed into a ceramic boat and placed in a horizontal tube furnace (HTF). The sample was purged for 15 mins in 100% N₂ (1 bar, 1 L/min) to remove air, then carbonised at 550, 700, 750, and 800°C for 0.5 hrs at a ramp rate of 10°C/min under 100% N₂ (1 bar, 1 L/min) and held isothermally for 30 minutes. Tests were carried out in duplicate with 30 being completed.

Medium-scale tests were carried out at CPL using the HTC biocoal produced from both the high and low plastic AD fibre with a kiln temperature close to 750°C. Since pelletised material was not available for testing, the > 2mm fraction was used to provide a strong indication of how pelletised material would behave for the low plastic HTC biocoal. Approximately 25 kg of the AD fibre HTC biocoal were fed which yielded 10 kg of biochar. The yields of 40% w/w is consistent with those from the laboratory-scale tests and the overall carbon mass balance where 40% of the initial carbon in the AD fibre ends up in the biochar.

1.4.2 Biochar characterisation

Elemental compositions, ash contents, textural properties and heavy metal concentrations have been determined and are summarised here. For the kiln-produced biochar, the particle size distributions have been compared. The long-term stability of the biochars have been assessed from their atomic H/C ratios and the fraction of stable polyaromatic carbon (SPAC) determined by hydrolysis (W. Meredith *et al.*, 2012. *Geochimica Cosmochimica Acta* 2012, 97, 131-147).

Proximate and elemental analyses - It is evident that increasing temperature results in a decrease in the moisture and volatile matter content, and a concurrent increase in both the fixed carbon and ash contents. However, >20% volatiles on a dry ash free basis could indicate that some mineral matter is volatilizing out under 100% N₂ gas (100 ml/min) in the TGA from proximate analysis and could overestimate the amount of volatiles. To better understand the fate of the carbon within the process, the trends in the carbon content from the ultimate analysis on a dry ash free basis showed an increase in the carbon content from the initial HTC digestate of 69%, to 79% after carbonisation at 550°C, 85% at 700°C 87% at 750°C and 90% at 800°C. This increase in carbon content is accompanied by a minor decrease in carbon yield retained within the biochar from approximately 51% at 550°C to 42% at 800°C. On the larger 10 kg scale at 750 °C, the biochar carbon content is 84-92%, with carbon yields in the range of 38-52% over the entire particle size range.

Stability - From the atomic H/C ratios and SPAC contents it is apparent that the quality of the biochar, in terms of its carbon stability, improves significantly as the HTF temperature increases from 500 to 750°C (Appendix 3, Table A3.1). The H/C ratio decreases from 0.6 (550°C) to 0.4 (750°C) on a dry ash free basis. However, there is little further improvement at higher temperatures implying that 750°C is the optimum temperature to balance yield, carbon stability and processing cost. On the larger 10 kg scale, the resulting biochar H/C ratios are all <0.3 throughout the particle size range at 750°C (Table A3.2, Figure A3.2), indicating improved biochar quality on a larger scale. The biochar produced from the low plastic AD fibre has a similarly low atomic H/C ratio.

These results are consistent with the SPAC contents of the lab-scale chars, which is a more sensitive measure of carbon stability. From 39.5% at 550°C this parameter increases to 89.9% at 700°C, indicating that these biochars will be highly resistant to degradation in the environment. Beyond 700°C there is little further increase in stability at higher production temperatures. The SPAC content of the biochar produced from the low plastic AD fibre had a SPC content of 84%, similar to the samples prepared from the high plastic samples (Table A3.1 and A3.2).

Figure A3.3 summarises the results from the series of tests in the demonstration facility where the temperature was increased where the atomic H/C ratio is plotted against the SPAC fraction from hydrolysis. This is a considerably higher atomic H/C ratio and lower SPAC content than from

the small and medium-scale tests. These results confirm that HTT needs to be carried out at a higher temperature (ca. 700°C) than can be achieved in the demonstration facility used. Therefore, in the design for the integrated HTC and HTT facility for the Phase 2 project (Section 2), it was decided to use a rotary kiln design for HTT very similar to those used commercially by CPL for activated carbon regeneration where temperatures > 700°C can be achieved.

Textural properties - BET surface area, total pore volume and porosity are summarised in Table A3.3a and b. For the samples prepared on a lab-scale (HTF carbonisation) there is a vast increase in BET surface area above 550°C, increasing from 12 to 108 m²/g, and it passes through a broad maximum at 750°C (217 m²/g) before decreasing slightly at 800°C. This is correlated by the volume of micropores having the same trend as BET specific surface area, reaching a maximum at 750°C (0.124 cm³/g). Correcting for ash, increases the maximum BET surface area of the biochar to ca. 300 m²/g, which is relatively high for biochar, suggesting that the samples prepared here will have good adsorptive properties for moisture and nutrients. On the larger scale kiln carbonisation, the biochar has a specific surface area in the range of 199 to 240 m²/g and micropore volume of 0.099 to 0.123 cm³/g. The data shows similar textural properties to that of the lab-scale biochar carbonised at 750°C (Figures A3.4a, b and c), indicating excellent uniformity of the 10 kg biochar. This biochar has a very high moisture uptake of 80% on a dry basis, indicating that high water retention should be achieved. This close to the theoretical value of 75% if moisture fills all the pore volume.

Heavy metal concentrations - Heavy metal contents for the biochar are summarised in Table A3.4. This analysis replaces the preliminary data derived from X-ray fluorescence (XRF) that was previously reported, and was done at Eurofins Umwelt, an accredited test laboratory according to DIN EN ISO/IEC 17025:2018. The metals were analysed by inductively coupled plasma optical emission spectrometry (ICP-OES) following microwave assisted digestion. All heavy metals are below the EBC-material class IV limits; all with the exception of copper are below the EBC-Agro class III limits; and all with the exception of copper and nickel are below the EBC-Agro-Bio class II limits.

PAH concentrations - PAH contents for the biochar are summarised in Table A3.5. As with the heavy metals this analysis was done at Eurofins Umwelt, according to DIN EN 16181. The PAHs were analysed by GC and HPLC. The total concentration of the 16 EPA priority PAHs is below the EBC-material class IV limits. While the total concentration exceeds the EBC-Agro class III and EBC-Agro-Bio class II limits, this is due almost entirely to the presence of naphthalene, and the concentrations of the most concerning compounds such as benzo(a)pyrene are below the limit of quantification. The occurrence of naphthalene is believed to be due to the configuration of the small kiln at CPL that results in some condensation while the cooling vapours are in contact with the biochar. The longer cool down phase encountered in the proposed larger Phase 2 kiln should result in the removal of naphthalene in line with the larger ring PAHs as seen in Table A3.4.

Plastic-derived (fossil) C fraction in the biochar - The biochar obtained from the rotary kiln was radiocarbon dated and had an age of 426 years which corresponds to only 6% plastic-derived (fossil) carbon in the biochar. The plastic content of the AD fibre used to prepare the biochar was approximately 15%. However, given the C content of common plastics is considerably higher than that in the organic matter remaining after AD, it is estimated that the plastic accounts for over 20% of the carbon in the AD fibre. From the high relative depletion of the plastic to only 6% in the biochar, clearly most of the plastic is volatilised. When better quality AD fibre is used containing only 5% w/w plastics, the fraction of plastic-derived carbon in the biochar will be very small, ca. 2%.

1.5 Monitoring reporting verification (MRV) requirements

For biochar to be deployed for GGR, firstly it must satisfy environmental standards, such as the voluntary European Biochar Certificate (EBC) in terms of low concentrations of heavy metals and organics, including polycyclic aromatic hydrocarbons (PAHs). Secondly, evidence must be obtained that the carbon will be stable over centennial timescales. Since it is challenging to monitor biochar in the ground, the latter must be based on structural characteristics. The EBC have produced a draft paper and propose an atomic H/C ratio below 0.5 as a measure of high stability.

As already described, we propose using SPAC (Section 2.2) as a considerably more sensitive measure of stability and have demonstrated that HTT at a lab-scale can produce SPAC contents of greater than 90% from HTC fibre biocoal. We propose that payments for biochar should be based on the stable carbon fraction, SPAC content as a reliable indicator, and this approach is currently being developed through the BBSRC Biochar Demonstrator with key stakeholders, including BEIS and Defra, who both have representatives on the Expert Advisory Group for the Demonstrator. Although biochar can be traded in current markets, such as Puro Earth, clearly there are no rules in place concerning MRV.

1.6 LCA including economics

1.6.1 Introduction and B to B carbon balance

As explained in the Proposal, the approach used here is attractive in that wet biowaste either degraded over short timescales in landfills or is combusted during incineration with only moderate levels of energy recovery. Thus, from an LCA perspective, it is far more beneficial than carbonising wood on the premise that all the carbon in wet biowaste would be converted to CO₂, although the situation is significantly worse for landfill, due to methane being formed. Therefore, the minimum amount of carbon avoided is the amount of carbon converted to biochar, assuming it can be established that the biochar produced is stable over suitable time periods.

The HTC biocoal contains approximately 80% of the initial carbon with approximately 5% being lost in CO₂ rich gas stream and the remaining 15% in the liquor, which has potential value as a nutrient or as a co-feedstock with food waste and maize in the AD plants operated by STGP. During HTT produce stable biochar, ca. 50% of the carbon is released in the volatiles, which are combusted for energy recovery with the remainder being in the biochar. Thus, the carbon sequestered represents 36-40% of the initial carbon in the AD solid residue.

1.6.2 Scope of study

Life cycle greenhouse gas (GHG) emissions and costs are assessed for biochar production from food waste digestate and agricultural field application. The study scope includes activities from food waste digestate supply (including avoided incineration), HTC+HTT process, transportation stages, and application to agricultural field. Scenario analysis is employed to assess impacts of facility scale, supply chains, and to quantify uncertainties:

- 1) Phase II: 10 kt/yr demonstration facility
- 2) Commercial 2030 base case: distributed HTC+HTT facilities co-located with food waste anaerobic digestion facilities, avoiding need to transport digestate to HTC+HTT facility
- 3) Commercial 2030 high transport: higher transport requirement as HTC+HTT facilities not co-located with anaerobic digestion
- 4) Commercial 2030 including soil effects: conservative estimate of biochar impacts on fertiliser use and field N₂O emissions
- 5) Commercial 2030 including optimistic soil effects: high fertiliser displacement, assuming all biochar nutrient content is available to plants

All model data and assumptions are included in the Appendix 4, with key parameters explained here.

Transportation: Digestate and biocoal are transported by 25t lorry. The current pilot scale and proposed Phase II facility are located at the Coal Products Limited site in Immingham requiring digestate transport for 206 km from Severn Trent Green Power in Coleshill. Process liquid (170L/t_{digestate}) is returned to AD at Severn Trent Green Power. In 2030 scenarios, digestate transport will be avoided if HTC-HTT is co-located with AD; a maximum digestate transport distance of 38 km is estimated based on projected food waste availability if facilities are sited independently. Biocoal transport to field is assumed to be 25 km (50 km in high transport scenario). Field spreading is included in the transportation stage.

Avoided digestate incineration and plastic content: Current incineration of food waste digestate is a net GHG emissions source, as direct emissions from the combustion of plastic content (5%, dry basis) exceed emissions benefits of electricity generation displacing the grid mix. Incineration of digestate has a small net energy yield, due to the high moisture content. On

balance, incineration of digestate results in a net GHG emission of 0.004 kgCO₂eq./kg_{digestate} in 2020, increasing to 0.017 kgCO₂eq./kg_{digestate} in 2030. During HTC+HTT processes, all plastic content is assumed to be oxidised, resulting in direction GHG emissions of 0.037 kgCO₂eq./kg_{digestate}. This emission source is exactly balanced by emissions from plastic combustion in incineration, and so does not increase GHG emissions to atmosphere relative to current practice of digestate disposal.

