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Technical Report

Loganholme Wastewater Treatment Plant:

Biosolids Gasification Demonstration Plant

(PBE-075)

March 2021

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Acronyms and Abbreviations

ARENA	Australia Renewable Energy Agency
BFP	Belt Filter Press
CEMS	Continuous Emission Monitoring Systems
CO	Carbon Monoxide
DM	Document management system
EA	Environmental Authority
EoW	End of waste Code
ESP	Electrostatic Precipitator
FTIR	Fourier Transform Infrared
HBCD	Hexabromocyclododecane
ID	Identification
LCC	Logan City Council
MJ	Megajoules
Mg(OH)2	Magnesium Hydroxide
NATA	National Association of Testing Authorities
NEMP	National Environmental Management Plan
NPV	Net Present Value
NOx	Nitrogen Oxide
O_2	Oxygen
OWT	Online waste tracking
PBDE	Polybrominated diphenyl esters
PFAS	Per- and poly-fluoroalkyl substances
PFFA	Total perfluoro alkyl acids
PFHxS	Perfluorohexane sulfonate
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
POEO	Protection of the environment policies
POPs	Persistent organic pollutants
SOx	Oxidised sulfurs
STP	Sewage Treatment Plant
TOPA	Total oxidisable precursor analysis
VS	Volatile Solids
WAS	Waste Activated Sludge
WESP	Wet Electrostatic Precipitator
w/w	Weight per weight

Executive Summary

Logan City Council, via the Logan Water Partnership, conducted the *Loganholme Wastewater Treatment Plant (WWTP) Gasification Demonstration Plant* that illustrates how to treat biosolids with gasification to produce a more environmentally friendly product, called biochar, and renewable energy while reducing the operation and maintenance costs of treating biosolids.

Gasification or carbonisation of biosolids produces biochar that is classified as a Grade A product. Gasification of biosolids destroys persistent organic pollutants (POPs), micro-plastics, and nano-plastics, while retaining phosphorus in a plant-available form. The final biochar product is sterile, does not generate odours, is not subject to a restricted storage time before application, and is easier to handle than the current biosolids form. Biochar also reduces the volume of biosolids (dewatered sludge cake) by more than 90%, requiring fewer truck movements and significantly reducing disposal volumes and costs.

Logan Water developed an industry-first demonstration facility at Loganholme Wastewater Treatment Plant (WWTP) to confirm that the production of biochar from biosolids is viable technology and that associated waste streams can meet the environmental license requirements. The overall project is split into two stages:

1. Stage 1: Demonstration plant designed to showcase both the technology process of gasification on dewatered sludge and its reliability for incorporation into a WWTP to assist obtaining all relevant approvals for the full-scale gasification facility.

2. Stage 2: Full-scale gasification facility will process sludge dewatering, drying and gasification at the Loganholme WWTP, including centrifuges, paddle dryers and gasifiers.

To approve the construction of Stage 2, the demonstration plant had five key objectives to validate or measure:

1. Reliability: to demonstrate reliable operation of the facility (see Section 3: Reliability)

2. Air emissions: to measure the air emissions from the facility and confirm compliance with Queensland regulations (see Section 4: Air emissions)

3. Persistent organic pollutants (POPs): to measure the quality of the biochar product and confirm the destruction of POPs (see Section 5: Biosolids and biochar characterisation and Section 6: Emerging contaminates of concern)

4. Heat balance: to confirm the heat balance for an integrated drying facility (see Section 7: Heat balance)

5. Operating costs: to assess operating costs of the facility (see Section 8: Operating costs).

Biosolids were sourced from two WWTP in Victoria (Source 1 and Source 2) for the demonstration plant as the gasification system requires a biomass that is 90% dry. In the full-scale facility, biosolids will be dewatered through centrifuges and then dried through belt dryers before being treated in the gasifier. In the demonstration plant, the sourced biosolids were from WWTPs that have waste activated sludge (WAS) that has been dried to 90% weight per weight (w/w) and then transported to the Loganholme WWTP.

In total, 12 runs of the demonstration plant were completed between 22 January and 11 August 2020. This consisted of small 4–6 hour runs ramping up to runs that were over 100 hours. The gasification plant had over 450 hours of run time on two sources of biosolids, demonstrating its reliability.

Reliability

Reliability is a major requirement for incorporating a permanent biosolids gasification facility at Loganholme WWTP. Loganholme WWTP is Logan City Council's (LCC) largest WWTP. In the future, Beenleigh WWTP could be diverted to Loganholme WWTP, which would mean that the WWTP will treat over 97% of LCC's wastewater network. The reliability of the demonstration plant was tested over two 100-hour trial runs, successfully processing biochar, and producing heat energy throughout these periods. The trial runs complied with the air emission limits set by the Logan City Council Environmental Authority (EA) (EPPR00867913). However, the trial runs were not completed at full operational threshold, as detailed in Section 3; throughput was reduced to ensure compliance with the requirements of the EA.

Air emissions

The requirements of air emission regulations in relation to the demonstration plant relate to emissions from the 7.1m stack. The stack allowed the discharge air/gas to mix and disperse quickly into the atmosphere, as well as allowing sampling and measuring of the quality. Most of the footprint of the demonstration plant is used to purify the off gas/biogas produced and for heat recovery. The demonstration plant was required to adhere to strict conditions as part of the EA Condition LGN-A2.

Two types of air emissions were monitored:

1. Basic air emissions: monitored on a continuous basis by the continuous emission monitoring systems (CEMS) unit for every run, including parameters for oxygen (O_2), nitrous oxide (NOx), carbon monoxide (CO), and oxidised Sulphur's (SOx).

2. Full air emissions: monitored by specialist samplers and equipment at times to measure all parameters required by the EA, including particulates, heavy metals and emerging contaminates of concern, such as per- and poly-fluoroalkyl substances (PFAS).

In summary, the air emissions passed most of the limits when an external NATA-accredited laboratory analysed the results. The only exceedance of the limits was the particulates for the second 100-hour test when the throughput was increased.

The CEMS unit concluded that the demonstration plant was unreliable, with condensate causing blockages; therefore, an additional monitoring unit was used throughout the trial period. The data from this second CEMS unit shows that the air emissions can be controlled when dosing magnesium hydroxide (MgOH2) to control SOx in the air stream and urea to control NOx. The levels of CO and particulates that occurred with increased throughput required modifications to the throughput; however, these modifications introduced complications with particulates. Solutions have been identified and outlined in Section 6 to ensure this issue will be engineered out in the full-scale facility design.

Persistent organic pollutants

Persistent organic pollutants (POPs) were a major driver for this demonstration plant, with the inclusion of PFAS into the Queensland Department of Environment and Science's (DES) *End of Waste Code for Biosolids* (DES, 2020). In the *End of Waste Code for Biosolids*, target limits have been set for soil application. The measurement of other POPs, such as microplastics, are under consideration and it is anticipated they will also be incorporated in some form into the *End of Waste Code for Biosolids* (DES, 2020).

Both sources of dried biosolids came from Victoria and contained PFAS limits that would have triggered the limits set for soil application. On average, Source 1 dried biosolids had a concentration of 0.173 mg/kg of PFOS and PFHxS. Source 2 dried biosolids had a concentration of 0.367mg/kg of PFOS and PFHxS, on average. The biochar produced from the demonstration plant had a concentration of <0.005 mg/kg of PFOS and PFHxS on average or were non-detectable. This means that the dried biosolids had PFAS that would not meet soil trigger values and, once processed through the gasifier, the biochar did not contain any PFAS. This shows that through the gasification process, the PFAS compounds are made volatile and are then treated through the oxidation process.

Microplastics are an emerging contaminant of concern and were analysed as part of the demonstration plant. Source 1 dried biosolids contained 8.8 particles/gram, on average. Once processed through the gasifier, the

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biochar contained 3.3 particles/gram, or a 63% reduction of this contaminant. Source 2 dried biosolids contains 8.8 particle/gram on average. Once processed through the gasifier, the biochar contained 5.06 particles/gram, or a 43% reduction of this contaminant. This source material was small and dense because it was pelletised; however, in the full-scale facility design, the belt dryers will produce a more uniform crumb rather than a pellet. Therefore, it is expected that the destruction of microplastics will be greater when processed through the belt dryer than what was achieved with the Source 1 and Source 2 dried biosolids.

