

A Review of the Benefits of Biochar and Proposed Trials

Potential to enhance soils and sequester carbon in the ACT for a
circular economy



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Client: Environment, Planning and Sustainable Development Directorate

ABN: 31 432 729 493

Prepared by

AECOM Australia Pty Ltd

Level 2, 60 Marcus Clarke Street, Canberra ACT 2600, Australia

T +61 2 6201 3000 F +61 2 6201 3099 www.aecom.com

ABN 20 093 846 925

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Prepared by Bruce Edgerton, Wolfram Buss

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Executive Summary

In April 2019 the ACT Government engaged AECOM to undertake a literature review of the status of agronomic biochars. Further AECOM, in consultation with relevant stakeholders, was to develop proposals to evaluate the potential costs and benefits of a sewage solids and woody-biomass derived biochar in ACT conditions.

Biochar is a type of charcoal produced by heating biomass under oxygen limited conditions (pyrolysis or gasification). Biochars can be produced from any materials containing organic matter, such as forest and agricultural residues, sewage sludge (biosolids) or food waste. Many different biochar applications have been investigated, ranging from their use in soil remediation, wastewater filtration to energy storage (Liu et al., 2019).

The biochar properties relevant to improving soils include: high porosity and low bulk density; liming potential; cation exchange capacity (CEC); nutrient content; high surface area; and improvement of microbial growth (Lehmann and Joseph, 2015).

Using biochar to improve the fertility and drought tolerance of agricultural soils may be an effective climate change adaptation strategy.

Pyrolysing or gasifying sewage solids has advantages over biological processes such as composting and anaerobic digestion. These include complete pathogen destruction and superior destruction or removal of a range of chemicals of concern such as pharmaceuticals, microplastic and PFAS (per- and poly-fluoroalkyl substances).

A 2018 report by the Intergovernmental Panel on Climate Change (IPCC) identified pyrolysis of biomass to make biochar as one of only a handful of technologies that have the potential to sequester significant quantities of carbon dioxide (Rogeli et al., 2018). Biochar also has significant potential co-benefits such as improved soil fertility and the potential generation of renewable heat and power increasing its value for large-scale application.

Furthermore, processing of sewage solids to produce biochar has the potential to reduce the life-cycle emissions associated with the beneficial use of sewage solids in Australia (especially those associated with the transport of sewage solids to agricultural markets).

On 16 May 2019 the ACT Legislative Assembly declared a climate change emergency (ACT LA 2019). This followed a similar declaration by the UK Parliament on 1 May 2019. The motion adopted by the ACT Legislative Assembly “acknowledges that we are in a state of climate emergency that requires urgent actions across all levels of Government” such that global temperature rises can be “limited to 1.5 degrees to minimise the risk of the worst impacts of climate change, a task the UN Intergovernmental Panel on Climate Change says requires urgent and unprecedented action” (ibid).

Making biochar from sewage solids and woody-biomass potentially creates a high-value product from low-value “waste” materials. Materials that often incur costs to dispose of sustainably. Hence, commercialisation of pyrolysis or gasification technologies along with biochar markets could support the circular economy and deliver triple bottom-line benefits to the ACT and Australia more widely.

Unfortunately, the uncertainty around biochars’ field performance in combination with the immaturity of large-scale pyrolysis and gasification technologies for processing these waste streams creates significant commercial, technical and regulatory risks for biochar projects.

This combination of significant public good and substantial commercial risk creates a powerful policy argument for Government investment in pyrolysis and biochar demonstrations to reduce the barriers to the technology’s wider uptake and commercial deployment.

This report outlines a number of trials and actions that the ACT Government, Icon Water and other interested stakeholders could undertake to prove the markets for biochar, reduce regulatory risk and help facilitate Australian water utilities establishing commercial biochar projects; these are listed below.

- Regulatory engagement:
 - with the ACT EPA, ACTNOWaste and Waste Manager;

- the NSW EPA; and with
- the Clean Energy Regulatory and Department of the Environment and Energy (Cwth).
- Market proving demonstrations and data collection projects:
 - a horticulture trial (plant production at nurseries and use in potting mix);
 - a silviculture trial (pine plantations for lumber and pulp production); and
 - a broad-acre agriculture trial (improved pasture establishment).

Of these three markets horticulture and potting mixes is easily the highest value. Biochar can potentially earn wholesale prices of \$50-200/tonne when blended into commercial potting mixes.

Silviculture is the lowest risk market and is large enough to use all the biochar that Icon Water could generate from its sewage solids. This provides a market with a single customer that is regulated by a single jurisdiction – further reducing project transaction costs and risks.

Biochar application is expected to improve the health and productivity of agricultural soils in the Canberra Region. This is the largest potential market in the region (by area) with the greatest potential for additional carbon sequestration.

1.0 Background

AECOM and Icon Water have been working together with the ACT Government, Dr Wolfram Buss (Fairtiliser) and Dr Anton Wasson (CSIRO) to assess the use of agronomic biochar made from the thermal processing of sewage solids.

Thermal processing has advantages over biological processes such as composting and anaerobic digestion. These include complete pathogen destruction and superior destruction or removal of a range of chemicals of concern such as pharmaceuticals, microplastic and PFAS (per- and poly-fluoroalkyl substances).

Significant regulatory, financial and technical challenges exist to commercialising this approach.

A small trial has been conducted at Yarralumla Nursery in the ACT. This trial involved the use of biochar made from a mix of Icon Water's stockpiled biosolids and woody-waste. The biochar trial is further described in **Appendix A**.

AECOM and Icon Water are seeking industry and Government partners to co-fund more extensive trials that are further described in this report in **Sections 9.0 to 12.0**.

The ACT Government Environment, Planning and Sustainable Development Directorate (EPSDD) funded this desktop review to help inform the scientific basis for further biochar research and to better refine the scope of possible field trials in the ACT.

1.1 ACT Policy Objectives

On 16 May 2019 the ACT Legislative Assembly declared a climate change emergency (ACT LA 2019). This followed a similar declaration by the UK Parliament on 1 May 2019 which received bipartisan support.

The motion adopted by the ACT Legislative Assembly "acknowledges that we are in a state of climate emergency that requires urgent actions across all levels of Government" such that global temperature rises can be "limited to 1.5 degrees to minimise the risk of the worst impacts of climate change, a task the UN Intergovernmental Panel on Climate Change (IPCC) says requires urgent and unprecedented action" (*ibid*).

A 2018 report by the IPCC identified pyrolysis of biomass to make biochar as one of only a handful of technologies that have the potential to sequester significant quantities of carbon dioxide (Rogeli et al., 2018). It was the only technology identified that also has significant potential co-benefits such as improved soil fertility and the potential generation of renewable heat and power.

Furthermore, the processing of sewage solids to produce biochar has the potential to reduce the life-cycle emissions associated with the beneficial use of sewage solids in Australia (especially those associated with the transport of sewage solids to agricultural markets).

Making biochar from sewage solids and woody-biomass potentially creates a high-value product from low-value "waste" materials. Materials that often cost money to dispose of sustainably. Hence, commercialisation of pyrolysis or gasification technologies along with biochar markets could support the circular economy and delivery triple bottom-line benefits to the ACT and Australia more widely.

1.2 Thermal Processing of Sewage solids

Thermal processing of sewage solids lost favour in a number of Australian jurisdictions during the 1960s and 1970s. However, technological progress and changing policy frameworks have lead AECOM and Icon Water to the view that thermal approaches deserve renewed analysis. In 2013 Icon Water co-sponsored Dr Jessica Shepherd to undertake a PhD into the production of biochar from sewage sludge at the UK Biochar Research Centre.

While thermal processing of sewage solids can lead to a loss of nitrogen it does preserve phosphorous, potassium, calcium and most micronutrients for beneficial use in agriculture or horticulture. Furthermore, by turning wet, malodourous sewage solids into a dry, friable material, thermal processing makes transporting sewage solids to market less carbon intensive and creates a more user-friendly product.

Thermal processing achieves complete pathogen destruction and superior destruction or removal of a range of chemicals of concern such as pharmaceuticals, microplastic and PFAS (per-and poly-fluoroalkyl substances). This reduces environmental, human health and regulatory risks associated with the beneficial use of sewage solids.

1.3 Replacing Icon Water's Sewage Solids Furnace

Currently Icon Water uses two 1970s furnaces at its Lower Molonglo Water Quality Control Centre (LMWQCC) to incinerate its including primary solids, activated sludge, grit and screenings. Icon Water is the only water utility in Australia that incinerates its sewage solids.

Icon Water's furnaces are nearing the end of their service life. Refurbishment is currently underway to enable operation until approximately 2030. When these furnaces are unavailable during maintenance or are unexpectedly out of service, Icon Water stockpiles the sewage solids onsite for eventual landfilling or use in agriculture (after static-pile stabilisation).