Carbon sequestration and soil effects: The carbon yield of biocoal is 41-47% (dry ash free basis) of the initial carbon in the AD digestate. Permanence of this carbon store post-application is not considered in this preliminary analysis, and all carbon contained in biochar is assumed to be permanently sequestered. Agricultural application may achieve additional benefits related to crop yield, nutrient provision, decreasing soil organic carbon decomposition, and reducing N₂O emissions. Limited data is available to approximate these effects. The emission reduction associated with a selection of soil effects is considered in the final two scenarios, based on limited available data. None of these soil effects are monetised.

1.6.3 Results

The resultant emissions and costs associated with the phase two and various commercial scenarios are presented in Figures 2 and 3, respectively. As demonstrated by Figure 2, the carbon sequestration potential is projected to increase by 45% from Phase 2 to the 2030 commercial facility. This is attributed to the lower natural gas and electricity use of the commercial facility, owing to the improved heat integration between the HTC+HTT process, and to a lesser extent the removal of digestate transportation emissions. Transport distance and soil effects are uncertain but are estimated to have a small impact on GHG emissions, highlighting that the majority of emissions reductions are from the physical storage of carbon in biochar.

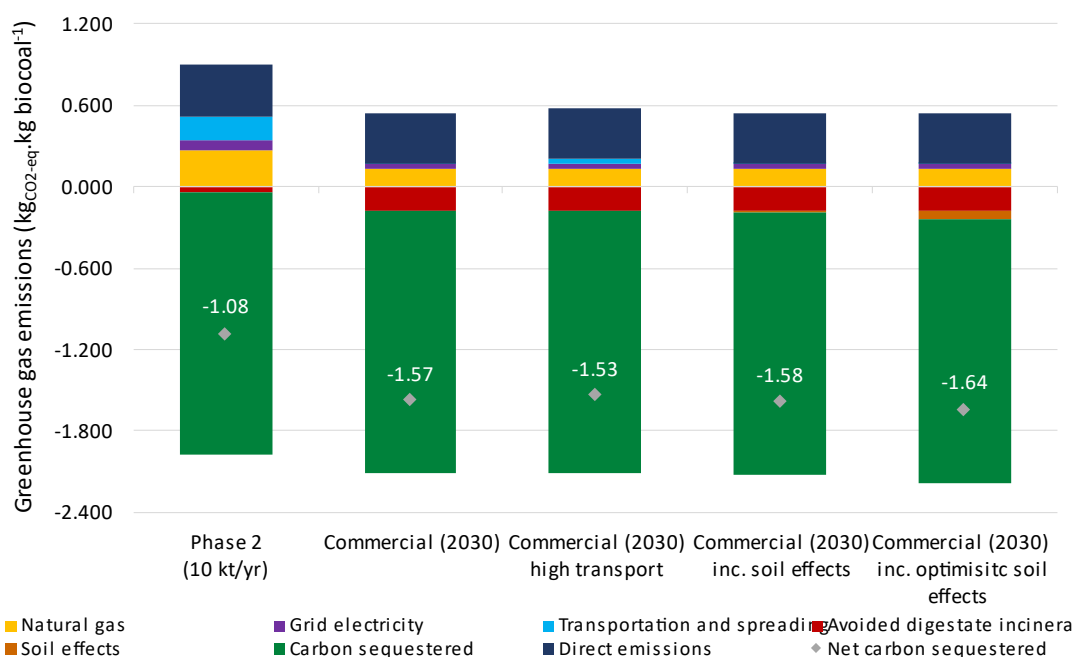


Figure 2 Carbon sequestration potential of the HTC-HTT process

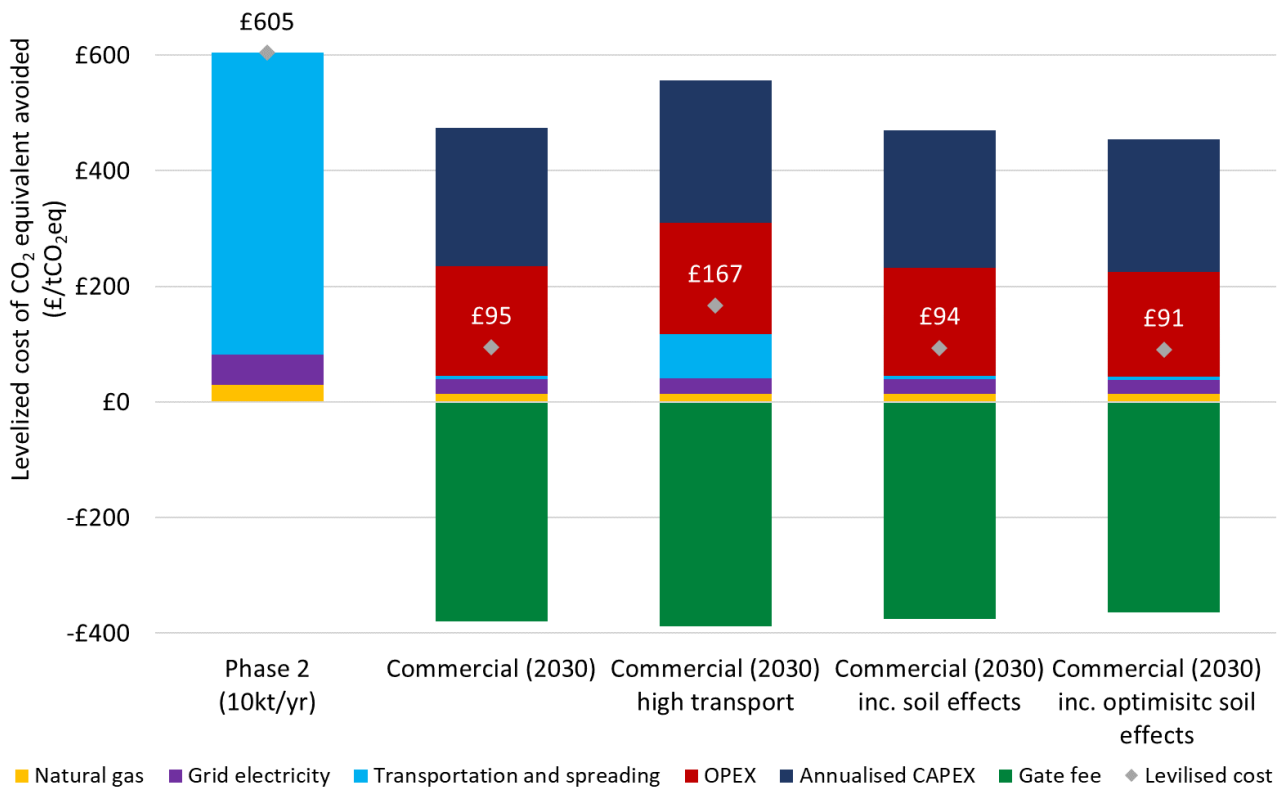


Figure 3 Levelized cost of CO₂ equivalent avoided for the HTC-HTT process

The Phase 2 case presents a high levelized cost of CO₂ avoided, primarily attributed to the large transportation costs which is not in line with expected commercial operation. Optimisation of digestate supply chain, energy efficiency through process co-location, and introduction of a gate fee (£58 tn⁻¹) expected for commercial case achieves just below £100 tn⁻¹ CO₂ avoided (Figure 3). Notably, the annualised capital and operating costs are the largest cost contributors. Whilst the high transport case has a negligible reduction in carbon sequestration, it presents a 76% increase in costs, highlighting the cost benefit associated with co-location of the HTC+HTT facility with an AD facility. Avoided fertilizer use has a minimal effect. However, as the fertilizer was not monetised, the difference is attributed to the increased carbon sequestration for these cases.

The total 2030 capacity, processing 41.6 kt/yr of dewatered digestate has the potential to sequester 6.36 kt CO₂ yr⁻¹. To sequester 50 kt CO₂ yr⁻¹, 17 20kt/yr facilities would be required, corresponding to the use of 28% of the projected food waste digestate by 2030.

1.6.4 Broader economic context

The LCA study has indicated that the overall cost of close to £100 per tonne of CO₂ equivalent avoided benefits from the gate fee which reduces the cost by ca. £250 (Figure 4). The overall cost will reduce further depending upon the level of integration that can be achieved between HTC and HTT. Other wet biowastes, such as green waste, will command much lower gate fees, probably close to £50 per tonne (Section 1.2). This would increase the overall cost to ca. £300 per tonne of CO₂ avoided.

Clearly, multiple sources of biochar will be needed to make contributions to the UK GGR's target of £30M tonnes of C by 2050. We are just looking at one of these options where there is clearly an environmental benefit in solving a waste disposal problem, which economically represents close to the lowest production cost.

Virgin wood can be ruled out currently because, costing ca. £100 per tonne, the feedstock cost alone is £400 per tonne of biochar, corresponding to £135 per tonne CO₂ equivalent avoided. For traditional carbonisation possible with some energy export, CAPEX and OPEX will be considerably lower than for B to B but still at least £100 per tonne equivalent avoided making the total cost well in excess of £200 per tonne of CO₂ equivalent.

For wood, the economics will only work currently for cuttings which come at a nominal zero cost, although, clearly, the costs and GG emissions associated with collecting and transportation need to be assessed. Further, production will need to be localised on a relatively small-scale (ca. 1 tonne of biochar per day) and will involve either relatively small kilns with little energy recovery or small existing biomass CHP systems, where biochar can be produced as a by-product. More evidence is required to provide a quantitative assessment, but the best-case scenarios might give comparable costs to HTC-HTT for AD fibre. However, the small scale of operation for wood cuttings will not lend themselves to low capex and opex.

1.7 Energy and fuel requirements

For the demonstration plant proposed for Phase 2, two possibilities were considered. In the first one, HTC and HTT are operated remotely with, clearly, no scope for heat integration. In such a scenario, the energy requirement for HTC would need to be covered by external sources. Carbonisation (HTT) processes are self-sufficient in energy, but clearly, it would not be possible to utilise any surplus heat and power efficiently being in a different location to HTC. In the favoured and adopted second scenario which has been used for the LCA study (Section 1.6), the two processes are operated in an integrated manner which would approach the situation in a commercial facility. The energy and fuel inputs have already been covered in the previous section, but the assumed fuel inputs do not have a major impact on the overall economics and these could be reduced further depending on the level of heat integration achieved in the Phase 2 project.

1.8 Environmental assessment

The emissions from the integrated HTC-HTT process are minimal, as already been described. However, the NO_x levels in the flue gas from combusting the volatiles released from the HTC biocoal in the kiln during HTT to generate process heat will be determined. The liquor from HTC will either be recycled for use in AD or spread to land, subject to meeting the PAS100 specification. The other key aspects of the environmental assessment are the situation of plants and any impact that the biochar might have, in addition to long-term carbon sequestration. The footprint of units processing 20,000 tonnes of AD fibre p.a. is less than 30 x 30 m and these will be co-located at either AD plants or other industrial facilities rather than on green field sites to minimise issues with permitting.

2. Engineering Design and the Phase 2 Project

2.1 Design overview

As already described (Section 1.6), the aim is to establish an integrated HTC-HTT pilot-plant with the facility for heat integration to approach the situation in a commercial facility. This involves upgrading the current HTC facility to improve performance and installing a new kiln for HTT. Although clearly the existing HTC plant and rotary kilns are operating at a high TRL level, the innovation is in combining the two processes.

The heat generated from combusting the volatiles from the kiln will provide the heat for HTT with sufficient surplus heat for the HTC plant and a small amount for export. Any excess heat will have multiple uses on site. Assumptions on heat recovery are conservative as is the assumed CV of 23 MJ/kg for the dry pyrolysis gas. The plant produces 150kg/hr of HTC biochar at 10% moisture which is an optimum level for extrusion. An availability of 75% for the plant this would produce ca. 450 tonnes of biochar p.a., corresponding to ca. 1000 tonnes of CO₂ equivalent. This satisfies the Phase 2 project requirements and, also, allows contingency time for unexpected plant downtime.