Heat balance

One of the main requirements of the demonstration plant trials was to confirm that sufficient heat could be produced for the permanent plant belt dryers. The heat recovery achieved was approximately 700kW at 85% of design rate, on the Source 2 dried biosolids. Scaling to 100% of the design rate (565 kg/hr) and 80% efficiency, the heat recovery is forecast to be greater than 1.1 MW, measured against a design requirement of 1 MW.

Operating costs

The main operational consumables and costs of the gasification facility include power, potable water, and chemical dosing. During the demonstration plant trials, the following consumables were monitored and optimised, where possible:

1. Chemical dosing for SOx control was initially via hydrated lime. Hydrated lime did not perform well and was replaced with $Mg(OH)_2$ The dosing locations and rates were optimised throughout the trials, with the optimal dosing rate was determined to be 0.4% of the weight of dried biosolids processed, or about 2.6 litres per tonne.

2. Chemical dosing for NOx control was via urea. The dosing locations and rates were optimised throughout the trials and the optimal dosing rate was determined to be around 20 litres per tonne.

3. Potable water and power usage were both as expected.

The demonstration plant confirmed that gasification of biosolids is a reliable process that can be incorporated into a WWTP. Each of the objectives set for the demonstration plant in terms of reliability, air emissions, persistent organic pollutants, heat balance and operating costs were achieved.

Therefore, it is recommended to proceed with the full-scale facility at Loganholme WWTP.

1.   Introduction

Biosolids treatment and disposal is a significant component of wastewater treatment plant operation and operating costs. In Australia, most biosolids are mechanically dewatered and disposed to land (land application) under programs aimed at 'beneficial re-use'. Biosolids are a source of organic material, nitrogen, and phosphorus; however, land application often requires dewatered biosolids to be transported long distances from metropolitan areas to farming areas. Transport is costly and impacts on communities via truck movements, fuel usage, fumes and odours, noise, and high greenhouse gas emissions.

In Queensland, land application of biosolids is regulated by the Department of Environment and Science (DES). The *End of Waste Code for Biosolids* (DES, 2020) require operators to meet stabilisation quality criteria and limits on land application uses and rates.

An emerging threat to existing practices of land application of biosolids is organic micro-pollutants and persistent organic pollutants (POPs). POPs are toxic chemicals that are not biodegradable and can accumulate up the food chain and within soils and within sludge produced by WWTP processes. Examples of POPs include polybrominated diphenyl esters (PBDEs), hexabromocyclododecane (HBCD), and perfluorooctanesulfonic acid (PFOS).

Another emerging issue for the land application of biosolids is microplastic and nanoplastic pollutants. These pollutants are shed during machine washing of certain fabrics such as those used to produce active wear. Plastic microfibres from the fabric enter the wastewater network. Where sewage is treated by activated sludge processes, the microfibres become enmeshed in the biosolids. These microfibres are not destroyed by anaerobic or aerobic digestion biosolid treatment processes. Consequently, there are concerns about the potential for these pollutants to enter the terrestrial food chain when biosolids are applied to land used for agricultural production.

While POPs and microplastic and nanoplastic pollutants are present in Australian biosolids, they are not listed as contaminants in Australian biosolids guidelines. In Europe, 50% of biosolids do not meet POPs limits set for land application. Switzerland and Germany have banned land application of biosolids, with incineration a more common practice of disposal (European Commission, 2008) (German Federal Environment Ministry, 2016). Many Australian biosolids would not meet the limits established in Europe. The Australian water industry is also not prepared for this threat to the land application of biosolids.

Logan City Council, via the Logan Water Partnership, has been investigating how to better treat biosolids to produce biochar a more environmentally friendly product, while reducing the operation and maintenance costs of treating biosolids. This work recommended treatment via gasification, with other upstream processes to obtain a biochar product and produce a renewable energy.

Thermally treating biosolids produces biochar, a Grade A pathogen product that meets the criteria set in the *End of Waste Code for Biosolids* (DES, 2020). Thermal treatment of biosolids destroys POPs, micro-plastics, and nano-plastics, while retaining phosphorus in a plant-available form. The final biochar product is sterile, does not generate odours, is not subject to a restricted storage time before application, and is easier to handle than the current biosolids form. Biochar also reduces the volume of biosolids (dewatered sludge cake) by more than 90%, requiring fewer truck movements and significantly reducing disposal volumes and costs.

Logan Water's industry-first demonstration plant confirmed that the production of biochar from biosolids is a viable technology and associated waste streams can meet the environmental regulations. Funding was made available for the Loganholme Wastewater Treatment Plant: Demonstration Biosolids Gasification Facility (demonstration plant) and the Loganholme WWTP Gasification Facility (full-scale).

1.1   Objectives

Five key objectives were set for the demonstration plant:

1. Reliability: to demonstrate reliable equipment operation

2. Air emissions: to measure the air emissions from the facility and confirm compliance with Queensland regulations

3. Persistent organic pollutants (POP): to measure the quality of the biochar product and confirm the destruction of POP

4. Heat balance: to confirm the heat balance for an integrated drying facility

5. Operating costs: to assess operating costs of the facility.

1.2   Components of the demonstration plant

Because the demonstration plant is a first of its kind in Australia, it was critical to demonstrate proof of concept using a sole supply of biosolids not a blend and therefore be able to move forward with the full-scale Loganholme WWTP Gasification facility.

The demonstration plant consists of eight key components that were part of Pyrocal's scope: dried biosolids feed system, hearth, biochar system, thermal oxidisers, heat recovery system, scrubber, air steam release and control room. Figure 1-1 illustrates these key components of the demonstration plant.
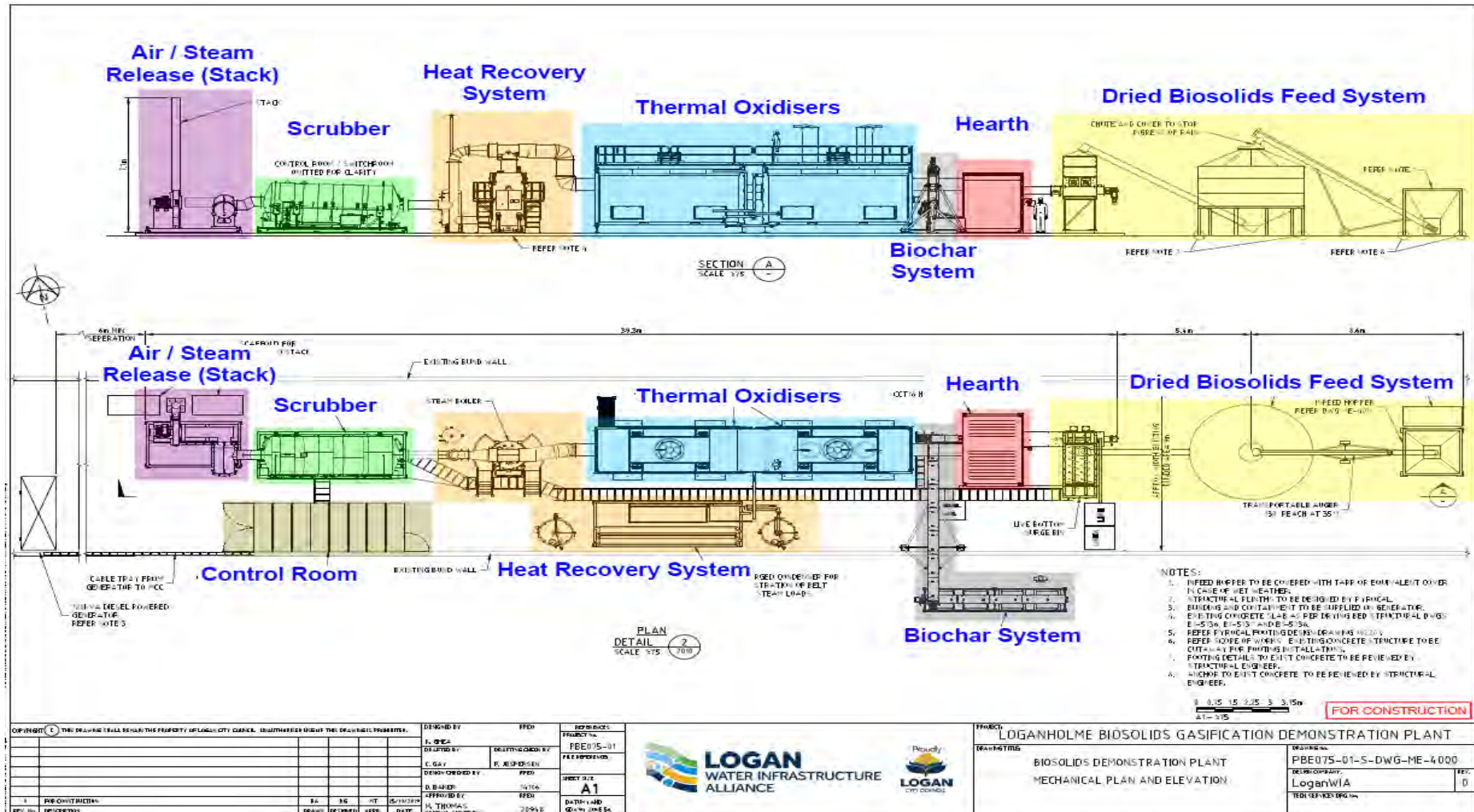
Figure 1-1: Key components of the Loganholme Wastewater Treatment Plant: Biosolids Gasification Demonstration Plant