Over 2017-18 Icon Water commissioned GHD to develop recommendations for suitable options for sewage solids treatment and end use at LMWQCC to provide more sustainable, energy efficient treatment process. The options were assessed using Multicriteria Analysis, high-level carbon foot-printing and Cost Benefit Analysis (ie a 30-year financial assessment of net present value). Shortlisted options included anaerobic digestion, co-digestion with regional organic biomass and combustion in a best-practice fluidised-bed incinerator. Initial assessment of options found that fluidized bed combustion has significantly lower capital and operating costs while providing key heat benefits for the plant and superior organic product reuse potential (Laginestra 2019). Given the early stage of technology assessment Icon Water have noted that it is not prudent to confirm a preference of any technology.

There are a number of advanced thermal processing technologies that were not shortlisted in the GHD study due to their immaturity and hence their technical, financial, regulatory and market risk profile. Nevertheless, Icon Water is interested in the potential of slow pyrolysis (350-750°C) and low temperature (700-800°C) gasification to produce biochar from sewage solids and woody-biomass. This has a number of potential benefits over incineration including a lower carbon footprint, the production of higher value products and the creation of a market for unutilised biomass from softwood plantations.

However, both the technology and the biochar markets need to be proven by 2024-25 if Icon Water is to select this technology to replace its sewage solids furnace.

Hence, Icon Water supported the 2018-19 pot trial at Yarralumla Nursery to explore the horticultural market for sewage solids-biochar (as described in **Appendix A**).

In June 2019 Icon Water engaged AECOM to review Australian and global providers of slow-pyrolysis and low-temperature gasification technologies and to undertake market sounding for the provision of biochar for use in the trials described below.

2.0 An Introduction to Biochar

Biochar is a type of charcoal produced by heating biomass under oxygen limited conditions (pyrolysis or gasification). When this charcoal is used for environmental applications, such as the application to soil, it is called biochar. It can be produced from any material containing organic matter, such as forest and agricultural residues, sewage sludge (biosolids) or food waste.

Many different biochar applications have been investigated, ranging from the use for soil remediation, wastewater filtration to energy storage (Liu et al., 2019). The first discovery of biochar was as a constituent of 'Terra Preta', a highly fertile soil in the Amazon (Glaser et al., 2001). Biochar can improve a variety of soil properties and therefore, can increase plant growth.

The biochar properties relevant for improving soils are (Lehmann and Joseph, 2015):

- **high porosity and low bulk density** - resulting in increased plant water availability and air supply to roots and microorganisms.
- **liming potential** - increasing the pH of soil, which in turn increases nutrient availability and decreases availability of toxic metals.
- **cation exchange capacity** – reducing nutrient leaching and increasing plant nutrient uptake.
- **nutrient content** - for direct nutrient provision.
- **high surface area** - for sorption of organic contaminants in soil.
- **improvement of microbial growth** - increasing plant-microbial symbiosis and nutrient availability.
- **recalcitrant carbon matrix** - sequestering carbon in soil for centuries and contributing to climate change mitigation.

The effects of biochar in soil and resulting plant growth performance is highly dependent on biochar type (feedstock type, production conditions) and the soil-plant system (Lehmann and Joseph, 2015). Biochars (or charcoal) based on woody feedstocks have been produced for thousands of years. In the last decade many other sources of input material for pyrolysis have been tested, including sewage sludge.

3.0 Greenhouse Gas Mitigation Potential of Biochar

3.1 Biochar Carbon Stability and Sequestration

Biochar has been mentioned as one of only six negative emission technologies in the most recent special report of the IPCC (Rogeli et al., 2018). It is the only technology mentioned that may actually enhance agricultural production and deliver positive environmental outcomes while also mitigating GHG emissions. Globally, the potential of carbon sequestration potential of biochar is around 0.7-1.8 Gt CO₂-C_e per year (Smith, 2016; Woolf et al., 2010).

During pyrolysis, the biomass carbon is restructured and rearranged to form aromatic carbon (6-ring-molecules) that fuse together and build a carbon matrix. This makes it very stable against chemical and biological degradation (Lehmann and Joseph, 2015). Hence, biochar in soil can store carbon for centuries, potentially millennia.

Biochar is much more stable than its parent material and the carbon stability increases with pyrolysis temperature and is also influenced by feedstock type (Ameloot et al., 2013; Calvelo Pereira et al., 2011; Y. Fang et al., 2014; McBeath et al., 2014).

The carbon sequestration potential of biochar can be determined by considering the biochar yield and the stability of the carbon within the biochar. The yield of stable carbon per biomass input is typically independent of the pyrolysis temperature (Mašek et al., 2013). However, minerals can be added before pyrolysis to increase biochar's carbon sequestration potential (Buss et al., 2019b; Mašek et al., 2019).

The residence time of biochar in soil has been estimated at between 90-4,000 years (McBeath et al., 2014; Singh et al., 2012; Wang et al., 2016; Kuzyakov et al., 2014). However, the decomposition rate of biochar is strongly dependent on biochar type and soil properties (Wang et al., 2016).

Not all the carbon in biochar degrades at the same rate, most often a biphasic degradation profile is seen with a carbon pool that is faster degraded (labile carbon, mean residence time in soil of 108 days) and a more stable carbon pool (mean residence time 556 years) (Ameloot et al., 2013; Wang et al., 2016). Biochar typically contains between 0.5-8.9% labile carbon, which is easily broken down (Singh et al., 2012).

The stable carbon pool can be approximated with various analysis tools which are easily performed on biochar before soil application. For example, hydrogen peroxide oxidation as a way to simulate accelerated ageing, which has been calibrated against historical charcoal (Cross and Sohi, 2013); or thermal oxidation (thermogravimetric analysis) (Crombie et al., 2013).

3.2 Carbon Sequestration Potential of Biochar in the ACT

Table 1, below, calculates the direct carbon sequestration of the stable carbon in the biochar at 700°C and 550°C if all Icon Water's sewage solids were pyrolysed.

It was assumed that sewage sludge and unutilised pine-forestry biomass would be mixed in a ratio of 1:1 on a dry mass basis and pyrolysed at either 700°C or 550°C. As Icon Water currently produces 13,000 dry-tonnes of sewage solids a year it is assumed that 13,000 dry-tonnes of pine biomass is also used.

At 700°C pyrolysis of sewage sludge should yield biochar equivalent to approximately 26% of its initial dry weight while the pine biomass should achieve a biochar to dry-weight yield of approximately 17%. At 550°C biochar to dry-weight yield should increase to approximately 40% for sewage sludge and 22% for pine biomass (Mašek, 2014).

The sewage sludge and pine biochars can be expected to contain approximately 29% and 90% carbon respectively when processed at 700°C. At 550°C the carbon content can be expected to be 30% and 86% for sewage solids and pine respectively (*ibid*). Mašek (2014) found that 96-97% of the carbon in the biochar was stable as 700°C while 70-84% was stable at 550°C¹.

¹ Mašek (2014) definition of carbon stability was based on the method described in Cross and Sohi (2013) and seeks to mimic the effect biochar being left in soil for at least 100 years.

While the lower temperature yields more biochar and more carbon, it yields a similar amount of stable carbon (2,875-2,984 tonnes/year). Hence, the two different processing temperatures would lead to a similar quantities of direct carbon sequestration (10,539-10,941 tonne CO₂ equivalent/year).

While this is a relatively modest quantity of direct carbon sequestration it would approximately offset the entire annual GHG emissions of the ACT's wastewater sector, estimated to be 11,600 CO₂-e/year by Saddler (2018), potentially making the ACT's wastewater sector carbon neutral.

Nonetheless, the more significant GHG savings, at least on a national basis, will relate to the reduced carbon footprint of biochar transport and utilisation compared to biosolids.

As an aside – if applied at 10 t/ha or 40 t/ha (equivalent to the application rate in Weng et al. (2017) and Silva et al. (2017)), the biochar could be applied to 200-500 ha of forest per year. The ACT currently plants around 300-600 hectares to softwood timbers each year. Note that besides the pine plantations there are likely to be other options available for biochar application in some years e.g. the planting of native trees and shrubs to restore land or sequester carbon.

Table 1: Direct CO₂ sequestration with biochar made from biosolids/sewage sludge and softwood at 700°C and 550°C.

	scenario 1: 700°C biochar		scenario 2: 550°C biochar	
	value	units	value	units
Woody biomass	13,000	dry tonne/yr	13,000	dry tonne/yr
sewage solids	13,000	dry tonne/yr	13,000	dry tonne/yr
biochar yield	22%		31%	
wood	17%		22%	
sewage solids	26%		40%	
total biochar yield	5,590	dry tonne/yr	8,047	dry tonne/yr
carbon content in biochar				
wood	90%		86%	
sewage solids	29%		30%	
stable carbon content of total carbon in biochar				
wood	97%		70%	
sewage solids	96%		84%	
stable carbon content in biochar				
wood	88%		60%	
sewage solids	28%		25%	
stable carbon yield in biochar	2,875	tonne C/yr	2,984	tonne C/yr
direct CO ₂ sequestration	10,539	tonne CO ₂ /yr	10,941	tonne CO ₂ /yr
application rate	10	tonnes/ha	10	tonnes/ha
areas covered	559	ha/yr	805	ha/yr

3.3 Biochar and Priming of Existing Carbon in Soil

Biochar application increases the stable carbon content of soil. Biochar amendments are also known to interact with 'native carbon' - carbon already stored in the soil, and cause 'positive' or 'negative' priming. 'Positive priming' refers to the loss of carbon already stored in the soil. 'Negative priming' refers to increased carbon sequestration as a result of the soil amendment.