2.2. Biochar deployment and stakeholder engagement

The intention is to deploy 600 tonnes of biochar in the second and third years of the Phase 2 project using our existing network of arable and forestry sites built up for the BBSRC Biochar Demonstrator programme. Here the aim is to address the uncertainties concerning the extent and scope of deployment of biochar, its stability with respect to carbon sequestration, and to quantify the effects on ecosystem services by establishing the most ambitious and comprehensive large-scale demonstration programme to date, deploying over 200 tonnes of biochar. This builds upon our excellent links with the farming sector, including the Agriculture and Horticulture Development

Board (AHDB) and the National Farmers' Union (NFU) and forestry, including the National Forest. To apply due diligence and prevent unintended negative consequences of large-scale applications of biochar at the 'whole' field scale, we will conduct a series of mesocosm (small tub) experiments to inform the small field-plot trials, which in turn will determine the suitability of selected treatments prior to system-level amendment.

Mesocosm experiments - Replicated experiments under controlled conditions will investigate interactions between the biochars application rate, soil ecosystem and plant responses. The feedstock/application combinations that elicit the most positive results will be selected and used in the field trials to ascertain if responses are replicated under field conditions. The experiments will enable us to evaluate the growth of a range of crops and allow investigation of more variables in the first instance (including co-amendments such as manures) than would be possible with the field trials alone. Mesocosm size and experimental duration will vary depending on species grown.

Small-scale agronomic field trials - These will enable the effects of varying biochar application rate and composition to be assessed to determine the maximum additions that can be applied without adversely affecting ecosystem functions. Crop trials will be established at the UoN's farm on a clay soil and a sandy loam, with 32 plots (10m × 3m) at each site, enabling us to test 7 biochar treatments plus a control (4 replicate plots). Trials will begin after the outcomes of the mesocosm experiments are known (Task 2.1). Combine harvestable (combinable) crops will be grown and rotated annually and crop yields and soil ecosystem processes evaluated.

Whole agronomic field trials - Ten Demonstrator farm sites across the Midlands will be selected in conjunction with the East Midlands Farm Managers' Association (EMFMA) and the AHDB. One-hectare permanent plots will be established on several fields (working farms) undergoing annual rotations of combinable crops (wheat, barley, oilseed rape, peas, beans), and one on semi-permanent grassland. Grasslands will be included to contrast with that in the Midlands. Fields will represent a range of soil textures and 'normal' tillage regimes. Specifically, AHDB Midlands' 'Monitor farms' include combinable crops, covering different cultivation techniques (conventional-to minimum-tillage), on soils ranging from heavy clay to sandy loam and can be used here. The EMFMA President's host site produces combinable crops (including grass leys) with flexible rotations, on soils ranging from Keuper marl to loamy clay. The biochar application rate will be 10 t ha⁻¹ and ploughed/tilled to a depth of ca. 20 cm. Based on previous field trials, this is sufficient to observe any agronomic benefit and pilot plot trials at UoN have demonstrated no negative effects of CEG's char.

Woodland/forestry trials - In collaboration with the national Forest, a minimum of 10 t ha⁻¹ of biochar will be incorporated into soil prior to planting trees at several sites. Prior to application, ecotoxicity tests to ensure due diligence prior to applying the char on site will be conducted to inform the maximum biochar concentration that may be applied. Soil will be collected from each site and char applied at an equivalent of 0 to 50 t ha⁻¹ and willow cuttings grown for a year in the biochar/soil mixtures in large tubs at the UoN. The tree species selected for planting at the English sites will depend on the pH of the soil after biochar amendment.

Stakeholder engagement - In the Demonstrator programme, we are using social research concepts and methods to understand stakeholder perspectives on biochar's role in GGR, specifically, how they know and respond to the environmental risks and opportunities involved and their proposals for biochar policy. We will extend this activity to form extensive links with the AD community to make them aware of the advantages of the technology through a series of meetings and events.

2.4 Consents and licences

The HTC pilot-plant is permitted by the Environment Agency (EA), and we will continue to work closely with the EA for the proposed integrated Phase 2 HTC-HTT plan. Further, as currently for the HTC pilot-plant, there will be minimal emissions from the proposed integrated HTC-HTT plant to air, water or land as already indicated in Section 1.8.

Regarding the application of biochar to land, the current EA LRWP limits addition to one tonne per hectare for resources classed as agricultural waste. Through the UKRI Biochar Demonstrator, we have established a dialogue over the mechanism for permitting trials where we intend to apply up to 10 tonnes per hectare to arable land.

The analysis to date indicates the AD fibre-derived biochar should satisfy the voluntary EMC guidelines regarding concentrations of heavy metals and organic pollutants, such as PAHs.

3. Programme and Business Plan after Completion of the Phase 2 Project

3.1 Next stage in the development – scale and locations

Based on achieving a levelised cost of CO₂ equivalent avoided being close to £100 per tonne (£370 per tonne of C) for the scenarios identified from the LCA where this cost can be met. the business plan for the route to commercialisation formulated during Phase 2 will comprise the following steps building on the construction and successful operation of the pilot-plant over the period 2023-2025.

- (i) Building a long-term deployment strategy for a minimum of 100,000 tonnes of biochar p.a., with each plant situated at or close to AD plants producing 5,000 tonnes of biochar for initial deployment.
- (ii) Continuing engagement with all relevant stakeholders, particularly end-users, and establishing partnerships, where appropriate, for example, with AD operators.
- (iii) Location of sites to initiate planning and permitting.
- (iv) Seeking investment capital with overall capital costs.

The business plan which will be developed supported by on-going techno-economic and life cycle analysis, will include revenue where biochar has economic value in agricultural and other settings. Clearly, early deployment is advantageous in settings where there are economic benefits. Examples of these include co-compositing, preventing agricultural run-off into water courses and helping to prevent ammonia release for poultry sheds.

To be operational by 2030, sites will need to be identified and planning permission obtained by 2027/2028, allowing two years for the construction and commissioning of the plant. The footprint of an integrated plant containing both HTC, post-carbonisation and storage facilities producing ca. processing 20,000 tonnes of AFD fibre p.a. is relatively small, occupying little more than 400 m². The LCA and economic assessment has shown that a such unit would consist of 4 HTC reactors linked to one kiln for HTT since, due to the operating pressure placing a maximum size on the reactor, HTC is modular. Higher material costs going to larger reactor sizes are not offset by the benefit of improved throughput and some savings on ancillary equipment. In contract, kilns benefit significantly from economics of scale due to the large cost of all the ancillary equipment required.

3.2 Social value update

Regarding the Phase 1 project, three operators have been employed by CPL for the HTC trials. The Phase 2 project will require two more experienced operators and two apprentices from the local area, a project administrator and the procurement and installation of the pilot facility will create further employment opportunities, together with dedicated research personnel at the University of Nottingham for the deployment trials on the biochar produced.

Deploying 100,000 t of biochar from the B to B Technology beyond 2030 would represent an industry with a turnover of ca. £50M p.a. employing over 100. Expanding this to 2 Mt of biochar by 2040 would increase the turnover to £1B p.a. Taking the 2030 scenario, if production is spread across 4 or 5 facilities geographically close to the source of the wet biowaste, this would employ 100 people directly and similar number would be employed in the supply chain where many of the parts required for the HTC and HTT plants would be sourced in the UK.

3.3 Dependencies including biochar deployment

Like all GGR technologies, B to B is dependent on the price of carbon and most estimates suggest that this will reach £100 per tonne of CO₂ avoided before 2030, the price required for B to B to be commercially viable. Further, MRV protocols need to be implemented as part of the overall UK emissions trading scheme and how this can be handled for biochar was outlined in Section 3.5. Biochar will only be able to be deployed at the scale required to make a significant contribution to the UK's 2050 target for GGR of ca. 30 Mtonnes of C p.a. if demonstrations are completed to fully

understand its stability, together with impact on soils, crop yields and ecosystem services. The proposed deployment of 400 tonnes of biochar in the Phase 2 project will contribute to this essential activity which will also involve extensive stakeholder and societal engagement.

Appendix 1 AD resource availability for the B to B Technology

Table A1.1. Breakdown of AD in the UK (May 2019)

	Number of AD plants	Feedstock processed (tpa)	Digestate produced (tpa)	Dry digestate produced (tpa)
UK total	486	12,477,000	10,855,000	543,000
Food waste including co-digestion	83	3,740,000	3,254,000	163,000
Food-waste	43	2,067,000	1,799,000	90,000
Average food-waste facility	-	49,000	43,000	2,000
Largest food-waste facilities	-	160,000	139,000	7,000

Table A2.2: Potential carbon storage from digestate in the UK, *experimental result for waste-based digestate, †experimental result for crop-based digestate. It is assumed that the carbon content of the treated hydrochar is 1.25x the carbon content of the raw hydrochar. All carbon contents are given on a dry basis.

	Low	Mid	High
Feedstock processed by AD in the UK, May 2019 ¹ (wet tonnes/year)		12,477,000	
Conversion rate ²		87%	
Whole digestate production (dry tonnes/year)		543,000	
Dewatering solids capture rate ¹⁰		85%	
Digestate fibre production (dry tonnes/year)		461,000	
Carbon content of digestate fibre (dry)	29%*	34%†	52% ²⁷
Carbon contained in digestate fibre (dry tonnes/year)	133,000	180,000	240,000
Carbon recovery in hydrochar	51%*	71%	91%†
Carbon contained in hydrochar (dry tonnes/year)	68,000	123,000	219,000
Mass yield from thermal post-treatment ¹⁹		73.5%	
Carbon densification after thermal post-treatment		1.25	
Overall carbon recovery from the digestate to the treated hydrochar	47%	65%	84%
Potential carbon storage in soil (dry tonnes/year)	62,000	118,000	201,000
Forecast increase in food waste digestion by 2030 (wet tonne/year)	4,800,000		
Increase in carbon storage in soil from increase in food waste digestion in 2030 (dry/tonnes)	24,000	45,000	77,000