2. Source of Biosolids

Biosolids were sourced from Victoria for the demonstration plant as the gasification hearth requires a biomass that is 90% dry. In the full-scale facility, biosolids will be dewatered through centrifuges and then dried through the belt dryers before being treated in the gasifier. In the demonstration plant, the sourced biosolids were from WWTPs that have waste-activated sludge (WAS) that has been dried to 90% w/w and then were transported to the Loganholme WWTP.

Two types of biosolids were processed in the demonstration plant. To de-identify the sources of these biosolids, throughout this chapter they are referred to as Source 1 and Source 2. This chapter details the biosolids from each source and outlines the approval process to move biosolids from Victoria to Queensland. The biochar produced that is available for beneficial reuse is also quantified.

Certain parameters of biosolids were required for the demonstration plant, as outlined in the Dryer Technology Review (LoganWIA, 2020; DT0007). These parameters include particle size, dust ratio, moisture content and volatile solids:

- The ideal particle size range for the carbonisation process gasifier unit is 3–10 mm

- Both regular and irregular particle shapes are acceptable

- Larger particles are also acceptable

- Concentration of fines/dust must comply with the specification for the carbonisation equipment that less than 2.5%, by mass, of dried particles must have an aerodynamic equivalent diameter below 3 mm.

2.1 Source 1 biosolids

The Source 1 facility uses a thermal sludge dryer to process waste. The sludge goes through a process of centrifuge, like the planned Loganholme WWTP full-scale design, through to a feed screw directly into the thermal dryer, which has a gas fired burner (up to 600 °C) that tumbles the product. The end-product is 90% dry biosolids. The biosolid are cooled in a water-cooled auger to 40°C.

However, the biosolids from Source 1 are processed through a third-party and the batch of ~60T received was several months old and had degraded with a lower calorific value of volatile solid (VS) around 73% and moisture content of 85% dry. The particle size was less than 5mm, and this meant that the hearth had to be retrofitted to receive smaller particles, which in turn affected the airflow. Figure 2-1 shows the Source 1 biosolids.

Figure 2-1: **Source 1 biosolids**

Although the batch that was received did not fit the specific design parameters for particle size set for the gasification unit, these biosolids were still able to be processed and provide assurance that the hearth can be adapted to fit the performance of the dryer units. This created confidence that although technical specifications for the dryer have been set, slight variations to particle size and distribution can be adapted so that the gasification unit can process slightly irregular material.

2.2   Source 2 biosolids

Source 2 biosolids uses a drum dryer to produce a biosolid pellet that is >88% dry. The sludge is dewatered through belt presses and then is brushed on a series of heated revolving turntables. The heat treatment kills all micro-organisms, resulting in a small, pelletised product that is safe to handle. As shown in Figure 2-2, the biosolids were pellet sizes of around 8–10 mm, with a VS 81% and greater than 90% dry.

Figure 2-2:   Source 2 biosolids—pelletised

The Source 2 biosolids granules were approximately ten times the size of the Source 1 biosolids. The size of the dry crumb produced by the belt dryers in the full-scale facility is expected to be between the size of the biosolids from Source 1 and Source 2, and similar to the Source 2 biosolids in terms of volatile solids and approximately 10% moisture. Table 2-1 shows the average calorific value of the biosolids from Source 2.

Table 2-1:   Average calorific value of biosolids from Source 2

Calorific value	Unit	Source 2
Net	MJ/kg dry matte (DM)	19.26
Gross	MJ/kg (calc)	2.23

2.3   Loganholme biosolids

In the full-scale facility design, strict criteria have been set for the dryers, outlined in the Dryer Technology Review (LoganWIA, 2020; DT0007) report. However, the Eliquo Stultz low-temperature dryer is the preferred supplier because it can produce the biosolid to 88% w/w solids at a particle size between 3–10mm. Also, a low- temperature dryer allows hot water to be used rather than thermal oil, providing improved efficiency in the heat–energy balance and reduced long-term operational costs. Because the process in the Loganholme gasification facility will be continuous (8000 hours per year), there will not be issues with the source material degrading during storage as it will be immediately transferred between the belt dryers and gasification unit.

As noted, the gasifier works optimally with biosolids ranging from 3–10mm due to the design of the rotating plates within the hearth and the ability to gain as much energy as possible from the sludge (greater than 70% volatile solids). The design has been optimised from paddle dryers to belt dryers due to the high dust fraction produced by paddle dryers.

The calorific value or net energy value of biosolids from Loganholme and Beenleigh WWTPs are shown in Table 2-2. This compares favourably with the calorific value of the biosolids from Source 2.

Table 2-2: Average calorific value of biosolids from Loganholme and Beenleigh WWTPs

Calorific value	Unit	Loganholme WWTP	Beenleigh WWTP
Net	MJ/kg dry matter (DM)	18.80	18.4
Gross	MJ/kg (calc)	2.25	2.20

2.4   Approvals process for movement of biosolids

Transporting biosolids from Victoria has a lengthy approvals process, which was heightened with the COVID-19 pandemic. Figure 2-3 provides an overview of the process.

Loganholme WWTP

Environmental approvals issued by Department of Environment and Science (DES) (Queensland Environmental Protection Agency).

Loganholme WWTP has an Environmental Approval (EA EPP00867913).

The environmental authority includes ERA633 to conduct wastewater activity.

The license includes the prescribed ERA61-Waste incineration and thermal treatment.

Under ERA61, Loganholme WWTP can accept regulated waste, such as biosolids.

Consignment Authority

Department of Science—Waste Track team issue consignment authorities for prescribed waste such as biosolids.

Movement of biosolids interstate requires a consignment authority.

The Waste Track team check that:

- the waste transporter holds the appropriate license to transport regulated waste
- the waste generator material is not going to cause environmental harm—for example they will check the biosolids' characteristics are within the PFAS NEMP 2.0
- the waste receiver (in this case Loganholme WWTP) is allowed to receive the waste.

Waste track then approves the consignment authority and LCC is issued with a consignment authorisation number.

Statutory Approval

Statutory Approval Document for the transport of waste from Victoria is issued by the Victorian EPA

LCC applies to the Victorian EPA for approval for the movement of prescribed industrial waste from Victoria (F1007), providing the Queensland DES Consignment Authority number

Victoria EPA provide an R26 Assessment Report—the assessment is based on the authority being satisfied that the proposed transport of the prescribed waste is for the purposes of reuse or recycling in accordance with the principal waste hierarchy

Victoria EPA then provide an approval for the movement of non-liquid prescribed industrial waste, issued to LCC.

Figure 2-3: Approvals process for transporting biosolids interstate

Until both approvals from Queensland DES and Victorian EPA were granted, the biosolids could not be moved between states. Because the biosolids moved through NSW, the NSW EPA was informed.