Soil CO₂ emissions often increase soon after biochar is applied to soil (Cross and Sohi, 2011; Y Fang et al., 2014; Singh et al., 2012; Zimmerman et al., 2011). However, this is due to the degradation of the labile carbon in the biochar. After the initial CO₂ release, biochar demonstrates negative priming potential with reduced mineralisation of native carbon (Cross and Sohi, 2011).

The effect of a wood biochar on native soil carbon was investigated in four different Australian soils (Inceptisol, Entisol, Oxisol, Vertisol) by Fang et al. (2015). The results indicate positive priming in the clay-poor soil and negative priming in the clay-rich soil. This is consistent with the findings of a meta-analysis of 21 studies, which indicated that significant positive soil organic carbon priming was possible in sandy soils (Wang et al., 2016).

In a key study published in "Nature", eucalyptus biochar (550°) applied at 10 t/ha (plus NPK fertiliser to replicate the treatment of pasture soil) was studied in Australian soil 9.5 years after its application. Biochar application increased the pool of soil organic matter by forming organo-mineral complexes that protect the soil organic matter from degradation (Weng et al., 2017). It was estimated, that this negative priming process slowed down soil organic carbon mineralization by 5.5% (46 g CO₂-C m⁻² yr⁻¹) under these particular conditions in a subtropical Ferralsol (Wollongbar, NSW) in a ryegrass system. Previously, it was shown that this effect does not only occur in Ferrasols; negative priming was found an Australian Arenasol and Cambisol (both Cobbity, NSW) (Keith et al., 2015).

Most of the ACT's softwood timber plantations are on sites which have high-clay soils with low organic carbon content. Hence, it can be anticipated that biochar application should lead to an increase in native soil carbon. Assuming 46 g CO₂-C m⁻² year⁻¹ of extra carbon in soil (consistent with the findings of Weng et al., (2017)), 400 ha of land would sequester an additional 184 tonnes of CO₂ per year. This adds around 6.4% a year to the carbon sequestration potential of the biochar itself (10,500 t CO₂/year). If this increase in soil organic carbon were to continue linearly for 30 years it could approximately double the total carbon sequestration. However, Weng's 2017 study was only over nine years so there is uncertainty regarding this extrapolation. The actual sequestration results in ACT conditions could well be significantly higher or lower than this.

3.4 Biochar's Impact on Methane and Nitrous Oxide Emissions from Soil

Soils emit nitrous oxide (N₂O) and methane (CH₄), gases with a 265 and 28 times higher global warming potential (GWP) than CO₂, respectively over a 100 year timeframe (IPCC, 2014).

Methane is generally only produced in water-logged soil. Similarly, N₂O is mostly produced from wet soils after nitrogen fertiliser application (Jeffery et al., 2016; Zwieten et al., 2010).

Biochar should reduce the emissions of N₂O and CH₄, by reducing soil's bulk density and increasing air supply to roots and microorganisms (Zwieten et al., 2015). However, it is difficult to accurately or repeatably measure methane and nitrous oxide emissions from soil. Hence, the literature results regarding these emissions is quite mixed.

Methane

Jeffery et al. (2016) compiled the results of different studies in a meta-analysis and demonstrated that biochar can decrease CH₄ emissions, in particular in acidic (pH < 6) and flooded soils but can increase CH₄ emissions in neutral and alkaline and non-flooded soils. Biochars produced at higher pyrolysis temperatures were more effective in decreasing CH₄ emissions. Overall, all biochar types reduced the CH₄ emissions to a similar extent, except for sewage sludge biochar, which demonstrated the greatest response by far but also the greatest variability.

Sewage sludge biochar was only investigated in Khan et al. (2013), where 5% sewage sludge biochar decreased CH₄ emissions by more than 100%, transforming the acidic, sandy soil from a CH₄ source to a sink (CH₄ uptake of 2.4–22.0 mg/m²/h in cultivated soil). It is suggested that improved aeration in

water-logged paddy soil resulted in stimulation of methanotrophs that utilise CH₄ as a carbon source and hence oxidise it.

The ACT forest soils under investigation are slightly acidic, and some areas suffer water-logging issues². However, it is also difficult to predict whether sewage sludge biochar would significantly reduce the pine forests CH₄ emissions and it is expensive and difficult to measure these emissions in the field. AECOM suggests that an additional \$150,000 of budget would be required to measure methane and nitrous oxide emissions, with no guarantee of statistically valid results. For the purposes of this study, and likely budget constraints, it is not recommended that CH₄ emissions be measured as part of this trial.

Nitrous Oxide

Few studies on biosolid biochar exist, and the few which do exist show highly variable results. In a meta-analysis summarising 30 studies, biochar was able to reduce N₂O emissions by 54% on average with woody biochars significantly reducing N₂O emissions by 50-60% (Cayuela et al., 2014).

In general, an application rate of 1-2% biochar has been found to significantly reduce N₂O emissions, with the effect increasing alongside the application rate. Under wet conditions, biochar greatly reduces the N₂O emissions in fine textured soils such as clays. Under dry conditions, the soil type is of less relevance for the effect of biochar in N₂O emissions. Soil pH is not a significant factor in N₂O emissions resulting from biochar application, however in soils <5 pH biochar is not as effective in reducing N₂O emissions.

Nelissen et al. (2014) tested the N₂O emission from soil after application of 7 different types of biochar (including pine biochar). In all cases, N₂O emissions were reduced by 52-84%. The effect was more pronounced when the biochar was produced at higher pyrolysis temperatures. In a study with biochars from 4 different feedstocks in an Australian acidic Ferrosol, 5% and 1% biosolid biochar (pyrolysis at 550°C) application, had the greatest impact on reducing N₂O emissions, 6 and 3 times lower N₂O emissions were observed compared to the control, respectively (Zwieten et al., 2010). In Khan et al. (2013), 5% sewage sludge biochar decreased N₂O emissions by 95%.

Changes in N₂O emissions due to biochar were attributed to pH increase and sorption of NO₃⁻, resulting in changes in microbial activity (Nelissen et al., 2014; Zwieten et al., 2010). The reduction of N₂O and methane emission by biochar were confirmed in forest soils (Li et al., 2018).

Biochar produced from sewage sludge (and pine) at high pyrolysis temperatures, applied to fine-textured soil (clay) at an application rate of at least 1% should significantly reduce N₂O emissions from soils with an existing N fertiliser treatment. In agricultural soils, nitrogen is applied annually and therefore, biochar can have a significant impact, however, the effectiveness of biochar mitigation of N₂O emissions in ACT forest soils, will be heavily impacted by the N fertilisation regime.

² Personal communications, ACT Parks and Conservation Service, July 2019

4.0 Sewage Sludge Biochar

Sewage sludge is the solid residue from wastewater treatment. It contains nutrients and organic carbon and therefore, has a high value as a soil amendment and fertiliser. The term biosolids refers to stabilised sewage sludge treated to reduce the pathogen load (Paz-Ferreiro et al., 2018).

Common sewage sludge treatments include composting, stockpile storage, lagoon storage and anaerobic digestion. One of the advantages of thermal treatment of sewage sludge (pyrolysis, gasification or incineration) over these methods is organic contaminant reduction and complete pathogen destruction.

During incineration the carbon in the feedstock is being oxidised to CO₂ and subsequently “lost” back to the atmosphere. Pyrolysis is a thermo-chemical conversion process under oxygen-limited conditions that ensures that more carbon is retained in the biochar. During this process the carbon is being converted into a carbon matrix that is very recalcitrant against chemical and biological degradation.

Pyrolysis reduces the concentration of toxins, such as polycyclic aromatic hydrocarbons, pharmaceuticals (e.g. estrogen) and other organic contaminants (e.g. plastics and surfactants). Typically temperatures of around 500°C are sufficient for contaminant removal (Hoffman et al., 2016; Ross, 2014; Sütterlin et al., 2007; Wijesekara et al., 2007; Zielińska and Oleszczuk, 2015). Under controlled pyrolysis conditions, biochar will have very low concentrations of organic contaminants potentially introduced during the production process, e.g. volatile organic compounds (VOCs) (e.g. phenols, organic acids) (Buss et al., 2015; Buss and Mašek, 2016, 2014), polycyclic aromatic hydrocarbons (PAHs) (Buss, 2016; Buss et al., 2016a) and furans and dioxins (Weidemann et al., 2017). Pyrolysis of biomass retains the phosphorus (P) present in the feedstock, while most of the N is vaporised or being stabilised and hence, rendered unavailable for plants (Buss et al., 2016b; Hossain et al., 2011; Paz-Ferreiro et al., 2018).