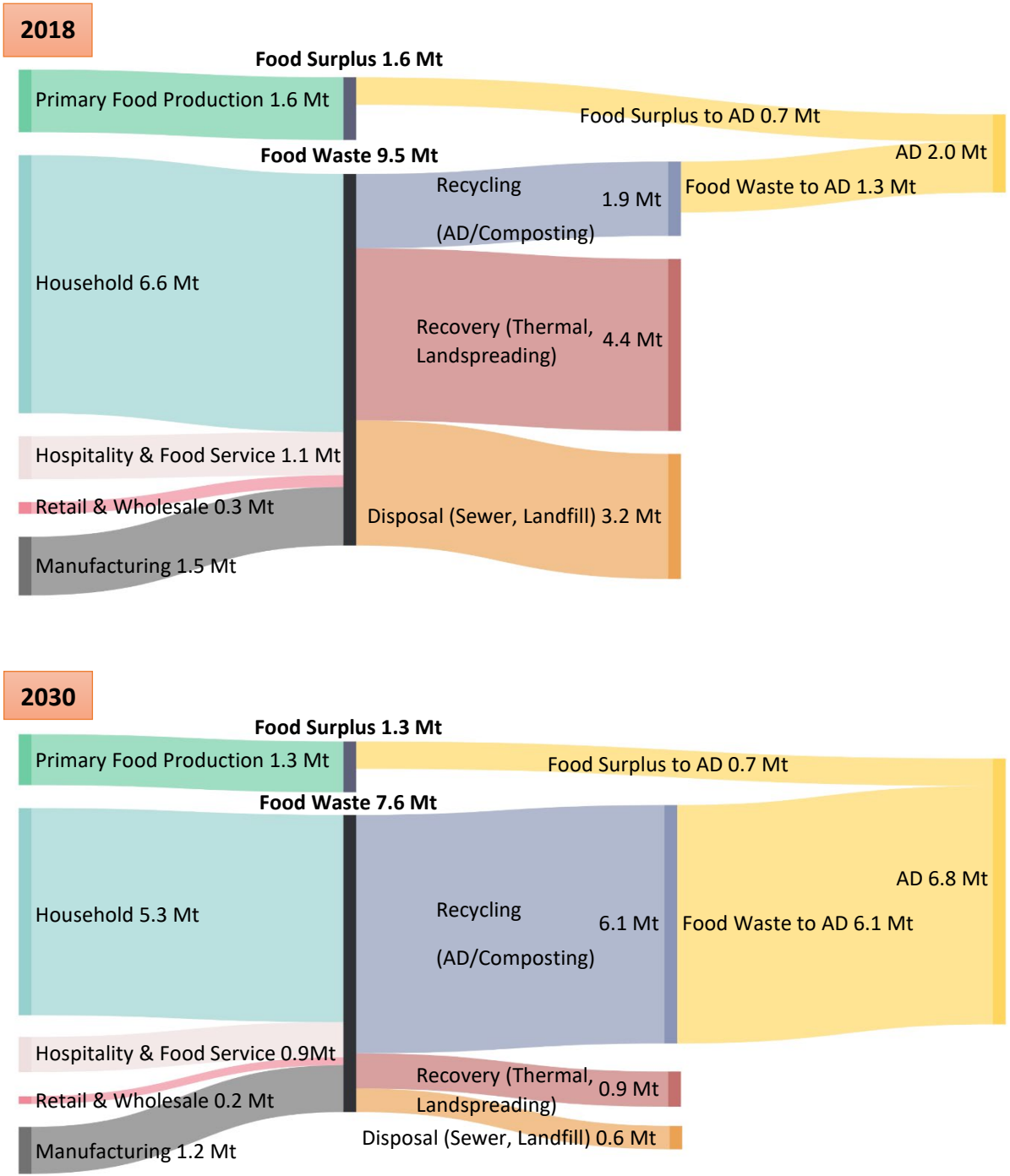


Figure A1.1 Food waste to AD in the UK in 2018 and projected values for 2030 assuming 80% of food waste is sent to AD facilities⁶

Appendix 2 Characterisation of the AD HTC biocoal and liquor

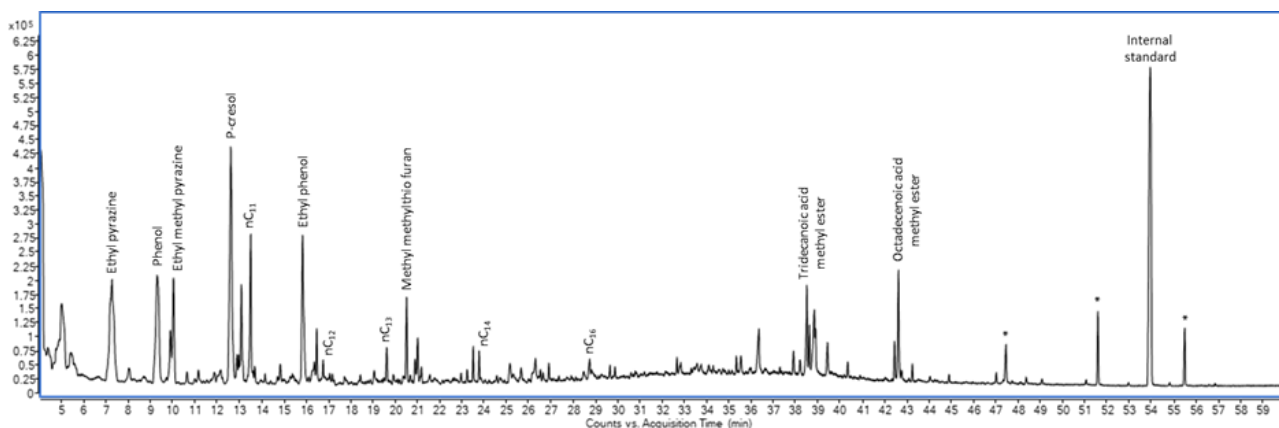


Figure A3.5 Total ion chromatogram from the GC-MS analysis of the liquid/liquid extraction (in dichloromethane) of the AD fibre HTC process water (* contaminant phthalates from sample storage).

Table A2.1 Particle size distribution of the HTC AD fibre biocoal.

Mesh size (mm)	Weight fraction (g)	% Fraction	% Cumulative
> 4.75	64.5	6.64	6.64
4.75	46.8	4.82	11.5
3.35	145.3	15.0	26.4
2.36	158.7	16.3	42.8
1.70	106.6	11.0	53.7
1.18	124.4	12.8	66.6
1.00	16.4	1.69	68.2
0.85	186.5	19.2	87.4
≤ 0.43	122.0	12.6	100

Sieving carried out on 1 kg HTC digestate

Two particle size ranges for 5-7.5 g lab scale carbonisation at 550 and 700°C using HTF (10°C/min, 0.5 hrs, 1 L/min N₂, 1 bar)

Fines < 1 mm to be pelletised

Table A2.2 Proximate and ultimate analysis of the AD fibre HTC biocoal. The methodologies used detailed in the footnotes.

Sample ¹	Proximate analysis ²				Ultimate analysis ³						C yield (%) ⁴	H/C ⁵
	Moisture	Volatiles	Fixed C	Ash	C	H	N	S	O6			
Digestate HTC biocoal (as received)	49.5 ± 0.5	32.1 ± 0.5	8.7 ± 0.6	9.7 ± 0.6	28.3 ± 0.4	8.3 ± 0.2	1.4 ± <0.1	0.5 ± <0.1	51.8 ± 0.5	-	-	
Digestate HTC biocoal (dry)	-	63.6 ± 0.2	17.2 ± 0.6	19.2 ± 0.8	56.0 ± 0.8	5.6 ± 0.4	2.8 ± <0.1	1.0 ± <0.1	15.6 ± 1.0	-	-	
Digestate HTC biocoal (dry ash free)	-	79.0 ± 0.5	21.3 ± 0.5	-	69.2 ± 1.0	6.9 ± 0.5	3.4 ± <0.1	1.3 ± <0.1	19.2 ± 1.3	-	1.19 ± 0.09	

¹ Biocoal characterisation and HTT carbonisation were undertaken on the >4.75 mm size fraction.

² Proximate analysis by thermo-gravimetric analysis (TGA, Ta Instruments). 50 mg of sample was weighed onto a platinum pan and heated to 110°C (10°C/min) under 100% N₂ (1 bar, 100 mL/min) and held for 30 minutes to determine moisture content. The sample was then ramped to 950 °C (10°C/min, 1 bar, 100 mL/min) and held isothermally for 30 mins to determine the amount of volatiles present. The gas was switched to air (1 bar, 100 mL/min) and held isothermally for 30 mins to determine fixed carbon and ash contents. Samples were run in quintuplicate.

³ Ultimate analysis by elemental analysis (EA) with a CHNS analyser (Leco Instruments). Calibration was carried out using BBOT ((2, 5-Bis (5-ter-butyl-benzoxazol-2-yl) thiophene). Approximately 50 mg of sample was used to determine CHN under combustion at 950°C in 100% O₂, while 250 mg of sample was used for S analysis at 1350°C. Samples were run in quintuplicate.

⁴ Carbon yield calculated on a dry ash free basis from ultimate analysis C Wt. %.

⁵ H/C on an atomic weight and dry ash free basis from ultimate analysis.

⁶ Oxygen determined by difference

Table A2.3 Heavy metal concentrations for the initial fibre and HTC biocoal

Sample	Heavy Metal Concentration (mg/Kg)																						
	Cr	Zn	Sb	As	Hg	Se	Tl	Sn	Al	Ba	Be	B	Cd	Ca	Co	Cu	Fe	Pb	Li	Mg	Mn	Mo	Ni
AD Fibre	53	88	2.8	2.3	<0.10	<0.50	<0.10	4.3	4240	96	0.21	20	0.58	61600	1.6	94	10050	7.2	3.0	1849	204	1.5	13
HTC Biocoal	16	138	9.6	1.5	<0.10	<0.50	<0.10	8.6	5785	40	<0.10	<10	0.82	59550	1.3	44	11850	7.7	<2.0	2125	215	1.1	6.1

Sample	Heavy Metal Concentration (mg/Kg)							
	Pb	Cd	Cu	Ni	Hg	Zn	Cr	As
AD Fibre	7.2	0.58	94	13	<0.10	88	53	2.3
HTC Biocoal	7.7	0.82	44	6.1	<0.10	138	16	1.5

Pb <150, Cd <1.5, Cu <100, Ni <50, Hg <1, Zn <400, Cr <90, As <13 mg/Kg on dry basis from EBC guidelines.

Table A2.4 PAH and PCB concentrations in the AD fibre and HTC biocoal

PAH	PAH Concentration (mg/Kg)	
	AD Fibre	HTC Biocoal
Acenaphthene	<0.09	<0.08
Acenaphthylene	<0.09	0.10
Anthracene	<0.09	<0.08
Benzo[a]anthracene	<0.09	<0.08
Benzo[a]pyrene	<0.10	<0.08
Benzo[b]fluoranthene	<0.09	<0.08
Benzo[g,h,i]perylene	<0.09	<0.08
Benzo[k]fluoranthene	<0.09	<0.08
Chrysene	<0.10	<0.08
Dibenzo[a,h]anthracene	<0.09	<0.08
Fluoranthene	<0.10	<0.10
Fluorene	<0.09	<0.10
Indeno[1,2,3-cd]pyrene	<0.09	<0.08
Naphthalene	0.16	0.09
Phenanthrene	<0.14	<0.14
Pyrene	<0.10	<0.09
Total PAH 16	1.59	1.42

The biochar's PAH content (sum of the EPA's 16 priority pollutants) must be under 12 mg/kg basic grade and under 4 mg/kg for premium grade on dry basis from EBC guidelines.

PCB	PCB Concentration (mg/Kg)	
	AD Fibre	HTC Biocoal
PCB 101	<0.0055	<0.0050
PCB 118	<0.0055	<0.0050
PCB 138	<0.0055	<0.0050
PCB 153	<0.0055	<0.0050

Table A2.5 Analysis of the HTC liquor

Kjeldahl Nitrogen % w/w	0.090
Ammonium Nitrogen mg/kg	633
Total Phosphorus (P) % w/w	0.005
Total Copper (Cu) mg/kg	0.210
Total Zinc (Zn) mg/kg	21.6
Nitrate Nitrogen mg/kg	<10
Total Lead (Pb) mg/kg	<0.5
Total Cadmium (Cd) mg/kg	<0.01
Total Mercury (Hg) mg/kg	<0.05
Total Nickel (Ni) mg/kg	<0.2
Total Chromium (Cr) mg/kg	<0.2

Appendix 3 Characterisation of the biochars produced from the AD fibre HTC biocoal

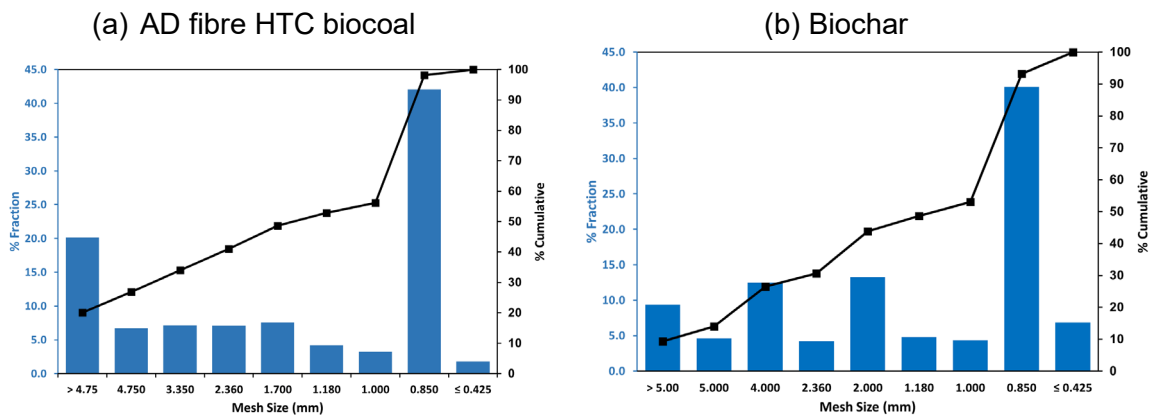


Figure A3.1 Particle size distributions for the AD fibre HTC biocoal and the biochar prepared from the kiln.