As NSW is only a transit state, NSW should be advised of the movement of trackable waste by the receiving jurisdiction when the consignment authorisation is generated. The NSW EPA waste tracking system (online waste tracking (OWT) system) is not used to track the waste. A waste transport certificate is used to track each load and would capture that the waste has passed through NSW as a transit state.

2.5   COVID-19

During the Phase 2 of the demonstration plant, when biosolids from Source 2 were tested, COVID-19 impacted the project, especially the freight component. Transporting biosolids from Victoria to Queensland became increasingly difficult from July, with several restrictions put in place. To transport freight from Victoria, the following documentation had to be obtained:

1. **NSW Border Pass:** NSW temporarily imposed border restrictions with Victoria. Only persons authorised under the Public Health Order could enter NSW if they had been in Victoria in the previous 14 days

2. **Queensland Border Pass:** Entry to Queensland was temporarily restricted under the Border Restrictions Direction. Personnel were only permitted to enter Queensland in accordance with the Border Restrictions Direction (No. 8), which required additional documentation and a completed Queensland Border Declaration Pass

3. **Letter of Exemption:** Letters of exemption were sent to the company transporting the biosolids stating that the transport of the material was an 'essential activity' as per the Queensland Border Directive No.8.

A journey plan was developed for each run of biosolids from Victoria and protocols were put in place at Loganholme WWTP to ensure minimum contact with drivers and written records of close contacts were maintained.

During this time, four runs of biosolids (160 t) were received at the Loganholme WWTP without issues or delays.

3. Reliability

The demonstration plant ran continuously for a series of shorter tests, including 6-hour, 24-hour and 48-hour tests, as well as two 100-hour tests. Stable reliability of the demonstration plant and the associated equipment was expected; however, some reliability issues were encountered.

During commissioning, a number of issues were experienced, and some modifications were required to optimise the operation to match the dried biosolids that were being used for testing, including modifications to cater for the different properties of the biosolids received from the two sources.

Table 3-1 outlines the reliability lessons learned, the implications for the permanent biosolids gasification facility and the modifications undertaken in the preparation phase and during the demonstration plant trials.

Table 3-1: **Plant performance and operations and lessons learnt**

Component/performance parameter	Findings	Implications for the permanent biosolids gasification facility
Bulk feed handling	Bulk handling via a modified grain silo was abandoned early in the trials due to blockages. A steeper-angled transfer hopper was found to be more suitable. Dust release during the transfer of biosolids to the feed metering system was a concern to consider for the permanent plant.	Control of fugitive dust release in the bulk feed handling systems will need to be minimised and managed. Minimising product handling and storage is a constraint of the design, to reduce the generation of fines in the feed. Handling and road transport of biosolids over 3000 km for the demonstration plant trial increased the dust fraction in the already partly degraded material.
Particle size	Source 1: particle size <5 mm Source 2: particle size 8–10 mm	The gasification unit can process particle sizes that vary against the optimum range of 3–7 mm. It does require a change to the hearth and can affect the heat exchange, but the process is robust enough to accommodate changes in particle size and, therefore, reduces the risk for the belt dryers to meet this requirement 100% of the time.
Oxidisers	The demonstration plant has two oxidisers to increase the retention time as part of destruction of POPs such as PFAS. To determine if the two oxidisers were necessary, air emissions were measured between the oxidisers, which proved that the second oxidiser was not necessary.	The second oxidiser was contributing more to heat loss than heat gain. As such, it provided additional residence time for the flue gases, but otherwise was not obviously performing a useful function.
Feed metering	The drop-out hatch burn-back prevention system proved to be unreliable (false trips) and was bypassed before the trials commenced. The feed metering system required minor modification to deal with the fine free-flowing biosolids that were initially used for the trials. Some logic changes were also required to alter the way the live bottom screws fed the metering screw, to avoid	Pyrocal has developed a new live bottom feed bin that uses a slow-moving agitator and metering flap, rather than multiple floor-mounted screws. This system also has a burn-back prevention arrangement that does not use a drop-out hatch. The system also includes online mass flow measurement.

	over filling. Once these changes were put in place, the feed system achieved a typical reliability of 98%. On rare occasions, the live bottom screws experienced over-torque protection events, causing temporary disruption to the feed and the need for operator intervention.	The revised system is being evaluated by Pyrocal, so that an optimised system is available for the permanent plant that incorporates all the lessons learned from this demonstration plant.
Hearth	Slagging, which is the partial or complete melting of ash species in contact with equipment surfaces, is of concern in the gasification, combustion, or incineration of fossil fuels, biomass, and wastes. Slags can cause fuel agglomeration, damaging ash deposits (e.g. clinker) or corrosion of equipment, which shortens the achievable run time between maintenance shutdowns. Pyrocal's rotary hearth and oxidiser are operated at temperatures well below the ash softening point for most feedstocks, typically 500–800 °C for the hearth and 750–900 °C for the oxidiser, relative to typical ash softening points of 1000–1400 °C. Where a feedstock has an exceptionally low ash softening point, the positive rotary action of the rake system in the hearth tends limit any the build-up. Flux agents, such as lime, are also used by Pyrocal to raise the ash softening point of problematic feeds, such as cotton gin trash. In the case of biosolids, lime dosing into the feed is used to control hot corrosion caused by the presence of Sulphur in the feed. Lime dosing also assists to raise the ash softening point, although the softening point is reported to be 980–1100 °C for sewage-derived biomass.	Fouling of duct work is a common concern for updraft gasifiers, as they are known to generate high concentrations of soot and tars (condensates with a condensation point as high as 400 °C). Pyrocal's systems use a close coupling between the hearth and the oxidiser, which ensures that the off-gas released from the hearth is maintained at temperatures exceeding 600 °C until they enter the oxidiser, where the tars are mixed with air and burned off at temperatures in the range of 750–900 °C and 2–4 seconds residence time. This leaves a hot flue gas that contains a moderate concentration of non-sticky carbon/ash dust to pass through to the downstream heat recovery system. This dust is periodically blown off heat exchange surfaces in a soot- blowing process. Soot and tar build-up in the hearth became apparent during the two longest test runs. This restricted the primary air manifolds, which significantly reduced the capacity of the equipment. The soot and tar build-up readily burned off during a pause in feed or shutdown. Inspections revealed that the hearth and associated equipment remained in good order throughout the tests. The dry crumb from the permanent plant is intended to have a median particle size greater than 6 mm, so that the feed is compatible with the standard hearth decks. For soot and tar build-up, the primary control measure will be to ensure that a hearth-operating temperature exceeding 600 °C is maintained. The permanent system will also include logic and a hearth primary air pressure sensor to detect fouling of the primary air manifolds, to enable a scheduled burn-off sequence to be triggered. The net result is expected to be 30 minutes of lost production every 50–80 hours.
Char Thermal combustion of char (4-day rule)	The char handling and quench system performed reliably for the duration of the tests, except for two incidents where the base of the char transfer conveyor flooded with quench fluid, causing char to float and back up. No quench failures or spontaneous combustion events were experienced during the trials.	Pyrocal's transfer conveyor design will be amended to ensure quench water flooding cannot occur in the permanent plant.
Radiant heat exchanger	The radiant heat exchanger in the shell of the thermal oxidiser removed excessive heat when the Source 1 biosolids were trialed. This exchanger performed according to design on the Source 2 biosolids feed and recovered approximately 360kW of heat at 85% of design rate. The design intent for this first	No changes are required for the permanent plant, as the desired 400 kW of recovery at the nominal design rate has been demonstrated.