With increasing pyrolysis temperatures, the availability of P in biochar changes (Buss et al., 2016c; Dai et al., 2017; Liang et al., 2017; Uchimiya and Hiradate, 2014). At low temperatures, the P in sewage sludge/biosolid biochar is similarly available to the P in the untreated source material, however, at temperatures above 600°, the P becomes less bio-available.

However, the true P available in soil is not clear, and many different measures of P are used to best represent P availability in different soils (e.g. Olsen, Resin, Bray, Colwell and Total P). The P release from biochar is particularly affected by the pH and Ca concentration (Buss et al., 2018a). Low P availability could be an advantage since the P is not leached through the soil easily (slow-release properties) (Dai et al., 2017; Kominko et al., 2017) or a disadvantage since the P is locked up and not available to plants. There are ways being explored to control the P release in biochar, which would enable the production at higher pyrolysis temperatures, e.g. 700°C, while maintaining high P availability (Buss and Mašek, 2018).

4.1 Heavy Metals in Biochar made from Sewage Sludge

Sewage sludge contains heavy metals. During pyrolysis heavy metals are concentrated in proportion to the amount of biomass that is volatilised as syngas, but generally become less mobile (Buss et al., 2016b).

In one study, it was demonstrated that 38 t/ha of sewage sludge biochar would need to be applied to exceed the maximum allowable soil contaminant concentration of copper in Western Australia (Department of Environmental Protection, 2002). For the same biochar only 160 kg/ha was required to provide the agronomic P requirements (Bridle and Pritchard, 2004). Hence, heavy metal limits would not likely be exceeded over 200 years of sewage sludge biochar application as a P fertiliser.

Another study on sewage sludge from wastewater treatment plants in southeast Melbourne (predominantly from municipal sources) total metal limit values for Victoria were exceeded by both, the sewage sludge and the biochar (Yang et al., 2018). Both materials have to be classified as Grade 2 according to the EPA Victoria Biosolid Guidelines. Grade 2 biosolids can be applied to land with specific management controls (EPA Victoria, 2004).

As a general observation, the compliance of sewage sludge biochar with regulatory heavy metal threshold values depend on the source of sewage sludge. Sewage solids in the ACT are relatively low

in heavy metals and other contaminants. Nevertheless, Agri-ash made from ACT sewage solids exceed Victorian EPA threshold values for zinc and copper and would thus be classified as C2 material in Victoria (Fertsread, 2018).

In the proposed scenario, biochar would be mixed with wood-waste containing very low heavy metal concentrations and in contrast to incineration, during pyrolysis a significant part of the carbon in the feedstock will be retained. Therefore, it is likely that biochar made from Icon Waters sewage solids will not exceed heavy metal limits. Further investigation of heavy metal concentrations in the biochar will be necessary as part of the trials proposed in this report. Whatever the actual concentration of these heavy metals is, pyrolysis of the parent material reduces the environmental and human health risk associated with them.

Pyrolysis reduces the availability of metals, such as copper, lead, chromium, cadmium or zinc, which reduces the risk for plant uptake and leaching into groundwater (Buss et al., 2016c; Khanmohammadi et al., 2015; Liu et al., 2014; Méndez et al., 2012; Waqas et al., 2014). Due to reduced metal leaching resulting from immobilisation during pyrolysis, biochars from sewage sludge are generally understood to be safe and hence, several authors recommend basing limit values in the Australian regulations on leachability of metals instead of total metal concentrations (Roberts et al., 2017; Yang et al., 2018). For example, in one Australian study (Hossain et al., 2010), 10 t/ha of biosolid biochar did not result in concentrations of potentially toxic metals in tomatoes being over maximum concentrations allowed by the Australian food standards (even though total metal concentrations in soil exceeded guidelines).

The typical temperature range for pyrolysis is 350-800°C and with increasing temperature, biochar pH and surface area increase, while the cation exchange capacity decreases (El-Naggar et al., 2019; Méndez et al., 2013). The amount of stable carbon (suitable for carbon sequestration) produced per feedstock amount (the stable carbon yield) does not vary much with pyrolysis temperature as the biochar yield decreases, while the stable carbon content in the biochar increases with pyrolysis temperature (Mašek et al., 2013).

There are advantages and disadvantages with using higher pyrolysis temperatures when producing biochar from sewage sludge. Higher pyrolysis temperatures are more beneficial to reduce the concentrations of organic contaminants and increase the pH/liming potential. However, higher temperatures also reduce P availability and cation exchange capacity. Hence, many biochar researchers including Lehmann and Joseph (2015) favour a medium pyrolysis temperature of around 500-550°C.

The final decision of sewage solids-wood processing temperature for biochar production will depend on a number of factors. Key among these will be the optimal operating parameters for commercial pyrolysis or gasification kiln – which will relate to process stability and syngas quality as well as biochar quality.

5.0 General Soil and Plant Responses to Biochar

5.1 All Biochar Types

Jien and Wang (2013) applied 2.5% woody biochar (~50 t/ha when incorporated into top 15 cm of the soil) to a highly weathered, acidic Taiwanese soil. The application improved all measured soil parameters, physical, chemical and biological properties, such as pH (3.95 to 4.65), cation exchange capacity (7.41 cmol(+) /kg to 9.26), base saturation (6.4% to 14.2), bulk density (1.42 t/ha to 1.15), microbial biomass (835 mg/kg to 977), porosity (41.0% to 51.0), saturated hydraulic conductivity (16.7 cm/h to 30.0) and soil erosion rate (1458 g/m²*h to 730). They also tested 5% biochar application rate (~100 t/ha), which further improved soil parameters.

Typically, high soil application rates are necessary to improve soil physical properties, such as water holding capacity or bulk density, i.e. >40 t/ha (Omondi et al., 2016). In specific cases, however, lower biochar application rates (~10 t/ha) have been shown to improve physical soil properties (Herath et al., 2013; Mukherjee et al. 2014).

5.2 Wood (Pine) Biochar

In Gao et al. (2016) pine biochar applied at 20 t/ha increased nutrient retention and available nutrients significantly. Yet, in other studies, pine biochar did not appear to help P sorption when applied at 15 and 30 t/ha (Soenne et al., 2014). In Paramashivam et al. (2016), pine biochar was able to reduce the leaching of ammonia but not nitrate. However, accelerated ageing of softwood biochar in soil through composting (prior to application) can result in changes in biochar surfaces and very efficient NO₃⁻ sorption capacity (Hagemann et al., 2017). Pure pine biochar has a low nutrient content and, in most cases, a low cation exchange capacity and hence, pine biochar application by itself for agronomic purposes might not be particularly beneficial according to Domingues et al., 2017. However, pine biochar can be enriched with nutrients to significantly increase its agronomic properties (Buss et al., 2019a). Blending woody-biomass with nutrient-rich sewage sludge (biochar) should achieve comparable effects.

5.3 Sewage Sludge Biochar

Biochar produced from sewage sludges collected from several Victorian wastewater treatment plants had high concentrations of P (0.43-5.9%) with a low available P content (~1% of the total P as predicted using Olsen testing), a moderate to high pH (7-8), ash contents of 55-75%, a medium N (0.13-3%) and low K content (0.2-0.8%) (Yang et al., 2018). In two studies it was concluded that sewage sludge biochar could not provide sufficient K for crop growth when applied as a sole fertiliser (Faria et al., 2017; Sousa and Figueiredo, 2016).

In some cases, sewage sludge biochar increased the cation exchange capacity of poor soil and reduced the leaching of nutrients, such as phosphate, nitrate, ammonium and potassium (Faria et al., 2017; Méndez et al., 2013; Sousa and Figueiredo, 2016). Sewage sludge biochar can also increase the pH of acidic soil (Buss et al., 2018b). Although sewage sludge biochar has shown to increase available water content in some studies (Dokht et al., 2017; Méndez et al., 2013), in a meta-analysis, it did not increase the available water capacity, in contrast to woody and crop residue biochar (Omondi et al., 2016). Overall, sewage sludge biochar can be a good source of P to plants (Faria et al., 2017; Rehman et al., 2018; Sousa and Figueiredo, 2016). Sewage sludge biochar can also sorb further nutrients from wastewater and subsequently be applied to soil to increase plant growth (Carey et al., 2015; Shepherd, 2016).

6.0 Soil and Plant Responses to Biochar in Forestry

6.1 All Biochar Types

Thomas and Gale (2015) performed a meta-analysis pooling all biochar studies related to effects of tree growth at that time. It showed that biochar, on average, increased tree growth by 41% in studies conducted in pots and in the field over 49 to 1460 days. In a majority of the investigated studies woody biochar was applied and the application rates were between 4 t/ha and 60% in soil (~1,800 t/ha). The biggest effects were seen at early growth stages of trees, in boreal and tropical forests (rather than temperate forests) and were more pronounced in angiosperms (rather than conifers). The different response of coniferous trees vs. angiosperms is likely related to adaptations of coniferous trees to poor soils with low nutrient supply and pH, hence more hardiness in regard to soil constraints.