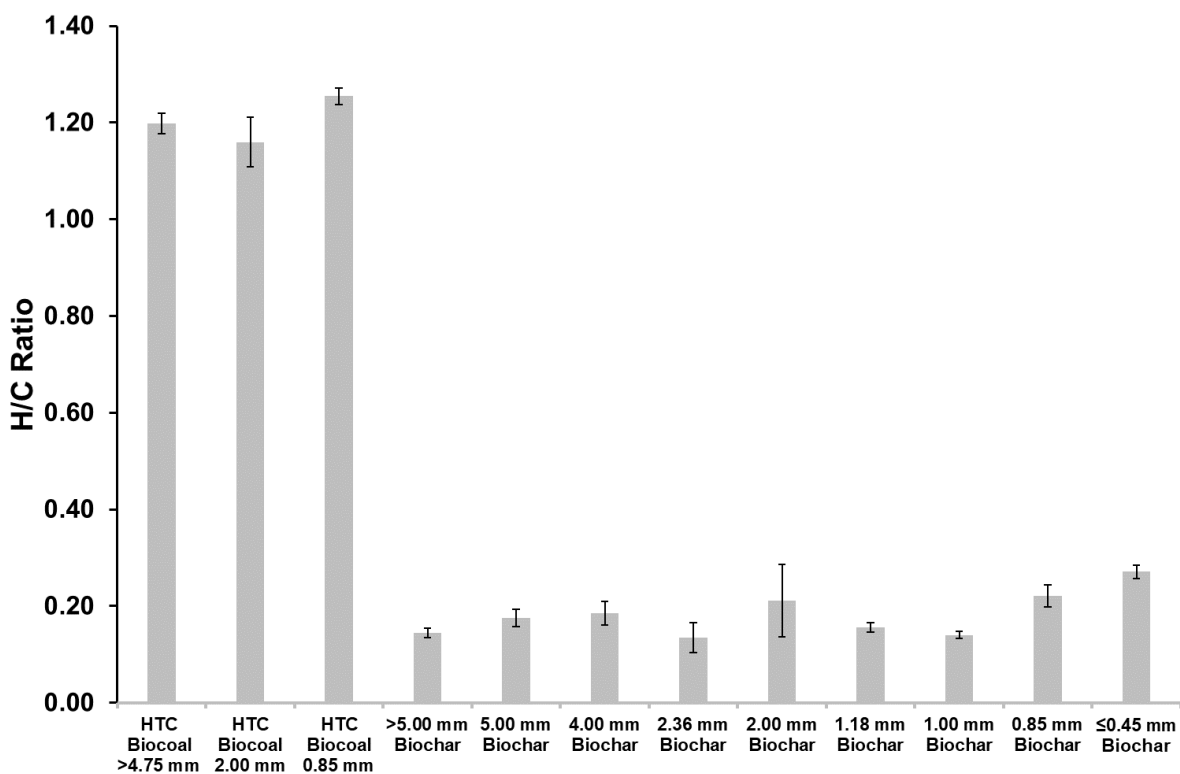


Figure A3.2 Atomic H/C ratios for ADS fibre HTC biocoal and the kiln biochar as a function of particle size.

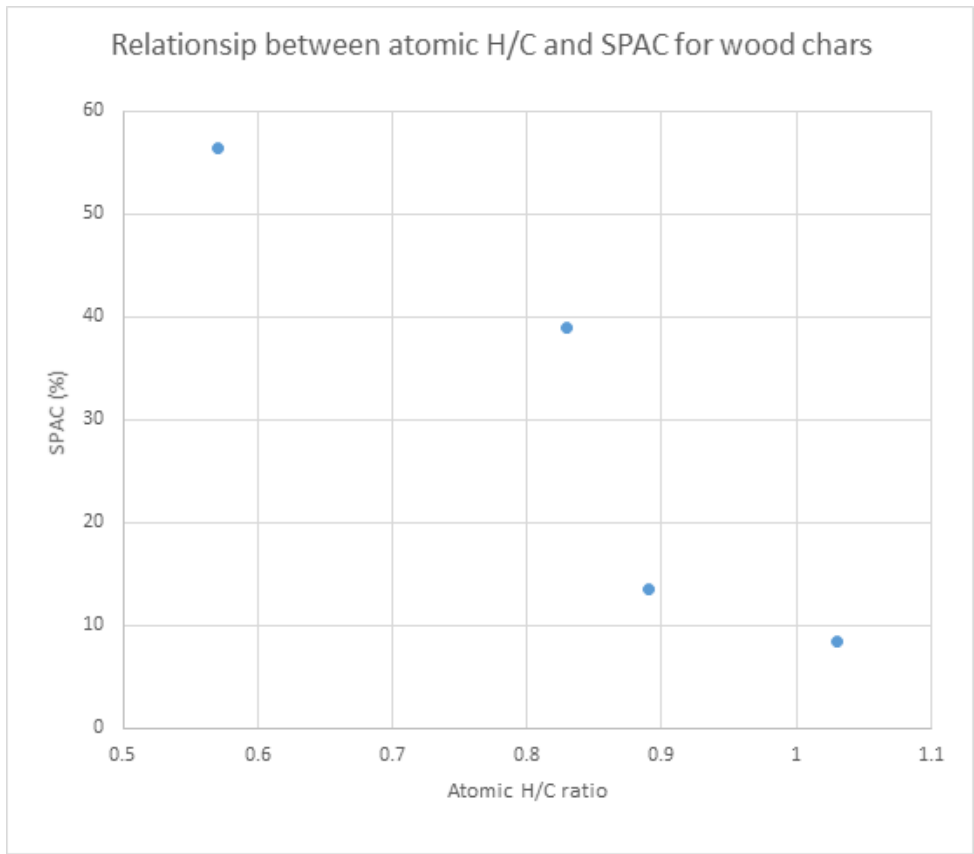


Figure A3.3 Relationship between atomic H/C ratio and SPAC content for the biochars prepared using the demonstration torrefaction plant at CEG.

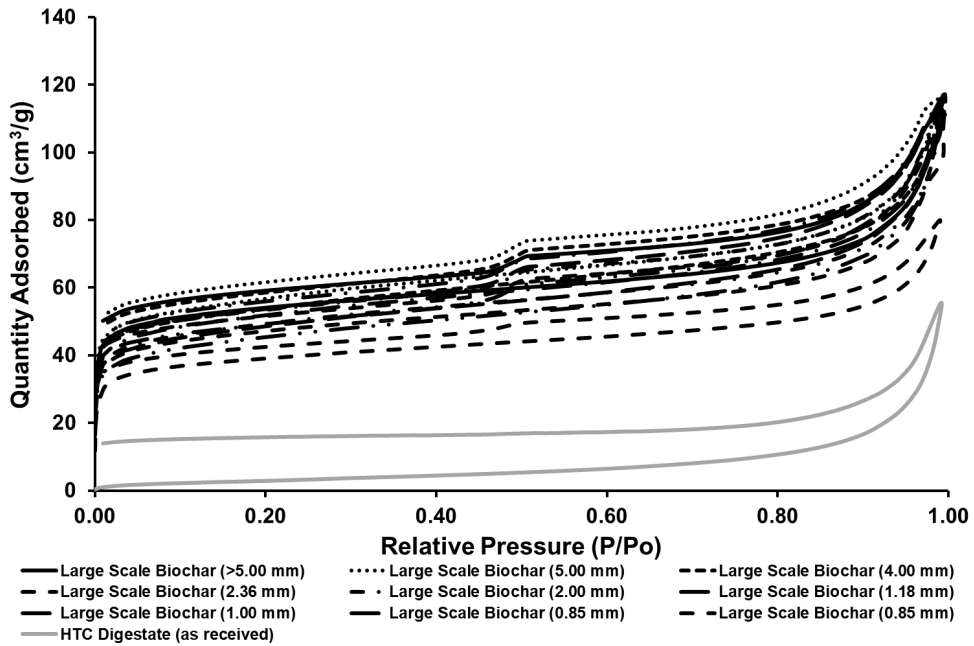


Figure A3.4a N₂ sorption isotherms for ADS fibre HTC biocoal and the kiln biochar as a function of particle size.

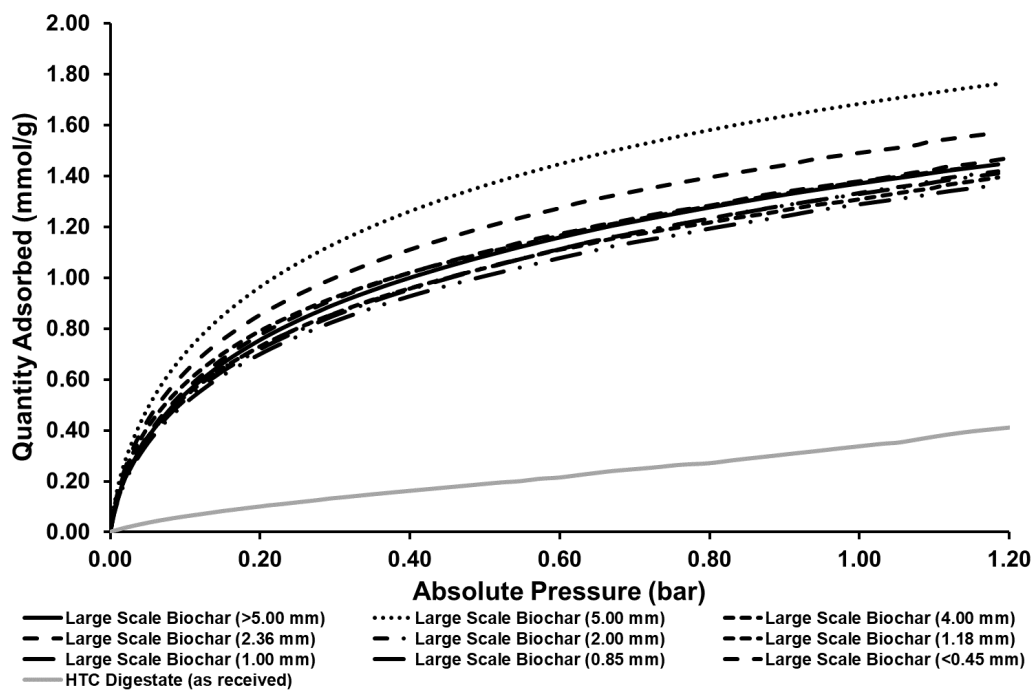


Figure A3.4b CO₂ adsorption isotherms for AD fibre HTC biocoal and the kiln biochar as a function of particle size.