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	stage heat recovery is 400 kW at a nominal design rate (565 kg/hr).	
Heat recovery steam boiler	The boiler performance was hindered by a relatively low inlet temperature (i.e. ~600 °C rather than the intended 800 °C and well below typical values of 1200 °C during conventional operation with a fossil fuel burner). In addition, fouling of the heat transfer surfaces was evident by the progressive increase in exhaust temperature from 205–300 °C during extended operation. This performance was typically restored via soot blowing operations, which could only be performed on shutdown or start-up. Hence, the typical heat recovery efficiency of this unit was 51–66% compared to an intended value of greater than 80%. Despite this, the heat recovery achieved by the boiler was approximately 700kW at 85% of design rate, on the Source 2 biosolids. Scaling to 100% of the design rate (565 kg/hr) and at 80% efficiency, the heat recovery is forecast to be greater than 1.1 MW, compared to a design requirement of 1 MW. Attempts to operate the system above 85% of the design feed rate led to the heat rejection system starting to reach capacity, which created condensate flow surging, resulting in signal noise in the heat recovery measurement.	The heat recovery steam generator will be replaced with a heat recovery water heating unit to better suit the requirements of the permanent plant. The proposed unit has in-built soot blowing arrangements (online compressed air type). The proposed heat exchanger is also designed to achieve a heat recovery exceeding 80% at the expected flue gas inlet temperatures (600–800 °C). Pyrocal recommends the addition of a downstream condensing heat exchanger (200 kW rating) to ensure that the overall heat recovery is achieved with a suitable design margin.
Scrubber	The absorption scrubber was upgraded with a venturi stage after the initial emissions tests, when it became apparent that the dust loads could not be catered for. This improved the emissions performance, at the expense of limiting the ID fan flow capacity by 15%, due to increased pressure differential. This directly impacted on the achievable feed rate of biosolids. As a result of very high dust loads, it was necessary to drain liquid from the scrubber, back into the treatment plant, on a continuous basis.	Pyrocal estimates that the PM10 and PM2.5 dust loading from the biosolids were four to ten-fold greater than that typical of plant derived biomass. Therefore, the permanent plant design has been amended to allow for a high pressure drop venturi and a downstream PM2.5 capture device (refer to the filter section in this table) and upgraded capacity ID fan.
Filter	The barrier type filter installed on the demonstration plant proved to be unsuitable as it fouled too rapidly in service.	Pyrocal recommends implementing a wet electrostatic precipitator (WESP) on the permanent unit, to cater for the high PM2.5 loads that the biosolids release into the flue gas. The benefit of this approach is improved reliability, lower operating costs and complexity compared to a barrier filter, as well as reduced ID fan pressure differential relative to barrier filters.

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Continuous Emissions Monitoring Systems (CEMS)	The online CEMS was installed as part of Pyrocal's scope. The unit that was installed by Aquagas was a MAMOS CEMS designed for online measurement of O, CO_2, SO_2, NO, NO_2. NOx and O_2 as well as stack gas temperature and velocity. However, this unit had several issues including blockages due to the high moisture content. The internal fix was to install a gravity head drain instead of the peristatic drain pump. This allowed a continuous monitoring, although this solution would not be suitable for the full-scale facility.	The appropriate CEMS monitoring system for this type of analysis would be an extractive system or Fourier Transform Infrared (FTIR). FTIRs can operate in a high moisture environment because every component of the system is heated above dew point, including the analyser itself; therefore, a condenser is not required. This recommendation is included in the scope of the full-scale facility.
Processing rate	The maximum processing rate achieved during the trials was 600 kg/hr. The absorption scrubber was upgraded with a venturi stage when it became apparent that the dust loads could not be catered for. This improved the emissions performance at the expense of increased pressure differential and reduced fan flow capacity. This addition of the venturi directly impacted on the achievable feed rate of biosolids.	Modifications to the thermal oxidiser and upgrading of the ID fan pressure and low capacity are planned to ensure that a capacity of 650 kg/hr is achievable.
Particulates	Venturi was added after running 2 of the full air emissions to mitigate particulates. When the threshold was increased, the venturi and fans could not cope and increased the particulates in the air stream. Another run was planned for September with the addition of a cyclone and modified oxidiser. This is so that the threshold can be optimised at the same time to obtain reliable results on dosing and chemical rates while still being within the limits set for air emissions and particulates.	In the full-scale facility, the issues surrounding the particulates has been engineered out with the inclusion of an ESP into Pyrocal's scope. An ESP is a filtration device that removes fine particles, like dust and smoke, from a flowing gas using the force of an induced electrostatic charge, minimally impeding the flow of gases through the unit.
Carbon monoxide (CO) Carbon monoxide exceedances related to particulates	The performance with respect to carbon monoxide slip vs excess O_2 and visual inspection of the swirl pattern suggested that turbulent mixing was less than desired. Therefore, a swirl vane was installed at the oxidiser inlet and a directional nozzle implemented for the secondary air inlet. This reduced the carbon monoxide slip; however, it was evident that further reduction in short circuiting was necessary as higher feed rates were required.	It is proposed to include a deflector baffle before the oxidiser outlet to reduce the ability for flue gas to short circuit from the inlet to outlet. Improved turbulence in the oxidiser is expected to reduce the residual oxygen concentration required to achieve the desired destruction in the thermal oxidiser. This will, in turn, reduce the necessary ID fan flow demand. Both solutions worked in the October trial and will be replicated on the full-scale facility.

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4. Air Emissions

4.1 Background

The air emissions from the gasification plant will be substantially less than a typical incineration plant because the carbonisation process is not destroying 100% of the mass, but rather removing the volatile fraction and treating that fraction, while carbonising the non-volatile fraction. The volatile fraction represents 40–60% of the total dry mass. Consequently, imposing best practice emission limits for incinerators on the plant for the demonstration plant was sufficient to protect environmental values while actual release data is gathered.

The gas residence time and temperature in the thermal oxidiser is 2 seconds at 800–850 °C. This residence time and temperature has been demonstrated in previous tests on a range of biomasses, sufficient to exceed 99% destruction of the organic matter presented to the oxidiser. The percentage destruction or alteration of halogenated species is not known and measuring this percentage was an objective of the demonstration plant.

After the thermal oxidiser, the next air emission control unit is a venturi through to a wet scrubber. The scrubber is a spray absorber with extended residence time for particulate-seeded condensation capture of the PM10 fraction. This allows rapid quenching of the gas to avoid the dioxin reformation temperature range. The gas/liquid contact allows acid gases and other species to be physically or chemically captured (Bouzaza, Laplanche, & Marsteau, 2003). Fine mist that carries over in the exit gas is captured in a wire mesh mist eliminator and recirculated to the scrubber sump.

The accumulated solids from the scrubber are discharged to the biochar from the carbonisation stage, to perform the quench duty. This results in no liquid emissions from the system.

In the first phases of the trial, lime was added to the biosolids feed and to the scrubber as many of the potential air pollutants can be are sequestered as calcium salts. This includes acid gas species such as HCl, HF, H_2SO_4, metals such as Hg, As, Cd, Pb, Zn, Cu and Cr and many of the halogenated species (Busca & Pistarino, 2003) (Dias, Alvim-Ferraz, Almeida , Rivera-Utrilla, & Sanchez-Polo, 2007) (Kailiva & Smith, 1983).

A change to Mg (OH)2 was made (5/05/2020) for the SOx control because although the lime dosing can hold the SOx concentration at around 30–150 mg/Nm³ (not oxygen corrected). The lime contributes to fouling in the wet scrubber, so it is prudent not to dose any more than necessary to protect the steel in the hot zones. Therefore, it was determined to use Mg (OH)2 dosing at the wet scrubber for mitigating SOx in the air emissions. The results are shown in Section 4.6.

In the original design, a moisture-tolerant, 5-micron-pleated filter element (barrier filter) followed the scrubber and captured the residual PM5 matter before the flue gases were drawn into an induced draft fan and discharged to the atmosphere. Experience proves that the action of the scrubber to remove the bulk of the particulate matter allows the barrier filter to be used without incurring impractical service intervals.

However, the Source 2 biosolids were extremely dusty materials and demonstrated that although the filters worked, they would have to be cleaned more often than expected compared to other types of materials processed through the gasification facility. Therefore, the filter element was removed, and a venturi device added at the entrance of the scrubber (12/05/2020). This configuration was used for all tests after this date, including the 100-hour reliability runs.

4.2 Regulation requirements

The regulation requirements mostly relate to the environmental harm perceived from the air emissions via the stack. Therefore, when designing the full-scale facility, 75% of the facility will be focused on purifying the biogas produced, with the dual purpose of measuring the heat recovery. The demonstration plant was run under strict conditions imposed as part of the Environmental Authority (EA) (EPPR00867913) Condition LGN-A2: Contaminants must only be released from the Biosolids Gasification Demonstration Plant to air via point release sources in accordance with Table 4—Point Source Air Release Limits and associated monitoring requirements.