The author's explanation for the different response of different ecosystem is the level of P in soil and biochar's ability to improve the P status, which typically limits productivity in boreal and tropical soils. Many Australian soils are P limited and therefore, P-rich biochar could be ideal for promoting tree growth in these silviculture systems. In the review by Thomas and Gale (2015), the authors suggest the application of a high-ash biochar (such as sewage sludge) for nutrient provision and pH increase.

In a review by Li et al. (2018), the effects of different biochars on forest ecosystems and soil properties were investigated. Many forest plantations have poor soil health, in particular the physical soil structure is deteriorated (Li et al., 2018). Biochars can increase soil physical properties, such as the soil's aggregate stability, bulk density, porosity and water holding capacity, however, it's still not fully understood as to which biochar works best in each system. Biochar generally increase the pH of soil which is particularly important for pine plantations, which are often acidic (Dai et al., 2017). Biochars can also increase the cation exchange capacity which is often low in degraded forest soils (Li et al., 2018).

6.2 Wood (Pine) Biochar

Scharenbroch et al. (2013) applied pine biochar (550-600°C) to three different soil types (pure sand, silt loam, compacted clay) as a topdressing application of 25 t/ha and monitored two tree species (*A. saccharum* Marsh and *G. Triacanthos*) over 18 months. The average across both tree species and three soil types showed greater leaf, root and stem biomass than the control; overall 44% across both plant species. However, the paper does not propose a mechanism by which the biochar might improve growth and from the data presented only the organic carbon content of the soil was increased. Pine biochar is able to increase soil pH, which can increase the fertility, in particular of acidic soils (Gao et al., 2016; Schulz and Glaser, 2012).

6.3 Sewage Sludge Biochar

Sewage sludge biochar was applied at 40 t/ha to 10 weeks old eucalyptus seedlings (4 replicates) that were grown for 8 weeks in a slightly acidic soil with pH of 5.8 (Silva et al., 2017). The sewage sludge biochar (450-650°C) with a pH of 7.5 and 25.6% ash content significantly increased the chlorophyll content of the seedlings, the plant height, the stem diameter and shoot and root biomass. The shoot weight between the biochar treatments with and without NPK treatments did not differ significantly. Biochar + NPK fertiliser increased the shoot biomass by ~58% compared to the NPK only control, while the pure biochar increased the shoot biomass by 500% compared to the unfertilised control.

6.4 Expected Plant Response in ACT Forests

Considering the P limitation of Australian soils and acidity of pine plantation soils, there is a good chance of positive growth effects due to pH increase and better P supply after the application of biochar. However, the actual effects on plant growth and pine yield are difficult to predict since no long-term studies could be found in this literature review.

7.0 Soil and Plant Responses to Biochar on Degraded Land

7.1 All Biochar Types

Degraded soils are often marked by a weak physical and chemical soil structure, high erosion rates, low water infiltration and low concentrations of available nutrients (Jien and Wang, 2013; Lal, 2015; Stavi, 2012). Biochar can remediate degraded and/or contaminated land and encourage revegetation. Many biochars can sorb heavy metals and organic contaminants in soil and decrease plant uptake (Beesley et al., 2011; Buss et al., 2012). Biochar also adds carbon to degraded soil, which can help reduce nutrient leaching and increase water holding capacity.

Biochar can help to establish vegetation on sites affected by contamination due to mining, e.g. bauxite-processing residue. Several studies conducted in Australia have shown that high application rates (5%, ~85 t/ha) of pine biochar and aged, acidic eucalyptus biochar can improve soil properties and plant growth in bauxite-affected sand, respectively (M. Rezaei Rashti et al., 2019; Mehran Rezaei Rashti et al., 2019a, 2019b).

7.2 Sewage Sludge Biochar

Sewage sludge biochar is nutrient-rich and hence, adds another dimension of soil improvement in degraded soil i.e. the direct supply of nutrients. An application of 2.5 t/ha sewage sludge biochar significantly increased ryegrass growth, the biomass yield was comparable to the treatment with conventional fertiliser (Wang et al., 2012). Ryegrass plants grown in the 2.5 t/ha biochar treatment took up more P than the plants grown in 200 kg/ha conventional P fertiliser.

Yue et al. (2017) added sewage sludge biochar at 1-50% by volume to a very poor soil (soil organic carbon 0.3%) with high pH (8.40) and elevated levels of heavy metals. Grass growth increased by 70% from 2.54 g/m² in the control to 4.30 g/m² with an application rate of 1% biochar. Application of 50% biochar even increased the growth by 128%. Overall, the concentrations of heavy metals in the plants grown in biochar-amended soil were lower than in the control plants in most cases. The authors hypothesise that this may be due to an increase in P and K supply and decreased heavy metal uptake.

7.3 Expected Plant Response in Degraded Land in the ACT

Woody (and straw) biochar at high application rates (>40 t/ha) can certainly increase soil physical (water availability) and chemical properties (pH, cation exchange capacity) of degraded soil with low organic matter content and poor physical structure. It is less certain, what the effect of lower, more realistic application rates will be on soil water availability in particular, e.g. 10-20 t/ha. Though the evidence suggests that these application rates can also improve soil properties and hence plant growth to some extent. Sewage sludge biochar is an ideal source of nutrients and also has the ability to improve some soil properties.

8.0 Carbon Sequestration Methodologies Associated with Biochar in Australia and other Jurisdictions

Australian Carbon Credit Units (ACCUs) are awarded by the Clean Energy Regulatory (CER) for projects that comply with provisions set out under relevant Carbon Farming Initiative (CFI) legislation, including the *Carbon Credits (Carbon Farming Initiative) Act 2011* (the Act) and the relevant Emissions Reduction Fund (ERF) method determination.

The Commonwealth has established contracts with registered projects to purchase ACCUs generated under this Act via the \$2.55 billion Emission Reduction Fund (ERF). The Morrison Government recently committed a further \$2 billion to the ERF (which will be renamed the Climate Solutions Fund³). There is also a strong secondary (non-Government) market for carbon credits which ACCUs can be sold into.

There is currently only one soil carbon methodology; namely the *Carbon Credits (Carbon Farming Initiative— Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology 2018* (Department of Energy and Environment (DoEE) Australian Government, 2018). However, this methodology excludes biochar derived soil carbon from earning ACCUs.

Hence, a new methodology would need to be developed for biochar, or this methodology would need to be updated to allow biochar. This would likely be a 2-3 year process which the ACT Government or Water Utilities could chose to sponsor in collaboration with the DoEE. AECOM is able to support such a process.

The simplest approach for establishing a methodology quickly may be to focus on stable carbon in biochar. The stable carbon in biochar is relatively easy to measure and this literature review has found a wealth of supporting evidence for the stability of this carbon in soil.

However, the greater promise in terms of large quantities of ACCUs relates to negative priming and life cycle emission reductions.

Biochar projects may involve a number of “eligible management activities” that the Soil Carbon Sequestration Methodology (Part 2—Soil carbon projects, Section 7: Soil carbon projects) already recognises as likely to increase soil carbon. These include:

- 2 (i) applying nutrients to the land in the form of a synthetic or non-synthetic fertiliser to address a material deficiency;
- (ii) applying lime to remediate acid soils;
- (ii) applying gypsum to remediate sodic or magnesic soils; and
- 2 (xi) using mechanical means to add or redistribute soil through the soil profile.

Such changes, in combination with biochar application, may achieve significant increases in biotic soil carbon. Hence, it may be desirable to have this recognised and to earn the associated ACCUs.

It may be possible to develop a methodology for the biochar and to separately use the Soil Carbon Methodology for any additional soil carbon generated. However, at present the soil carbon methodology does not apply to forestry projects – so this would only apply to broad acre agricultural systems.

A methodology awarding ACCUs for the GHG emissions avoided over the life cycle of a sewage-solids and woody-biomass biochar project would, by necessity, be specific to the business implementing the project and the business as usual scenarios for both the sewage solids and the woody-biomass.

³ <https://www.abc.net.au/news/rural/2019-03-03/govt-climate-initiatives-see-some-agribusinesses-flourish/10849462>

9.0 Biochar Trial Proposals

This section outlines three trials to prove the value of biochar in different agronomic applications, namely:

- Horticulture (plant production at nurseries and use in potting mix);
- Silviculture (softwood plantations for timber production); and
- Broad acre agriculture (improved pasture establishment).

Of these three markets horticulture and potting mixes is easily the highest value. Biochar can potentially earn wholesale prices of \$50-200/tonne when blended into commercial potting mixes.

Silviculture is the lowest risk market that can safely accommodate the biochar trial, operating in highly disturbed environments, with minimal exposure to humans directly or indirectly (via food production and consumption). Softwood timber production is a relatively low-value industry in terms of income generated per hectare per year. However, it produces products that are valued by our society eg saw logs and structural timber for building frames as well as paper and cardboard. These products are produced as sustainably as possible and are unlikely to become redundant in the foreseeable future.