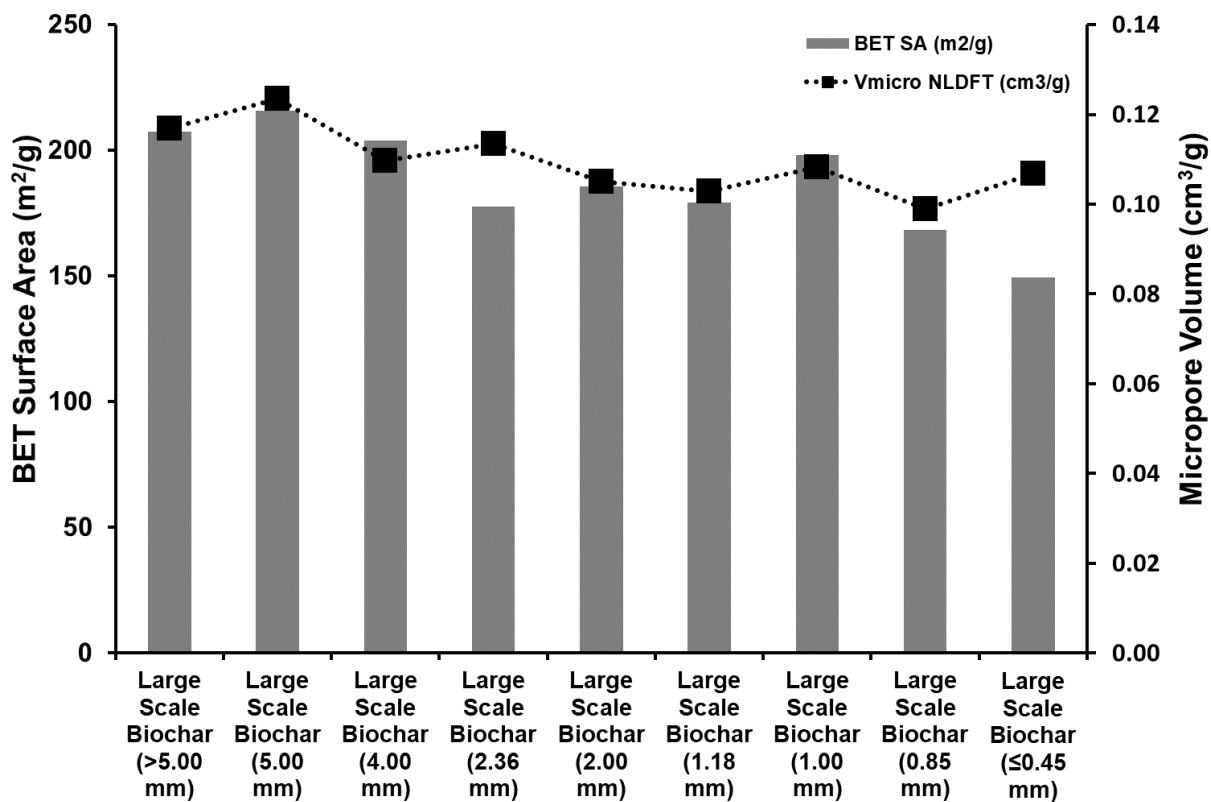


Figure A3.4c Micropore volume and BET specific surface area for the kiln biochar as a function of particle size.

Table A3.1 Characterisation (proximate, ultimate and SPAC analysis) of the biochars by lab-scale HTF. Methodologies used detailed in the footnotes.

Sample ¹	Proximate analysis ²				Ultimate analysis ³					C yield (%) ⁴	H/C ⁵	SPAC (%) ⁶
	Moisture	Volatiles	Fixed C	Ash	C	H	N	S	O ⁷			
HTT 550°C 0.5 hr (as received)	4.2 ± 0.5	26.0 ± 1.0	37.0 ± 1.3	32.9 ± 0.5	49.3 ± 0.4	2.8 ± 0.3	2.7 ± <0.1	0.6 ± <0.1	11.8 ± 0.3	-	-	
HTT 550°C 0.5 hr (dry)	-	27.1 ± 1.2	38.6 ± 1.2	34.3 ± 0.5	51.7 ± 0.4	2.4 ± 0.3	2.8 ± <0.1	0.6 ± <0.1	8.2 ± 0.5	-	-	
HTT 550°C 0.5 hr (dry ash free)	-	41.3 ± 1.8	58.7 ± 1.8	-	78.6 ± 0.7	3.6 ± 0.4	4.3 ± <0.1	0.9 ± <0.1	12.5 ± 0.8	51.4 ± 0.5	0.6 ± 0.1	39.5
HTT 700°C 0.5 hr (as received)	3.6 ± 0.4	17.9 ± 1.2	40.8 ± 1.4	37.7 ± 0.3	49.9 ± 1.4	2.5 ± 0.6	1.9 ± 0.1	0.7 ± <0.1	7.3 ± 1.4	-	-	
HTT 700°C 0.5 hr (dry)	-	18.5 ± 1.2	42.4 ± 1.4	39.1 ± 0.3	51.8 ± 1.5	2.2 ± 0.6	2.0 ± 0.1	0.7 ± <0.1	4.3 ± 1.6	-	-	
HTT 700°C 0.5 hrs (dry ash free)	-	30.4 ± 2.1	69.6 ± 2.1	-	85.0 ± 2.7	3.6 ± 0.9	3.3 ± 0.2	1.1 ± <0.1	7.0 ± 2.7	43.5 ± 2.0	0.5 ± 0.1	89.9
HTT 750°C 0.5 hrs (as received)	3.5 ± 0.4	15.6 ± 0.4	42.8 ± 0.7	38.1 ± 0.6	51.0 ± 1.8	2.2 ± 0.5	1.8 ± 0.2	0.7 ± <0.1	6.3 ± 1.3	-	-	
HTT 750°C 0.5 hr (dry)	-	16.2 ± 0.5	44.4 ± 0.6	39.4 ± 0.6	52.8 ± 2.0	1.9 ± 0.5	1.9 ± 0.2	0.7 ± <0.1	3.3 ± 1.6	-	-	
HTT 750°C 0.5 hr (dry ash free)	-	26.7 ± 0.7	73.3 ± 0.7	-	87.2 ± 3.1	3.1 ± 0.8	3.1 ± 0.3	1.2 ± <0.1	5.5 ± 2.6	43.5 ± 1.5	0.4 ± 0.1	92.2
HTT 800°C 0.5 hr (as received)	3.1 ± 0.2	13.4 ± 1.4	43.2 ± 1.6	40.3 ± 0.4	50.8 ± 0.6	2.0 ± 0.1	1.4 ± 0.1	0.7 ± <0.1	4.8 ± 0.7	-	-	
HTT 800°C 0.5 hr (dry)	-	13.8 ± 1.5	44.56 ± 1.6	41.6 ± 0.4	52.5 ± 0.7	1.7 ± 0.1	1.5 ± 0.1	0.7 ± <0.1	2.1 ± 0.8	-	-	
HTT 800°C 0.5 hr (dry ash free)	-	23.7 ± 2.6	76.3 ± 2.6	-	89.8 ± 1.3	2.9 ± 0.2	2.5 ± 0.2	1.2 ± <0.1	3.6 ± 1.4	41.9 ± 0.2	0.4 ± <0.1	92.5

¹ Large-scale biochar, multiple particle sizes.

² Proximate analysis by thermo-gravimetric analysis (TGA, Ta Instruments). 50 mg of sample was weighed onto a platinum pan and heated to 110°C (10°C/min) under 100% N₂ (1 bar, 100 mL/min) and held for 30 minutes to determine moisture content. The sample was then ramped to 950 °C (10°C/min, 1 bar, 100 mL/min) and held isothermally for 30 mins to determine the amount of volatiles present. The gas was switched to air (1 bar, 100 mL/min) and held isothermally for 30 mins to determine fixed carbon and ash contents. Samples were run in quintuplicate.

³ Ultimate analysis by elemental analysis (EA) with a CHNS analyser (Leco Instruments). Calibration was carried out using BBOT ((2, 5-Bis (5-ter-butyl-benzoxazol-2-yl) thiophene). Approximately 50 mg of sample was used to determine CHN under combustion at 950°C in 100% O₂, while 250 mg of sample was used for S analysis at 1350°C. Samples were run in quintuplicate.

⁴ Carbon yield calculated on a dry ash free basis from ultimate analysis C Wt. %.

⁵ H/C on an atomic weight and dry ash free basis from ultimate analysis.

⁶ Stable polycyclic aromatic carbon. SPAC represent the % of carbon remaining after HyPy analysis and represents the portion of the carbon thought to be stable in the environment over centennial timescales. HyPy performed with heating under a hydrogen pressure of 150 bar and a flow rate of 5L/min from ambient to 250°C at 300°C/min, and then to 550°C at 8°C where it was held for 2 mins.

⁷ Oxygen determined by difference.

Table A3.2 Characterisation (proximate, ultimate and SPAC analysis) of the biochars by the medium-scale kiln at CPL. Methodologies used detailed in the footnotes. All the results are for the biochar produced from the high plastic AD fibre. Apart from the last two rows.

Sample ¹	Proximate analysis (Wt.%) ²				Ultimate analysis (Wt.%) ³					Carbon yield ⁴			H/C ⁵	SPAC (%) ⁶
	Moisture	Volatiles	Fixed carbon	Ash	C	H	N	S	O ₇	>4.74 mm	2.00 mm	0.85 mm		
>5.00 mm biochar 750 °C 0.5 hrs (as received)	3.3 ± 0.7	15.6 ± 0.4	40.5 ± 0.3	40.6 ± 0.5	51.5 ± 0.4	1.0 ± <0.1	1.4 ± <0.1	0.7 ± <0.1	4.8 ± 0.4	-	-	-	-	-
>5.00 mm biochar 750 °C 0.5 hrs (dry basis)	-	16.1 ± 0.4	41.9 ± 0.2	42.0 ± 0.3	53.3 ± 0.4	0.6 ± <0.1	1.4 ± <0.1	0.7 ± <0.1	2.0 ± 0.5	-	-	-	-	-
>5.00 mm biochar 750 °C 0.5 hrs (dry ash free basis)	-	27.8 ± 0.6	72.2 ± 0.6	-	91.9 ± 0.8	1.1 ± <0.1	2.4 ± <0.1	1.2 ± <0.1	3.4 ± 0.8	44.1	40.4	48.7	0.1 ± <0.1	-
5.00 mm biochar 750 °C 0.5 hrs (as received)	3.2 ± 0.7	16.3 ± 1.0	43.1 ± 2.2	37.4 ± 0.8	53.9 ± 1.5	1.2 ± 0.1	1.3 ± <0.1	0.8 ± 0.1	5.4 ± 1.5	-	-	-	-	-
5.00 mm biochar 750 °C 0.5 hrs (dry basis)	-	16.9 ± 1.1	44.5 ± 2.1	38.6 ± 1.0	55.6 ± 1.6	0.8 ± 0.1	1.3 ± <0.1	0.8 ± 0.1	2.9 ± 1.6	-	-	-	-	-
5.00 mm biochar 750 °C 0.5 hrs (dry ash free basis)	-	27.5 ± 2.3	72.5 ± 2.3	-	90.7 ± 2.5	1.3 ± 0.1	2.1 ± 0.1	1.3 ± 0.1	4.6 ± 2.6	46.1	42.2	50.9	0.2 ± <0.1	-
4.00 mm biochar 750 °C 0.5 hrs (as received)	2.5 ± 0.6	15.2 ± 0.5	42.4 ± 1.0	39.9 ± 0.2	53.2 ± 0.8	1.1 ± 0.1	1.3 ± <0.1	0.8 ± <0.1	3.7 ± 0.7	-	-	-	-	-
4.00 mm biochar 750 °C 0.5 hrs (dry basis)	-	15.5 ± 0.6	43.4 ± 0.8	41.1 ± 0.2	54.6 ± 0.8	0.9 ± 0.1	1.3 ± <0.1	0.8 ± <0.1	1.3 ± 0.8	-	-	-	-	-
4.00 mm biochar 750 °C 0.5 hrs (dry ash free basis)	-	26.3 ± 1.1	73.7 ± 1.1	-	92.5 ± 1.3	1.4 ± 0.2	2.2 ± <0.1	1.3 ± 0.1	2.6 ± 1.3	45.5	41.7	50.2	0.2 ± <0.1	-
2.36 mm biochar 750 °C 0.5 hrs (as received)	4.5 ± 0.4	15.0 ± 3.7	38.2 ± 0.7	42.3 ± 3.5	47.8 ± 0.8	1.1 ± 0.1	1.1 ± <0.1	0.8 ± <0.1	6.9 ± 0.9	-	-	-	-	-
2.36 mm biochar 750 °C 0.5 hrs (dry basis)	-	15.7 ± 3.8	40.1 ± 0.8	44.2 ± 3.8	50.2 ± 0.8	0.6 ± 0.1	1.2 ± <0.1	0.8 ± <0.1	3.0 ± 0.9	-	-	-	-	-
2.36 mm biochar 750 °C 0.5 hrs (dry ash free basis)	-	28.2 ± 4.0	71.8 ± 4.3	-	90.0 ± 1.5	1.0 ± 0.2	2.1 ± <0.1	1.4 ± <0.1	5.5 ± 1.7	41.0	37.5	45.2	0.1 ± <0.1	-
2.00 mm biochar 750 °C 0.5 hrs (as received)	2.5 ± 0.4	14.2 ± 0.8	38.6 ± 0.8	44.7 ± 1.4	48.0 ± 0.8	1.1 ± 0.3	1.2 ± <0.1	0.8 ± 0.1	4.2 ± 1.1	-	-	-	-	-
2.00 mm biochar 750 °C 0.5 hrs (dry basis)	-	14.6 ± 0.9	39.6 ± 0.9	45.8 ± 1.4	49.3 ± 1.4	0.9 ± 0.3	1.2 ± 0.1	0.8 ± 0.1	2.0 ± 1.1	-	-	-	-	-
2.00 mm biochar 750 °C 0.5 hrs (dry ash free basis)	-	26.9 ± 1.1	73.1 ± 1.1	-	90.9 ± 1.5	1.6 ± 0.6	2.2 ± <0.1	1.5 ± 0.3	3.8 ± 2.0	41.1	37.6	45.3	0.2 ± 0.1	-
1.18 mm biochar 750 °C 0.5 hrs (as received)	2.8 ± 1.0	14.1 ± 0.4	39.8 ± 1.4	43.3 ± 2.1	49.5 ± 0.4	1.0 ± <0.1	1.2 ± <0.1	0.8 ± <0.1	4.2 ± 0.5	-	-	-	-	-
1.18 mm biochar 750 °C 0.5 hrs (dry basis)	-	14.6 ± 0.5	40.9 ± 1.7	44.5 ± 1.8	51.0 ± 0.5	0.7 ± <0.1	1.2 ± <0.1	0.8 ± <0.1	1.8 ± 0.5	-	-	-	-	-
1.18 mm biochar 750 °C 0.5 hrs (dry ash free basis)	-	26.2 ± 0.9	73.8 ± 0.9	-	91.9 ± 0.8	1.2 ± <0.1	2.2 ± <0.1	1.4 ± 0.1	3.3 ± 0.9	42.4	38.8	46.8	0.2 ± <0.1	-
1.00 mm biochar 750 °C 0.5 hrs (as received)	3.4 ± 0.1	13.6 ± 0.3	39.4 ± 1.2	43.6 ± 1.1	48.2 ± 0.9	0.9 ± <0.1	1.1 ± <0.1	0.7 ± <0.1	5.5 ± 0.9	-	-	-	-	-
1.00 mm biochar 750 °C 0.5 hrs (dry basis)	-	14.1 ± 0.3	40.8 ± 1.3	45.1 ± 1.1	49.9 ± 0.9	0.6 ± <0.1	1.1 ± <0.1	0.8 ± <0.1	2.5 ± 1.0	-	-	-	-	-
1.00 mm Biochar 750 °C 0.5 hrs (dry ash free basis)	-	25.6 ± 0.9	74.4 ± 0.9	-	90.9 ± 1.7	1.1 ± 0.1	2.0 ± <0.1	1.4 ± <0.1	4.6 ± 1.8	41.2	37.7	45.5	0.1 ± <0.1	84