Table 4-1 is the point source air release limits set for the demonstration plant.

Table 4-1:   Point source air release limits for the demonstration plant

Contaminant	NSW EPA Protection of the environment policies (POEO) Regulation (see Note 2)	European Commission (2000/76/EC) (see Note 3)	Target limits for the demonstration plant
Total solid particulate	50 mg/Nm^3 (dry)	30 mg/Nm^3 (dry)	30 mg/Nm^3 (dry) at 11% O$_2$
Carbon monoxide (CO)	125 mg/Nm^3 (dry)	-	125 mg/Nm^3 (dry) 11% O$_2$
Oxides of nitrogen as NO$_2$	350 mg/Nm^3 (dry)	400 mg/Nm^3 (dry)	400 mg/Nm^3 (dry) at 11% O$_2$
Sulphur dioxide (SO$_2$)	-	200 mg/Nm^3 (dry)	200 mg/Nm^3 (dry) at 11% O$_2$
Hydrogen chloride (HCl)	-	60 mg/Nm^3 (dry)	60 mg/Nm^3 (dry) at 11 % O$_2$
Total fluoride (as HF)	50 mg/Nm^3 (dry)	4 mg/Nm^3 (dry)	4 mg/Nm^3 (dry) at 11 % O$_2$
Total volatile organic compounds	20 mg/Nm^3 (dry)	20 mg/Nm^3 (dry)	20 mg/Nm^3 (dry) at 11% O$_2$
Cadmium and its compounds	0.2 mg/Nm^3 (dry)	0.05 mg/Nm^3 (dry)	0.05 mg/Nm^3 (dry) at 11% O$_2$
Mercury and its compounds	0.2 mg/Nm^3 (dry)	0.05 mg/Nm^3 (dry)	0.05 mg/Nm^3 (dry) at 11% O$_2$
Total heavy metals (see Note 1)	1 mg/Nm^3 (dry)	0.5 mg/Nm^3 (dry)	0.5 mg/Nm^3 (dry) at 11% O$_2$
Dioxins and furans (I-TEQ for PCDDs and PCDFs, including half LOD)	0.1 ng/Sm^3 (dry) at 11% O$_2$	0.1 ng/Sm^3 (dry)	0.1 ng I-TEQ/Nm3 (dry) at 11 % O$_2$
Polycyclic aromatic hydrocarbons (PAH)	-	-	-
PFAS extended suite containing 28 compounds (see Note 4)	-	-	-

Table notes:

Note 1: Total heavy metals limit is for the total of antimony, arsenic, cadmium, lead, mercury, beryllium, chromium, cobalt, manganese, nickel, selenium, and vanadium and their compounds.

Note 2: The concentrations limits for solid waste incineration refer to 7% O$_2$, except dioxins that refers to 11% O$_2$.

Note 3: All concentrations limits (100% compliance) refer to 11% O$_2$ reference level and average over the sample period of 30 minutes.

Note 4: The samples should be analysed to quantify the PFAS, by applying the total oxidisable precursor analysis (TOPA), to analyse the PFAS extended suite of 28 compounds. To determine PFAS concentrations, at least the PFAS extended suite containing 28 compounds should be analysed from the following sources:

- sewage sludge used in the demonstration plant

- stack emissions during the selected demonstration plant where emissions are expected to be maximum.

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4.3   Status of air pollution control equipment used for the demonstration plant

The online CEMS was installed as part of Pyrocal's scope. The unit installed by Aquagas was a MAMOS CEMS designed for online measurement of O, CO_2, SO_2, NO, NO_2. NOx and O_2 as well as stack gas temperature and velocity. However, this unit had several issues including blockages due to the high moisture content and a gravity-head drain in place of the peristatic drain pump. This allowed continuous monitoring, although labour intensive and would not be suitable for the full-scale facility.

The appropriate CEMS monitoring system for this type of analysis would be an extractive system or FTIR as both systems can withstand a high-moisture environment because every component of the system is heated above dew point, including the analyser; therefore, a condenser is not required. This approach is included in the scope of the full-scale facility.

4.4   Stack emission results

Two types of air emissions analysis were undertaken for the demonstration plant:

1. Basic air emissions: This analysis is performed by the CEMS unit for every run and including parameters: O_2, NOx, CO, and SOx. All data is stored, but a summary is in Section 4.6.

2. Full air emissions: This analysis includes all parameters including particulates, heavy metals and emerging contaminates of concern, such as PFAS. Three runs were performed, and a summary is in Section 4.6 and full reports supplied by Assured Environmental are included in Appendix D.

Stack monitoring was conducted by Assured Environmental, an external third party. This approach ensured that all air emission stack monitoring was conducted by an experienced provider holding current National Association of Testing Authorities (NATA) accreditation. Due to the CEMS unit having issues, for example blockages, some of the results for the continuous monitoring were also undertaken by Assured Environmental. This approach ensured that the demonstration plant was meeting all required parameters, not causing environmental harm, and meeting all conditions stipulated in the license to operate issued by DES.

4.5   Timeline

Table 4-2 lists of all the runs that were performed, and the analysis undertaken.

Table 4-2:   **Timeline of runs of the demonstration plant**

		Date	Comment
4–6-hour run			
Run 1	SOx, NOx, and heat balance	22/01/2020	CEMS unit
Run 2	SOx, NOx, and heat balance	04/03/2020	CEMS unit
Run 3	SOx, NOx, and heat balance	17/03/2020	CEMS unit
6-hour run			
Run 4	SOx, NOx, and heat balance	23/03/2020	CEMS unit
Run 5	SOx, NOx, and heat balance	02/04/2020	CEMS unit
Run 6	SOx, NOx, and heat balance	11/06/2020	CEMS unit
Run 7	SOx, NOx, and heat balance	11/08/2020	CEMS unit
24-hour run			
Run 8	SOx, NOx, and heat balance	10/08/2020	Assured Environmental
Run 9	Full air emissions, SOx, and NOx	02/04/2020	Assured Environmental—full air emissions data
48-hour run			
Run 10	SOx, NOx, and heat balance	21/07/2020	CEMS unit
100-hour run			
Run 11	Full air emissions, SOx, NOx, and heat balance	22/7/2020	Assured Environmental—full air emissions data
Run 12	SOx, NOx, and heat balance	27/07/2020	CEMS Unit supplied by Assured Environmental

4.6   Summary of continuous stack monitoring results.

Figure 4-1 to Figure 4-13 provide an overview of each of the runs performed. The data shown is the chemical parameters for the basic air emissions: NOx, SOx, and CO. Each run highlights the set limit in red.

This section presents the data from the online CEMS unit. As discussed, this unit had issues and was found not to be fit-for-purpose and therefore will be replaced for the full-scale facility; however, it does give an overall perspective of the range of each analyte: NOx, Sox and CO.

Figure 4-1 was one of the first runs completed using the Source 1 biosolids after the hearth had been fitted for the difference in the material size. However, this run was also completed when the throughput was not at full capacity; rather, it was gradually increased starting at 320kg/hour. This run illustrates that the gasification unit can meet the criteria set in the license limits.