The Softwood timber plantations operated by ACT Parks and Conservation, EPSDD, are sufficiently large to use all the biochar that Icon Water could generate from its sewage solids. This provides a market with a single customer that is regulated by a single jurisdiction – further reducing project transaction costs and risks.

Many agricultural soils in the greater Canberra region including the Central and Southern Tablelands, Monaro and Upper South West Slopes of New South Wales have depleted soil carbon levels and low pH due to land clearing and past agricultural practices. Generally, these agricultural lands are more productive and more intensive managed than areas under forestry, with higher inputs and outputs per hectare per year.

Biochar application may help improve the health and productivity of these agricultural soils. This is the largest potential market in the region (by area) with the greatest potential for additional carbon sequestration.

9.1 Manufacturing the Biochar

Before biochar trials can be conducted sufficient biochar needs to be manufactured. Ideally this biochar should be manufactured from feedstocks as similar as possible to those which will be used in the long term. The biochar should also be manufactured to specifications that match a future pyrolysis or gasification kiln.

To this this end Icon Water engaged AECOM in June 2019 to undertake a review of the suppliers of pyrolysis and gasification equipment in Australia and internationally as well as conduct market sounding for the production of biochar to supply the trials outlined in this report. The following project outlines do not incorporate the findings of this review and market sounding.

9.1.1 Characterising the Biochar

Once the biochar is made it needs to be characterised. Minimum parameters of interest include:

- macro and micro nutrients (N, P, K, Ca, Mg, S, Si, B).
- pH and salinity (pH, EC, Na).
- heavy metal as listed in the NSW EPA biosolids regulations (Cu, Zn, Pb, Cr, Ni).
- contaminants of concern as listed under the Environmental Investigation levels (Total Polychlorinated Biphenyls, Total Organochlorine Pesticides, Total Phenolic Compounds, Total Polynuclear Aromatic Hydrocarbons, Total Petroleum Hydrocarbons, Total Recoverable Hydrocarbons, BTEX & Naphthalene).
- Total carbon content and stable carbon (elemental/ultimate analysis and thermogravimetric/proximate analysis).

A minimum of three samples of each batch of biochar will be required.

9.1.2 PFAS Destruction

A parallel study could be undertaken where the sewage solids are blended with the more common per- and poly-fluoroalkyl substances, also known as PFASs in particular perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). Sewage solids would be blended with PFAS at concentrations consistent with the highest levels that have been found in Australian biosolids eg 0.4 mg/kg for PFOS and 0.05 mg/kg for PFOA⁴.

Likely compounds to include in the spiking may include:

1. Perfluorooctane sulfonate (PFOS);
2. Perfluorooctanoic acid (PFOA);
3. 6:2 Fluorotelomer sulfonic acid; and
4. 8:2 Fluorotelomer sulfonic acid.

The sewage solids could then be pyrolysed at a range of realistic temperatures, say 500°C, 600°C, 700°C and 800°C and tested for remaining concentrations of PFAS.

Alternatively, sewerage solids could be sourced from a wastewater utility already has PFAS contaminated sewage solids. This has the benefit of the PFSA being more weathered and will be more representative of real-world conditions⁵.

If this PFAS project is undertaken when the biochar is being made it should not greatly increase the cost of the main project (less than 10% increase in project cost).

9.2 Regulatory Engagement

Further consultation is required with the Environmental Protection Authority (the statutory authority under the *Environment Protection Act 1997*) and the Waste Manager (the statutory authority under the *Waste Management and Resource Recovery Act 2016*) to ensure appropriate approvals are granted for the trials. This consultation should also seek to determine what would be the requirements for any future commercial process.

Additionally, consultation should be progressed with the NSW EPA such that the trials provide sufficient data to inform a future resource recovery exemption under the *Protection of the Environment Operations (Waste) Regulation 2014* (NSW).

9.3 Carbon Sequestration Methodology

The following trials are designed such that they should provide enough data to inform a carbon sequestration methodology for biochar use. However, it does not outline the process to establish a carbon sequestration methodology with the DoEE.

AECOM is willing to work with stakeholders to develop such a proposal; however, it was beyond the scope of this study.

⁴ Australian and New Zealand Biosolids Partnership – Assessment of Emergent Contaminants in Biosolids, September 2017. <https://www.biosolids.com.au/wp-content/uploads/Emerging-Contaminants-in-Biosolids-Research-report.pdf>

⁵ Personal communication with Ross McFarland, AECOM Chief Scientist, July 2019.

10.0 Expanded Nursery Trials

Based on our research to date, blending biochar into potting mixes is likely to be the highest value market for biochar. Biochar can potentially earn wholesale prices of \$50-200/tonne when blended into commercial potting mixes. Furthermore, in most Australian cities, the market for potting mixes and landscaping composts is closer to where the sewage solids are generated compared to forestry and broad acre agriculture.

AECOM, Icon Water, Fairtiliser and the CSIRO undertook a trial at Yarralumla nursery using Dwarf Abelia (*Abelia x grandiflora*) over 2018-19. This trial had 10 plants per treatment and showed no significant impact in growth rates from the addition of biochar or amino acids demonstrating that the traditional expensive potting mix can successfully be substituted with 5% and 10% sewage sludge/wood biochar. However, each sample group had highly variable results. Hence it has been concluded that larger sample sizes are required for any future study.

10.1 Hypothesis

1. Biochar can be used in potting mixes to replace traditional soil density and drainage modifiers (such as vermiculite & perlite) and fertiliser (P in particular) without adverse effects:
 - a. in low P potting mixes;
 - b. in high P potting mixes;
 - c. in low P potting mixes with the addition of amino acids; and
 - d. in high P potting mixes with the addition of amino acids.
2. Biochar will remain stable in the potting mix and hence can be credited as a long-term form of carbon sequestration.

Category	Trial details (or options)	Responsible party
Production systems	Commercial nursery	TCCS Yarralumla Nursery
Species	Pittosporum 'Green Pillar' (High P). Pittosporum tenuifolium 'Silver sheen' (High P). Rosmarinus officinalis (High P). Pinus radiata (High P) Correa glabra (Low P) Grevillea lanigera 'Mt. Tamboritha' (Low P)	TCCS Yarralumla Nursery
Biochar application rate	0%, 5% and 10%	Provided by research project
Other inputs (optional)	Amino acids – watered into half of the plants at the time of potting	TCCS Yarralumla Nursery staff
Biochar incorporation method	Blended into the potting mix prior to potting. Resulting potting mix corrected for consistent N,P,K in all samples	TCCS Yarralumla Nursery staff or Martins Fertiliser (overseen by research provider)
Number of repetitions	100 of each treatment (minimum)	Pots to be labelled individually
Plot size	Not applicable	Locations within nursery to be determined by TCCS Yarralumla Nursery staff in consultation with the research provider
Timing	September and October	TCCS Yarralumla Nursery

Category	Trial details (or options)	Responsible party
Trial length	Up to 6 months. Data collection in Nov-Dec prior to first pruning and then in Feb-March prior to second pruning. Destructive testing of at least 10 plants to determine root biomass – probably in Feb-March.	Research Provider
Data collection	Soil characterisation (before and after biochar application) and potentially plant nutrient analysis	Research provider (with in-kind support from TCCS Yarralumla Nursery staff to collect and move pots)
Biochar required (minimum)		
Key subcontractors		CSIRO

11.0 Forestry Trials

Silviculture is the lowest risk market, operating in highly disturbed environments, with minimal exposure to humans directly or indirectly (via food production and consumption). Softwood timber production is a relatively low-value industry in terms of income generated per hectare per year. However, it produces products that are valued by our society e.g. structural timber, paper and cardboard. These products need to be produced as sustainably as possible and are unlikely to become redundant in the foreseeable future.

The softwood timber plantations operated by ACT Parks and Conservation, EPSDD, are sufficiently large to use all the biochar that Icon Water could generate from its sewage solids. This provides a market with a single customer that is regulated by a single jurisdiction – further reducing project transaction costs and risks.

11.1 Hypothesis

1. Biochar application can improve pine seedling establishment in the capital region.
2. Biochar application can improve biomass yields in the capital region pine plantations.
3. Biochar can safely sequester carbon in the capital region's forestry properties:
 - a. Biochar will remain stable in the soil & can be credited as long-term form of carbon sequestration; and
 - b. Biochar will promote natural soil organic carbon establishment enabling long term carbon sequestration.