0.85 mm biochar 750 °C 0.5 hrs (as received)	2.8 ± 0.6	16.3 ± 0.4	41.1 ± 0.3	39.8 ± 0.4	50.7 ± 0.3	1.2 ± 0.1	1.1 ± <0.1	0.8 ± <0.1	6.4 ± 0.4	-	-	-	-
0.85 mm biochar 750 °C 0.5 hrs (dry basis)	-	16.7 ± 0.4	42.2 ± 0.4	41.1 ± 0.3	52.1 ± 0.4	1.0 ± 0.1	1.1 ± <0.1	0.9 ± <0.1	3.8 ± 0.4	-	-	-	-
0.85 mm biochar 750 °C 0.5 hrs (dry ash free basis)	-	28.4 ± 0.6	71.6 ± 0.6	-	88.4 ± 0.6	1.6 ± 0.2	1.9 ± <0.1	1.4 ± <0.1	6.7 ± 0.6	43.4	39.7	47.9	0.2 ± <0.1
≤0.45 mm biochar 750 °C 0.5 hrs (as received)	6.4 ± 0.5	20.2 ± 0.6	45.9 ± 0.3	27.5 ± 0.1	55.6 ± 0.1	2.0 ± 0.1	0.8 ± <0.1	1.0 ± 0.1	13.1 ± 0.1	-	-	-	-
≤0.45 mm biochar 750 °C 0.5 hrs (dry basis)	-	21.6 ± 0.5	49.0 ± 0.4	29.4 ± 0.2	59.4 ± 0.1	1.4 ± 0.1	0.9 ± <0.1	1.0 ± 0.1	7.9 ± 0.1	-	-	-	-
≤0.45 mm biochar 750 °C 0.5 hrs (dry ash free basis)	-	30.6 ± 0.7	69.4 ± 0.7	-	84.2 ± 0.1	1.9 ± 0.1	1.2 ± <0.1	1.5 ± 0.1	11.2 ± 0.1	47.6	43.5	52.5	0.3 ± <0.1
Biochar from low plastic AD fibre (as received)	6.4	20.8	39.3	33.3				N					
Biochar from low plastic AD fibre (dry basis)		22.2	42.0	35.7	51.4	0.8	2.1	N.D.					0.2

¹ Large-scale biochar, multiple particle sizes.

² Proximate analysis by thermo-gravimetric analysis (TGA, Ta Instruments). 50 mg of sample was weighed onto a platinum pan and heated to 110°C (10°C/min) under 100% N₂ (1 bar, 100 mL/min) and held for 30 minutes to determine moisture content. The sample was then ramped to 950 °C (10°C/min, 1 bar, 100 mL/min) and held isothermally for 30 mins to determine the amount of volatiles present. The gas was switched to air (1 bar, 100 mL/min) and held isothermally for 30 mins to determine fixed carbon and ash contents. Samples were run in quintuplicate.

³ Ultimate analysis by elemental analysis (EA) with a CHNS analyser (Leco Instruments). Calibration was carried out using BBOT ((2, 5-Bis (5-ter-butyl-benzoxazol-2-yl) thiophene). Approximately 50 mg of sample was used to determine CHN under combustion at 950°C in 100% O₂, while 250 mg of sample was used for S analysis at 1350°C. Samples were run in quintuplicate.

⁴ Carbon yield calculated on a dry ash free basis from ultimate analysis C Wt. %.

⁵ H/C on an atomic weight and dry ash free basis from ultimate analysis.

⁶ Stable polycyclic aromatic carbon. SPAC represent the % of carbon remaining after HyPy analysis and represents the portion of the carbon thought to be stable in the environment over centennial timescales. HyPy performed with heating under a hydrogen pressure of 150 bar and a flow rate of 5L/min from ambient to 250°C at 300°C/min, and then to 550°C at 8°C where it was held for 2 mins. This parameter for the large-scale kiln trials to follow.

⁷ Oxygen determined by difference.

N.D. = not determined

Table A3.3a Textural characterisation data of HTC digestate biocoal and lab-scale HTF biochars.

Sample ¹	BET SA ² (m ² /g)	V _{ultra} ³ (cm ³ /g)	V _{micro} ³ (cm ³ /g)	V _{meso} ³ (cm ³ /g)	V _{tot} ³ (cm ³ /g)	D ⁴ (nm)	Bulk density (g/cm ³)	Skeletal density (g/cm ³)	Porosity ⁵ (%)
Digestate HTC biocoal	12.0	0.011	0.018	0.061	0.095	31.4	0.71	1.47	51.9
HTT 550°C 0.5 hr	108.2	0.063	0.100	0.066	0.178	6.6	0.61	1.78	65.6
HTT 700°C 0.5 hr	201.8	0.076	0.112	0.075	0.198	3.9	0.58	1.90	69.6
HTT 750°C 0.5 hr	217.3	0.079	0.124	0.106	0.238	4.4	0.53	1.94	72.8
HTT 800°C 0.5 hr	203.2	0.064	0.097	0.106	0.217	4.3	0.57	2.02	72.0

¹ Biocoal characterisation were undertaken on the >4.75 mm size fraction of the dried HTC biocoal and HTF biochars.

² BET SA = specific surface area using the BET model at a relative pressure (P/P₀) 0.02-0.05.

³ V_{ultra}, V_{micro}, V_{meso} and V_{tot} = volume of ultra-micropores (<0.7 nm), volume of micropores (<2.0 nm), volume of mesopores (2-50 nm) and total pore volume (up to 100 nm) using NLDFT carbon slit pore model combining N₂ and CO₂ isotherms.

⁴ D = average pore diameter.

⁵ % porosity = (1-(Bulk/Skeletal))*100.

Table A3.3b Textural characterisation data of HTC digestate biocoal and medium-scale biochars.

Sample ¹	BET SA ² (m ² /g)	V _{ultra} ³ (cm ³ /g)	V _{micro} ³ (cm ³ /g)	V _{meso} ³ (cm ³ /g)	V _{tot} ³ (cm ³ /g)	D ⁴ (nm)	Bulk density (g/cm ³)	Skeletal density (g/cm ³)	Porosity ⁵ (%)
HTC digestate >4.75 mm (dry basis)	12.0	0.011	0.018	0.061	0.095	31.4	0.71	1.47	51.9
>5.00 mm biochar 750 °C 0.5 hrs (dry basis)	204.9	0.070	0.117	0.075	0.200	3.9	0.60	1.97	69.6
5.00 mm biochar 750 °C 0.5 hrs (dry basis)	240.0	0.086	0.123	0.087	0.218	4.0	0.60	2.19	72.6
4.00 mm biochar 750 °C 0.5 hrs (dry basis)	205.4	0.068	0.110	0.084	0.201	3.9	0.43	2.17	80.4
2.36 mm biochar 750 °C 0.5 hrs (dry basis)	218.8	0.073	0.114	0.077	0.194	4.4	0.63	2.04	69.2
2.00 mm biochar 750 °C 0.5 hrs (dry basis)	209.7	0.064	0.105	0.079	0.200	4.3	0.67	2.22	69.7
1.18 mm biochar 750 °C 0.5 hrs (dry basis)	199.6	0.063	0.103	0.089	0.207	4.6	0.72	2.20	67.3
1.00 mm biochar 750 °C 0.5 hrs (dry basis)	203.5	0.066	0.108	0.086	0.208	4.2	0.73	2.21	67.1
0.85 mm biochar 750 °C 0.5 hrs (dry basis)	201.4	0.064	0.099	0.088	0.204	4.8	0.75	2.12	64.5
≤0.45 mm biochar 750 °C 0.5 hrs (dry basis)	200.4	0.068	0.107	0.055	0.171	4.6	0.45	1.84	75.4

¹ Biocoal characterisation were undertaken on all particle size fractions of the dried large-scale biochars.

² BET SA = specific surface area using the BET model at a relative pressure (P/P₀) 0.02-0.05.

³ V_{ultra}, V_{micro}, V_{meso} and V_{tot} = volume of ultra-micropores (<0.7 nm), volume of micropores (<2.0 nm), volume of mesopores (2-50 nm) and total pore volume (up to 100 nm) using NLDFT carbon slit pore model combining N₂ and CO₂ isotherms.

⁴ D = average pore diameter.

⁵ % porosity = (1-(Bulk/Skeletal))*100.

Table A3.4 Heavy metal concentrations (mg/Kg) determined by ICP-OES according to DIN EN ISO 17294-2 (DIN 22022-4 for Hg).