With regards to start-up and shutdowns, there will be a spike in air emissions until the system is stable (~1 hour) and this should be factored for license limits. However, the full-scale facility is being designed to run with fewer shutdowns limiting the start-up and shutdowns and to integrate with the heat energy balance, keeping the continuous loop. Therefore, this spike would not be a daily occurrence, but rather once every few couple of weeks.
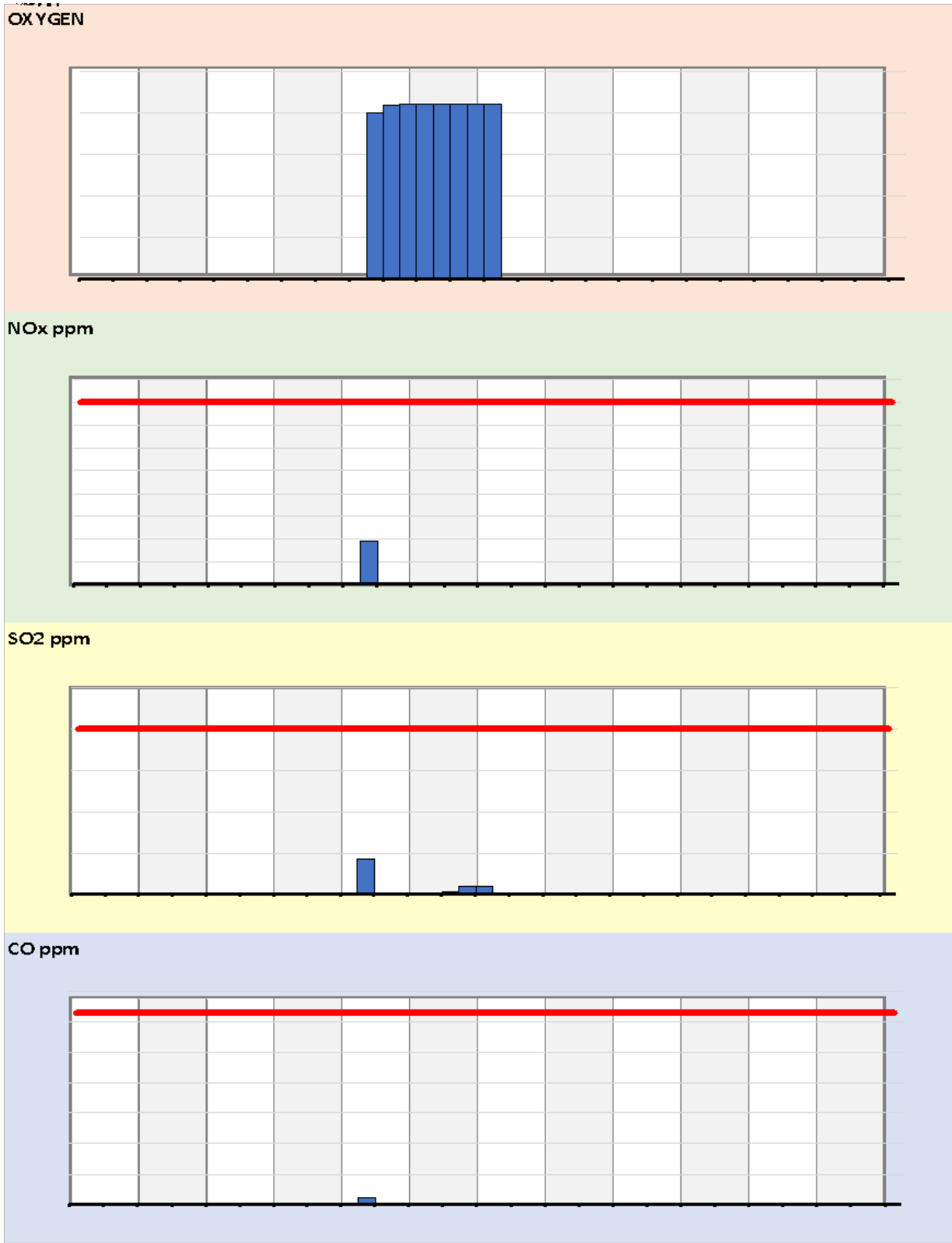
Figure 4-1: **Run 1: 4–6 hour run (22/01/2020)**

Run 2 (Figure 4-2) was completed using Source 1 biosolids and again illustrates that the license limits can be achieved on biosolids through a gasification system. There was an apparent spike in SOx concentration levels for this run; however, this was the result of a blockage in the CEMS unit.
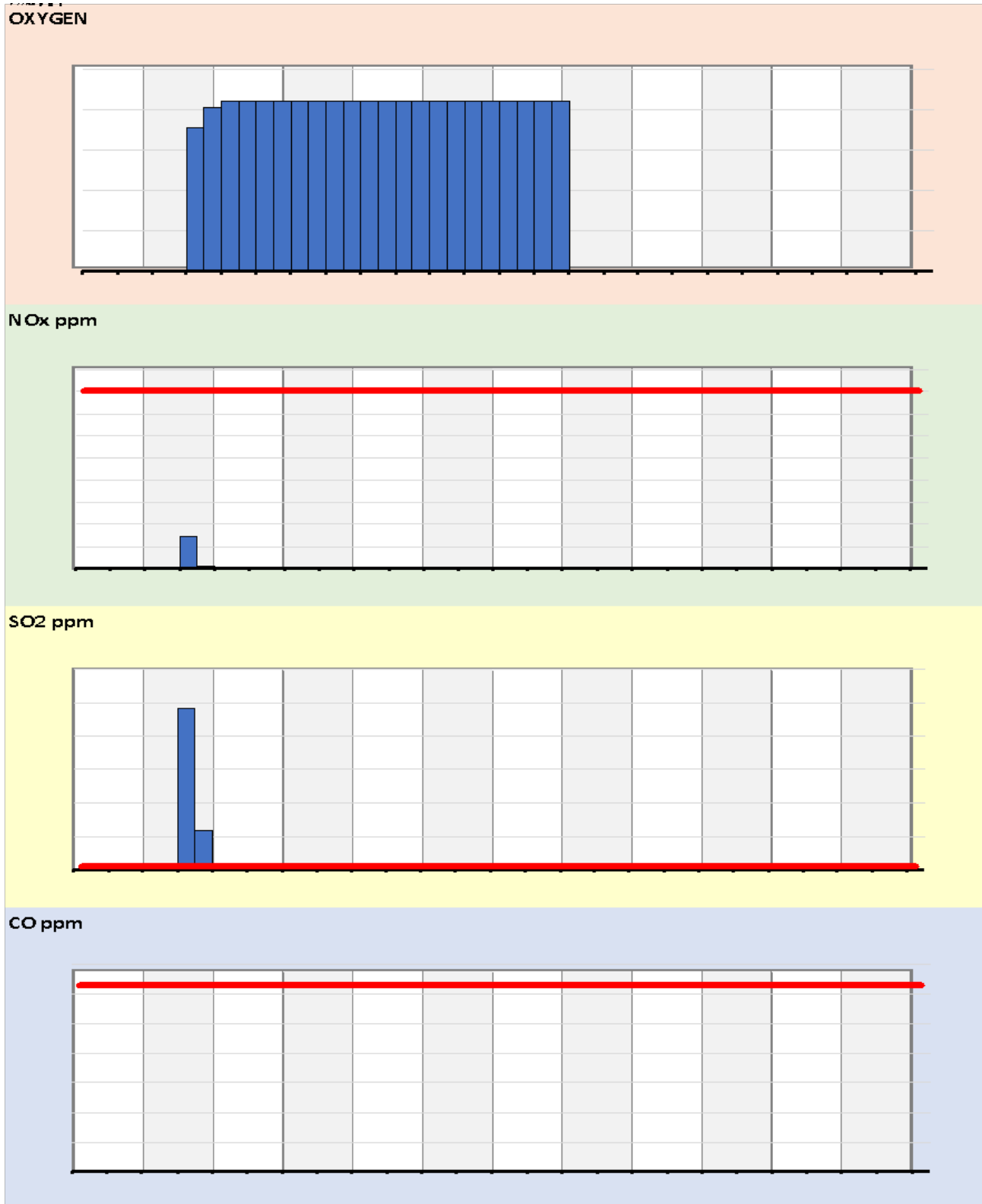
Figure 4-2: **Run 2: 4–6 hour run (04/03/2020)**