Category	Trial details (or options)	Responsible party
Production systems	Silviculture for structural timber and pulp.	ACT Parks and Conservation-Forestry
Species	Pinus radiata	Sown by ACT Parks and Conservation – Forestry contractors
Biochar application rate	0,5,10,20 tonnes per hectare	Provided by research project
Other inputs (optional)	Liming Gypsum Deep ripping Macronutrients Micronutrients	ACT Parks and Conservation-Forestry to determine
Biochar incorporation method	Top dress and plough in (twin disc plough set at between 10-25 cm)	Contractors (overseen ACT Parks and Conservation's Forestry team)
Number of repetitions	Three of each treatment	Sites to be marked with metal stakes, caps and notes by research provider
Plot size	20 x 50 m (0.1 ha) 110 pine seedlings per block	Locations agreed between research provider and ACT Parks and Conservation - Forestry
Total area (minimum)	1.2 ha (4 treatments x 3 repetitions)	
Timing	Soil preparation in January to May Planting in June-July	To be determined in discussions with ACT Parks and Conservation - Forestry and their contractors.
Trial length	12-24 months for stage 1. Potentially continuing up to harvest (at around 30 years)	Research provider & ACT Parks and Conservation- Forestry.

Category	Trial details (or options)	Responsible party
Data collection	Soil characterisation (before and after biochar application) Options Height & colour Hyperspectral imaging (via drone) of biomass yield and health ⁶	Research provider & ACT Parks and Conservation - Forestry)
Biochar required (minimum)	For three application rates and three repetitions.	

⁶ Initial quote for hyperspectral images was over \$100,000. AECOM is seeking an MOU with the ARC training centre for CubeSats, UAVs and their application (CUAVA) for access to their drones, cameras, software and a PhD student such that this can be delivered more cheaply.

12.0 Farm Restoration Demonstrations

Many agricultural soils in the in greater Canberra region including the Central and Southern Tablelands, Monaro and Upper South West Slopes of New South Wales have depleted soil carbon levels and low pH due to land clearing and past agricultural practices. Generally, these agricultural lands are more productive and more intensive managed than areas under forestry, with higher inputs and outputs per hectare per year.

Biochar application may help improve the health and productivity of these agricultural soils. This is the largest potential market in the region (by area) with the greatest potential for additional carbon sequestration.

12.1 Hypothesis

1. Biochar application can improve fodder crop and pasture establishment in the capital region.
2. Biochar application can improve fodder and pasture yields in the capital region.
3. Biochar can safely sequester carbon in the capital region's agricultural soils:
 - a. Biochar will remain stable in the soil & can be counted as long term form of carbon sequestration; and
 - b. Biochar will promote natural soil organic carbon establishment enabling long term carbon sequestration.

Category	Trial details (or options)	Responsible party
Production systems	Improved pasture (for grazing or hay production)	Land holder
Species	Options: <ul style="list-style-type: none"> • Oats then improved pasture establishment • Brassica then improved pasture establishment • Improved pasture establishment 	Sown by contractor
Biochar application rate	0, 5, 10, 20 tonnes per hectare	Provided by research project
Other inputs (optional)	Options: <ul style="list-style-type: none"> • Liming • Gypsum • Deep ripping • Macronutrients • Micronutrients 	Land holder in consultation with research provider and ACT NRM team
Biochar incorporation method	Options: <ul style="list-style-type: none"> • Deep rip and fill rip lines • Top dress and irrigate • Top dress and plough in (twin disc plough set at between 10-25 cm) • Direct drill into soil 	Contractors (overseen by land holder and ACT NRM team)
Number of repetitions	Three of each treatment	Sites to be marked with metal stakes, caps and notes
Plot size	20 x 50 m (0.1 ha)	
Total area (minimum)	1.2 ha (4 treatments x 3 repetitions)	

Category	Trial details (or options)	Responsible party
Timing	<ul style="list-style-type: none"> Autumn sowing (fodder crops) Autumn or early winter (improved pasture establishment e.g. phalaris) 	To be determined in discussions with landholder and contractors.
Trial length	6-24 months	Research provider (farmer agreement required)
Data collection	Soil characterisation (before and after biochar application) Dry mater yield Hyperspectral imaging (via drone)	Research provider (overseen by ACT NRM team)
Biochar required (minimum)	For 3 application rates and three repetitions	

13.0 Conclusion

Making biochar from local sewage solids and woody-biomass has the potential to reduce the ACT's GHG emissions, progress the circular economy and deliver triple bottom line benefits to the Territory. There is a wealth of scientific literature that demonstrates that biochar could improve soil health and productivity in the Canberra region as well as sequestering carbon. However, the literature reports widely variable outcomes and the actual results in the ACT context are difficult to predict with any certainty.

The uncertainty around biochars' field performance in combination with the immaturity of pyrolysis and gasification technologies for processing these materials creates significant commercial, technical and regulatory risks for any biochar project in the ACT.

There is a clear case for Government investment in pyrolysis/gasification and biochar demonstrations to reduce the barriers to this technology as it offers significant public goods, particularly in the area of climate change adaptation and mitigation.

This report outlines a number of steps that the ACT Government, Icon Water and other interested stakeholders could undertake to prove the markets for biochar and reduce the risks associated with Australian wastewater utilities establishing commercial biochar projects.

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Appendix A

Yarralumla Nursery Trial

Appendix A: Yarralumla Nursery Trial

Note: This abstract supported a presentation by Mr Bruce Edgerton and Dr Joel Edwards at the AWA/ANZBP Biosolids National Conference, Brisbane, 21-22 February 2019.

Pyrolysis and Gasification of Biosolids and Woody-Wastes – Barriers and Opportunities

Bruce Edgerton ¹, Dr Joel Edwards ², Nathan Wells³, Ben Bryant ², Dr Anton Wasson⁴, Dr Wolfram Buss⁵

1. AECOM Australia, Canberra, ACT, Australia
2. Icon Water, Canberra, ACT, Australia
3. Yarralumla Nursery, a business unit of TCCS, ACT Government, Australia
4. CSIRO, Black Mountain, ACT, Australia
5. Australian National University, ACT, Australia

KEYWORDS

Pyrolysis, gasification, biochar, regulation, resource recovery exemptions

EXECUTIVE SUMMARY

AECOM is working with Icon Water to assess the use of pyrolysis or gasification to process biosolids into value-added products, particularly biochar and renewable energy.

Thermal processing has advantages over biological processes such as composting and anaerobic digestion. These include complete pathogen destruction and superior destruction or removal of a range of chemicals of concern such as pharmaceuticals and PFAS (per- and poly-fluoroalkyl substances).

Significant regulatory, financial and technical challenges exist to commercialising this approach. This paper explores some of these challenges and opportunities and presents promising results from a biosolids-biochar pot-trial at Yarralumla Nursery, ACT.

INTRODUCTION

Thermal processing

Thermal processing of biosolids lost favour in Australia during the 1960s and 1970s. However, technological progress and changing policy frameworks have led AECOM and Icon Water to the view that thermal approaches deserve another look. In 2013 Icon Water co-sponsored Dr Jessica Shepherd to undertake PhD research into the production of biochar from sewage sludge at the UK Biochar Research Centre.

While thermal processing of biosolids can lead to a loss of nitrogen it does preserve phosphorous, potassium, calcium and most micronutrients for beneficial use in agriculture or horticulture. Furthermore, by turning wet, malodorous biosolids into a dry friable material, thermal processing makes transporting biosolids to market less carbon intensive and creates a more user-friendly product.

There are a number of next generation thermal processing technologies that have matured over the last 30 years including gasification, pyrolysis and plasma gasification. This research focuses on mid-temperature (450-700 deg C) pyrolysis and low temperature (800 to 1000 deg C) gasification to make agronomic biochars.

Biochar

Agronomic biochar is a form of charcoal made from biomass for use in agriculture or horticulture. Biochar can improve soil or potting mixes and promote plant growth. Biochars made from wood improve soil structure and increase water holding capacity. Biosolids provide macro and

micronutrients that woody-wastes generally lack. Blending woody-waste and biosolids prior to pyrolysis or gasification also ensures a positive energy balance, eliminating the need for an external energy source or fossil fuels usage.

A large proportion of the carbon in biochar is stable. This means it does not break down rapidly when added to soil. Hence, soil application of biochar can be considered a method of carbon sequestration. By contrast, biosolids and composts largely break down to carbon dioxide over the short to medium term and provide less long-term agronomic benefits than biochar.

Regulations

Land application of biosolids is subject to increasingly stringent regulations around pathogens and chemicals of concern such as pharmaceuticals, endocrine disrupters, microplastics and PFAS. Pyrolysis and gasification can achieve complete destruction of pathogens and superior destruction or volatilisation of most problematic compounds. However, regulators have indicated concern with air emissions from these processes even for small scale trials.

Presently, the NSW EPA has no general Resource Recovery Exemption and Resource Recovery Order for the application of biochar, derived from thermal treatment of biosolids, to land under the *Protection of the Environment Operation Act 1997* (NSW). However, biochar may be substituted for vermiculite or ash clinker in a product classified as a fertiliser under the *Fertilisers Act 1985* (NSW) if it is used in potting mixes.

Market Value

As a rough guide, sale of organic amendments (biosolids and manure) for use in broad-acre agriculture typically earn less than \$80/tonne and are often sold at a loss. Bagged compost products retail for \$400-

\$2,000/tonne while bulk nursery composts typically sell for \$30-\$300/tonne. Hence, moving from broad-acre agriculture to potting mixes for sale to nurseries and landscapers, or as a bagged product, can increase the value of biosolids by an order of magnitude.