Umwelt

Parameter	Lab	Accr.	Method	Limit values				Description		UoN: CPL	
				EBC-Feed class I	EBC-AgroBio class II	EBC-Agro class III	EBC-material class IV	Sample number		ar	db
								LOQ	Unit		
Elements from the micro wave pressure digestion acc. to DIN 22022-1: 2014-07											
Arsenic (As)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01		13	13	15	0.8	mg/kg	-	2.3
Lead (Pb)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01		45	150	250	2	mg/kg	-	16
Cadmium (Cd)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01		0.7	1.5	5	0.2	mg/kg	-	< 0.2
Copper (Cu)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01	70	70	100	250	1	mg/kg	-	120
Nickel (Ni)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01	25	25	50	250	1	mg/kg	-	28
Mercury (Hg)	FR	RE000 FY	DIN 22022-4: 2001-02		0.4	1	1	0.07	mg/kg	-	< 0.07
Zinc (Zn)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01	200	200	400	750	1	mg/kg	-	158
Chromium (Cr)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01	70	70	90	250	1	mg/kg	-	41
Boron (B)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01					1	mg/kg	-	14
Manganese (Mn)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01					1	mg/kg	-	587
Silver (Ag)	FR	RE000 FY	DIN EN ISO 17294-2 (E29): 2017-01					5	mg/kg	-	< 5

Table A3.4 PAH concentrations (mg/Kg) determined by GC & HPLC according to DIN EN 16181



Umwelt

Parameter	Lab	Accr.	Method	Limit values				Description		UoN: CPL	
				EBC-Feed class I	EBC-AgroBio class II	EBC-Agro class III	EBC-material class IV	Sample number		ar	db
								LOQ	Unit		
Organic contaminants from toluene extraction acc. to EN 16181:2019-08 (method 2)											
Naphthalene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	15
Acenaphthylene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	0.6
Acenaphthene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	0.1
Fluorene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	0.1
Phenanthrene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	2.7
Anthracene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	0.6
Fluoranthene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	1.3
Pyrene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	1.4
Benz(a)anthracene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	0.2
Chrysene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	0.3
Benzo(b)fluoranthene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	0.3
Benzo(k)fluoranthene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	< 0.1
Benzo(a)pyrene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	0.2
Indeno(1,2,3-cd)pyrene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	< 0.1
Dibenz(a,h)anthracene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	< 0.1
Benzo(g,h,i)perylene	FR	RE000 FY	DIN EN 16181:2019-08					0.1	mg/kg	-	< 0.1
Total 16 EPA-PAH excl. LOQ	FR	RE000 FY	DIN EN 16181:2019-08	4	4	6	30		mg/kg	-	22.8

Appendix 4 Supporting information for life cycle analysis and process economics

Introduction

The existing pilot scale facility is operated by Coal Products Limited, Immingham. The facility processes 3 kt/yr of dewatered, 70% moisture content, digestate supplied by Severn Trent Green Power, East Birmingham AD Facility. The phase 2 facility is due to be an expansion of the current Immingham site, upgrading to an operational capacity of 10 kt/yr dewatered food waste digestate. The inventory data for the pilot scale and phase 2 facility is based on this existing plant. The 2030, commercial, case is spread across 2 separate facilities, each using 4 HTC reactors and 2 rotary kilns, collectively processing 41.6 kt/yr of dewatered food waste digestate at 70% moisture content.

Process inventory

A simple process diagram, demonstrating the process boundary considered in the Life Cycle Analysis (LCA) is presented in Figure A4.1.

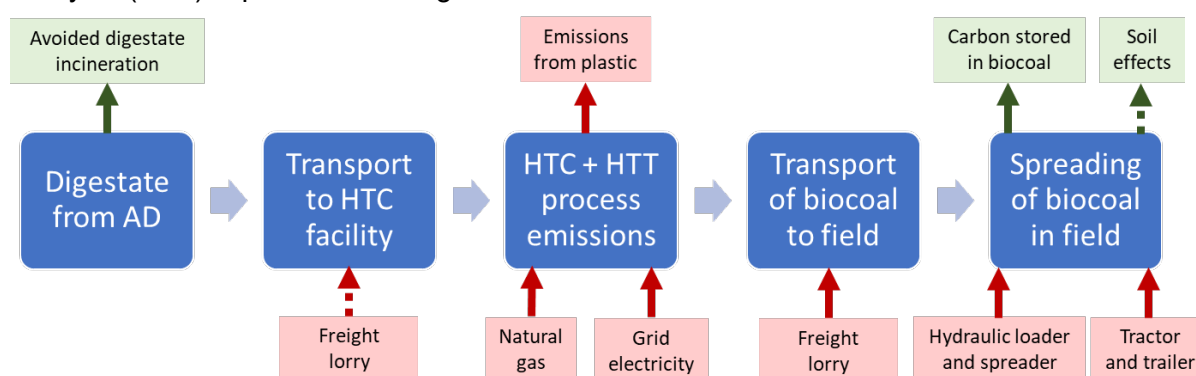


Figure A4.1: Life cycle assessment system boundary

To heat the HTC and HTT reactor up to temperature during start-up, a biomass boiler will be utilised at the commercial site. However, as this is not utilised during normal operation the associated emissions are omitted from the analysis. Emissions associated with plant construction are also omitted from this analysis. This is supported by the findings of Owsianiak *et al.* (2016), who undertook an LCA on into the performance of a pilot and commercial HTC facility for energy production. In both cases they found the emissions associated with plant construction, decommissioning and disposal to be negligible compared with the process emissions.

Digestate and biocoal transportation

Digestate and biocoal are transported by a 25 tn lorry. The current pilot scale and phase 2 facility are located at the Coal Products Limited site in Immingham, (DN40 2NX) with the digestate sourced from Severn Trent Green Power in Coleshill, (B46 1DG). The transport distance is calculated as 206 km using Google Maps. The process produces 170L/tn_{digestate} of process liquid which can be returned, by truck, to the AD facility to be recycled in the AD process.

Table A4.1 Digestate transportation assumptions based on evenly distributed HTC+HTT facilities

Parameter	Value	Comments
2030 food waste digestate, 70 wt% moisture (Mt/yr)	1.12	Meeting Courtauld and SDG 12.3 targets (WRAP, 2021)
Total commercial scale facilities required	54	10 kt/yr plant capacity, 2 HTC reactors
Average area facility is servicing (km ²)	4,518	Evenly distributed facilities across UK
Maximum transport distance to facility (km)	38	Radius of area being serviced

The proposed commercial scale HTC facilities are to be co-located with an AD facility, negating the need for digestate transportation. The current average food waste AD facility produces 7 kt/yr of

dewatered digestate, 35% of the quantity required for the proposed 20 kt/yr capacity. Whilst food waste collection mandates are likely to increase AD facility sizes, based on the current average facility size, digestate transportation may be required. This was considered in a high transport case, a maximum transportation distance of 38 km was assumed, based on the even distribution of HTC+HTT facilities across the UK, Table A4.1

The biocoal transportation distance to field is assumed to be 25 km, and varied up to 50 km as part of the high transport case. The biocoal is to be spread in the field using a tractor and trailer, with emissions data taken from Ecoinvent for both an agricultural tractor and trailer and solid manure loading and spreading by a hydraulic loader and spreader (Wernet *et al.*, 2016). A tractor transportation distance of 2.5 km and 10km were used for the base case and high transport case, respectively. However, using a 10 tn/ha application rate and 25 tn lorry the area required for spreading per truckload is 2.5 ha, corresponding to an area with radius of 0.1 km. As such, the tractor transportation distance used is conservative.

Avoided digestate incineration

At present, digestate screenings are disposed of via landfilling or incineration, at a cost to the operator, with incineration as the preferred option. Whilst incineration results in the release of all the carbon content to the atmosphere as CO₂, it also generates renewable electricity. As such, the loss in renewable electricity generation needs to be accounted for when diverting to biocoal production. The duty required to evaporate the moisture content of the dewatered digestate was subtracted from its LHV to calculate the available energy from incineration. This was translated to electrical energy and offset against the emissions produced by the grid electricity required to replace it. Details are presented in Table A4.2.

Table A4.2: Avoided digestate management emissions

Parameter	Value	Comments
LHV of feedstock (MJ/kg)	16.1	Dry basis
Water content (%)	70	
Latent heat of vaporisation (MJ/kg)	2.26	
Net energy generation (MJ/kg)		
Net energy generation (MJ/kg)	3.25	
Electricity conversion efficiency (%)	27	(DEFRA, 2013)
Net electricity generation (KWh/kg)	0.24	
Foregone emission reduction (kg_{CO2}/kg_{digestate})		
Foregone emission reduction (kg _{CO2} /kg _{digestate})	0.033	2020 grid electricity
Foregone emission reduction (kg _{CO2} /kg _{digestate})	0.020	2030 grid electricity

The food waste digestate contains approximately 5% plastic, as received. The carbon content of the plastic is realised as CO₂ during both incineration and in the HTC+HTT process. The carbon content, and subsequent emissions, was estimated based on the composition of recycled plastic (Chruszcz and Reeve, 2018), summarised in Table A4.3.

Table A4.3 Direct emissions from plastic composition

Plastic	Composition	CO ₂ eq/kg
PET	40.3	2.38
HDPE	21.6	3.14
PP	10.2	3.14
Film (assumed LDPE)	15.7	3.14
kgCO₂eq/kg plastic		2.45
kgCO₂eq/kg digestate		0.123

Carbon sequestration

Biocoal produced by HTC contains approximately 80% of the digestates initial carbon content, with 15% leaving in the process liquid and the remaining 5% lost in a CO₂ rich gas stream (>95% CO₂).

The produced process liquid is used internally within the HTC and HTT plant with the residual 170L/tn_{digestate} returned for use in the AD facility. The HTT process is undertaken to stabilise the biocoal, ensuring permanent carbon sequestration. This process captures approximately 50% of the carbon recovered from the HTT process, with the other half released in the volatiles, combusted for energy recovery. Overall, the process sequesters approximately 40% of the initial carbon in the AD solid residue.

Soil effects

In addition to carbon sequestration, there are also soil benefits related to biocoal application. In previous works the; increase in primary productivity, decrease in soil organic carbon decomposition, reduction in N₂O soil emissions, and decrease in N, P and K fertilizer use have been investigated (Matuščík, Hnátková and Kočí, 2020). The emission reduction associated with these soil effects was considered as an additional case study, based on the parameters presented in Table A4.4. Another, optimistic, scenario was considered whereby it was assumed that all the nitrogen in the biocoal is available for use, further reducing the N fertilizer requirement.

Table A4.4: Soil effects investigated

Parameter	Base	Percentage changed (base)
Soil organic carbon (C t/ha)	47.3a	10
Primary productivity	-	10
N fertilizer use (kg/ha)	92b	10
P fertilizer use (kg/ha)	16b	5
K fertilizer use (kg/ha)	22b	5
N ₂ O emissions (kg/ha)	1.012c	25

^a (Emmett *et al.*, 2010); ^b (Department for Environment Food and Rural Affairs, 2020); ^c Calculated with N fertiliser use and N₂O emission factor (Intergovernmental Panel on Climate Change, 2006); ^d (Hammond *et al.*, 2011)

Costs

The costs associated with utility use, transportation, fixed operating and annualised capital along with their assumptions are summarised in Table A4.5.

Table A4.5: Operating cost summary

Parameter	Value	Comments
Grid electricity (£/MWh)	110	Provided by CPL industries
Natural gas (£/MWh)	22.3 (2020) 29.8 (2030)	
Digestate and biocoal transport (£/tn.km)	0.22	Provided by STGP
Biochar spreading (£/tn)	3.5	(WRAP, 2016)
Operating costs (£/yr)	1.2 million	Provided by CPL industries
Annualised capital costs	1.52 million	£9.5 million per 20kt site, 5% discount rate
Gate fee (£/tn digestate)	58	

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