METHODOLOGY

Biosolids, at approximately 30% total solids, were collected from stockpiles at Icon Water's Lower Molonglo Water Quality Control Centre on the western outskirts of Canberra. These biosolids (bulk density 820 g/L) were mixed with eucalyptus woodchips (220 g/L) in a 1:2 volume ratio, approximately 2:1 wet-mass basis.

A small 10 L RIVA batch kiln was used to produce the biochar. The RIVA unit is heated externally via LPG burners. The biosolids-woodchip mix was heated for approximately an hour at 350-450 deg C. The biochar was then quenched with water. Due to difficulties with the RIVA kiln, less biochar was produced than anticipated. However, there was enough biochar for 10 repetitions within each treatment.

The biochar properties were characterised by ALS Global (see **Table 1** below).

The biochar was blended with Yarralumla Nursery's standard potting mix on a volume basis. Half of the samples were watered in with an amino acid solution (AAS) that is designed to promote root growth. However, no AAS was added to the second set of controls. Hence, there were five treatments in total: control (no AAS); 5% biochar; 5% biochar (plus AAS); 10% biochar; 10% biochar (plus AAS). The level of controlled release fertiliser (CRF) in the biochar-potting mix blends was not adjusted to account for the nutrients in the biochar nor the displacement of CRF via the biochar addition.

Abelia x Grandiflora Nana (Dwarf Abelia) tubestock were added to each 140 mm (1.3 L) pot on 2 Nov 2018. Note: Dwarf Abelia plants are flowering shrubs that do not produce food or edible foliage. Dwarf Abelia are tolerant to high concentrations of phosphorus and were expected to demonstrate a strong response to nutrient levels.

Planting and ongoing care of the seedlings was provided by Yarralumla Nursery staff overseen by Nathan Wells.

Plant growth was measured on 20 December 2018 and again on 9 January 2019. The number of branches per plant, longest stem length, number of leaves on the longest stem and internodal length between these leaves was recorded at each of these times.

After the second set of onsite measurements the pots were taken to CSIRO Black Mountain Laboratories where total above ground and below ground biomass was measured by Dr Anton Wasson.

RESULTS/OUTCOMES

The results of the onsite measures are shown in **Figure 1**. The results of the biomass testing are shown in **Figure 2**.

Results indicate that neither the biochar, nor the combination of AAS and biochar, had a significant negative impact on the growth of the Dwarf Abelia over the 68 day trial. This gives confidence to Yarralumla Nursery to undertake larger trials (100 or more per treatment) with a broader range of species. Note that Yarralumla Nursery grows over 280 species and produces around 290,000 plants per year.

AECOM is now developing a larger research proposal in conjunction with Icon Water, the CSIRO, the ANU, and the ACT Government. This trial will likely incorporate some of the seedlings being planted to enable longitudinal studies of the impact of biochar and provide data to inform the development of a carbon sequestration methodology under the *Carbon Credits (Carbon Farming Initiative) Act 2011* (Cwth).

CONCLUSION

In collaboration with a number of Australian water utilities, AECOM is exploring opportunities to create value-added products from biosolids using pyrolysis or gasification. AECOM and Icon Water are supporting trials of biosolids-biochar at Yarralumla Nursery in the ACT to determine the agronomic value of this product within potting mixes as well as the carbon sequestration potential.

Initial trials show that potting mixes containing biosolids biochar perform as well as those without. Further, trials are proposed for 2019-2020 with more species and more repetitions. While this approach shows great promise, significant regulatory, financial and technical challenges exist to bring these opportunities to fruition.

Table 1: Biochar characterisation (average of three samples)

pH Value	Electrical Conductivity @ 25°C	Total Nitrogen as N	Fluoride Extractable P (Bray)	Organic Matter %	Total Organic Carbon %	Total Cr mg/kg	Total Ni mg/kg	Total Pb mg/kg
pH Unit	dS/m	mg/kg	mg/kg	%	%	mg/kg	mg/kg	mg/kg
7.5	1.61	8,000	26.3	7.8	4.5	18.0	10.0	12.3

Note: The biochar samples were analysed for the full suite of parameters required under “Health Investigation Levels – A (residential)” to ensure suitable product for use as residential soil. All results were below reportable levels including Total Polychlorinated Biphenyls, Total Organochlorine Pesticides, Total Phenolic Compounds, Total Poly Aromatic Hydrocarbons, Total Recoverable Hydrocarbons and BTEX.

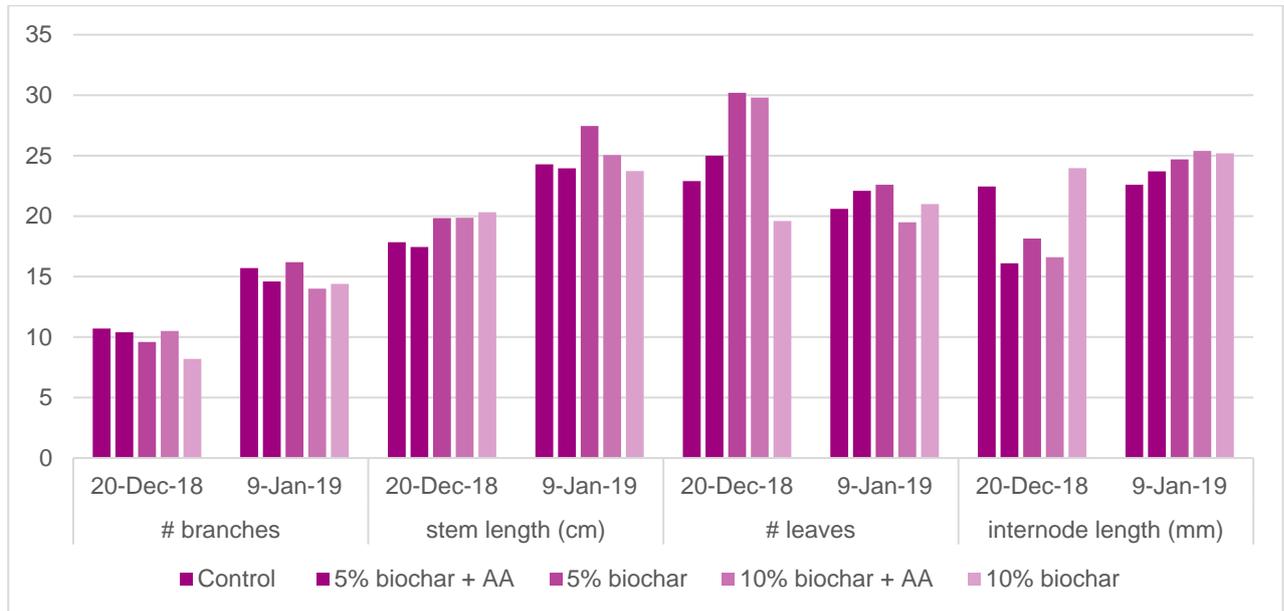


Figure 1: Dwarf Abelia plot trial results (average of 10 samples)

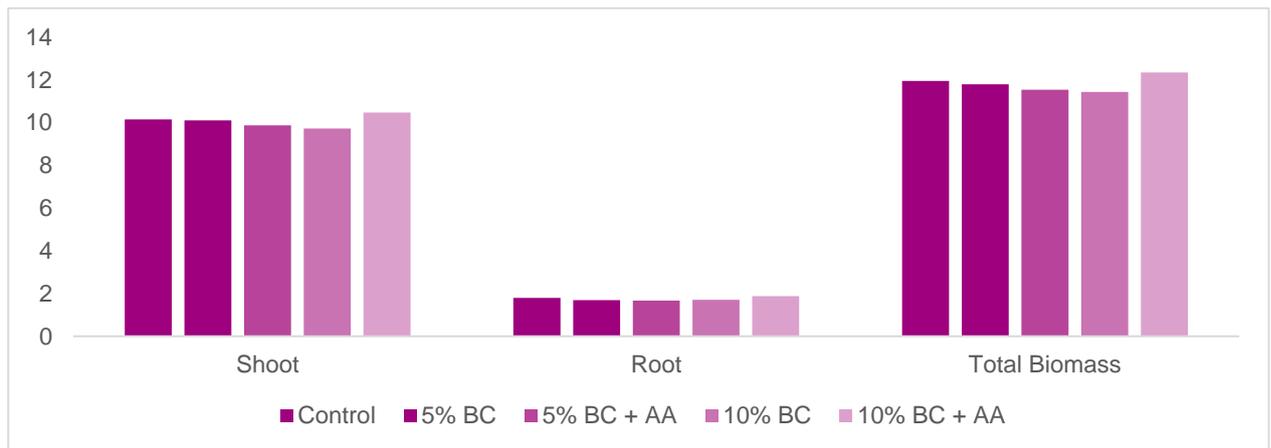


Figure 2: Average Dwarf Abelia shoot, root and total biomass (dry weight in grams)