Run 3 (Figure 4-3) was completed using Source 1 biosolids and illustrates that the license limits can be achieved on biosolids through a gasification system. There was a spike in SOx, firstly on start-up, which is to be expected, and then an hour later, which was brought under control. This result is discussed in the lessons learnt in Table 3-1 and is one of the reasons for the change from lime dosing to MgOH because the lime dosing system consistently had blockages and was not the best agent for mitigating SOx.
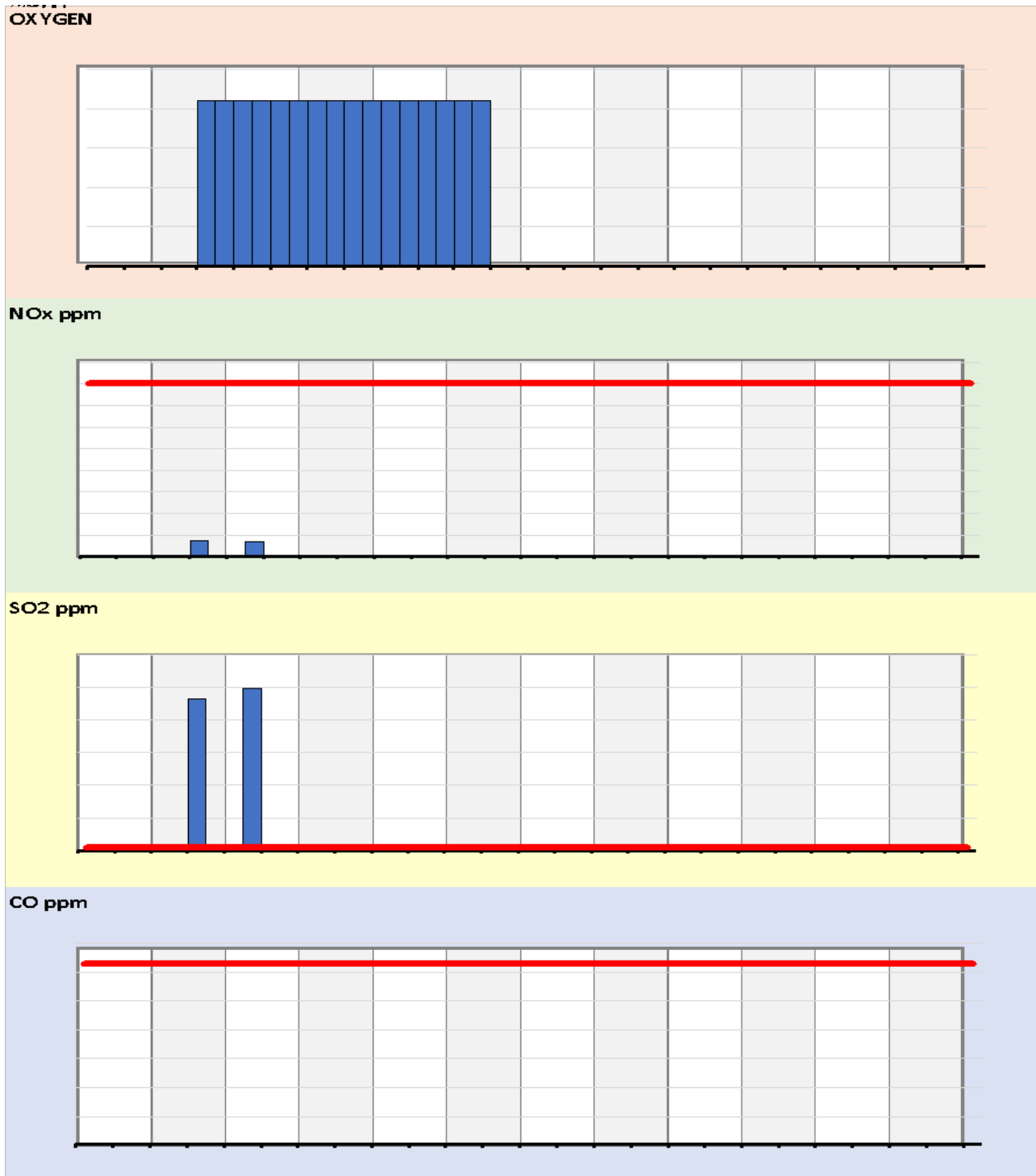
Figure 4-3:   Run 3: 4–6 hour run (17/03/2020)

The following data is from the four 6-hour runs and provides an overview of the early lessons learnt on the reliability of the demonstration plant.

Figure 4-4 demonstrates a typical run that occurred on the Source 1 biosolids with spikes in SOx but relatively low NOx and CO. The NOx levels were mostly due to the nature of the biosolids and because they had been stored for such a long period. Ammonia (NH_3) is oxidised, which promotes the simultaneous oxidation of NO to NO_2 (Leppaelahti, Simell, & Kurkela, 1991). If not controlled, this would result in an undesirable visible brownish colour of the plume from the stack. Another nitrogen species that can be present is di-nitrous oxide (N2O), which is a greenhouse gas. This run gave the indication that, for SOx mitigation, the chemical agent did need to be changed to MgOH.
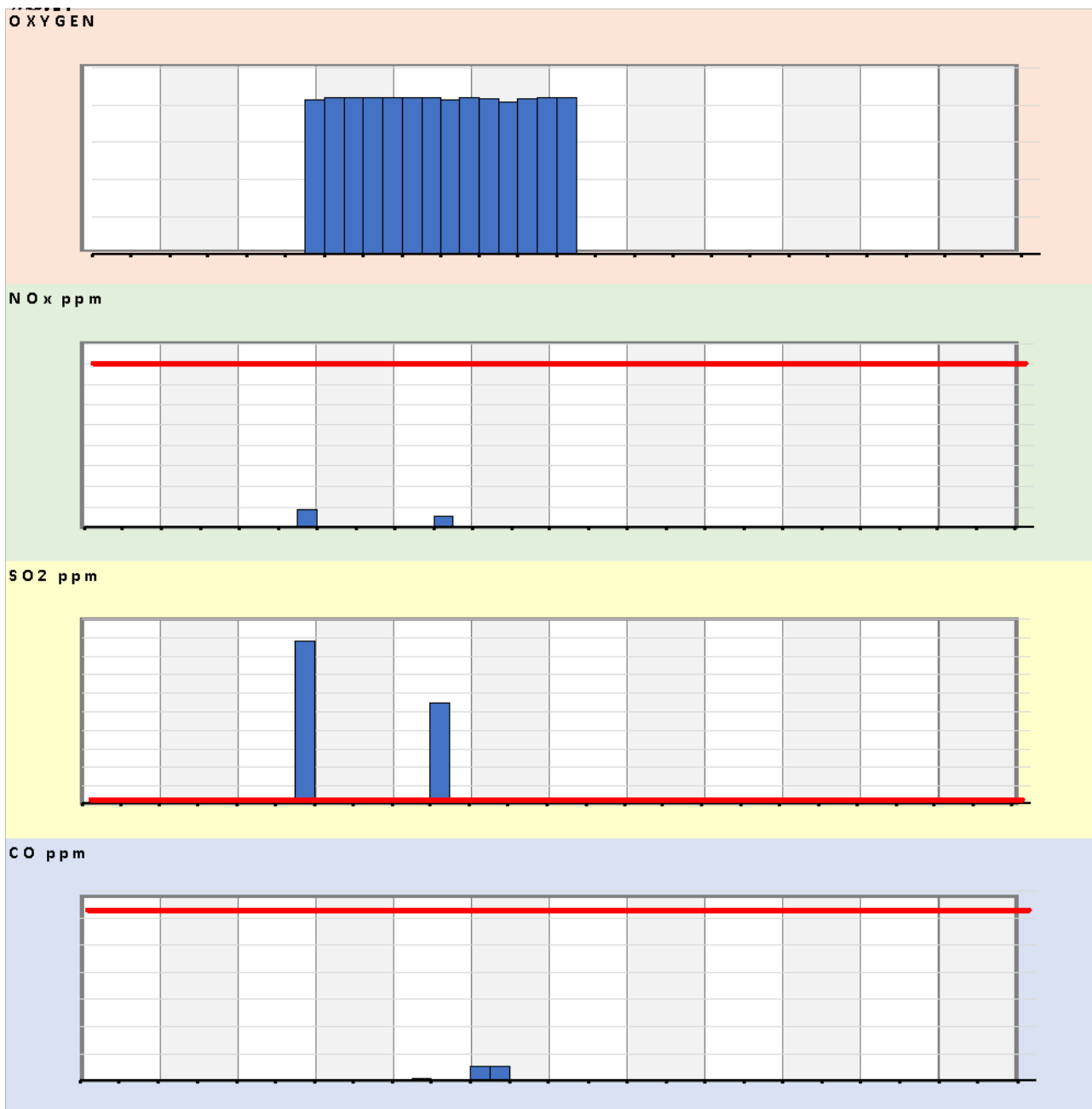
Figure 4-4: **Run 4: 6-hour run (23/03/2020)**

Run 5 (Figure 4-5) was completed using the Source 1 biosolids and the data reinforces the findings found in the previous runs.
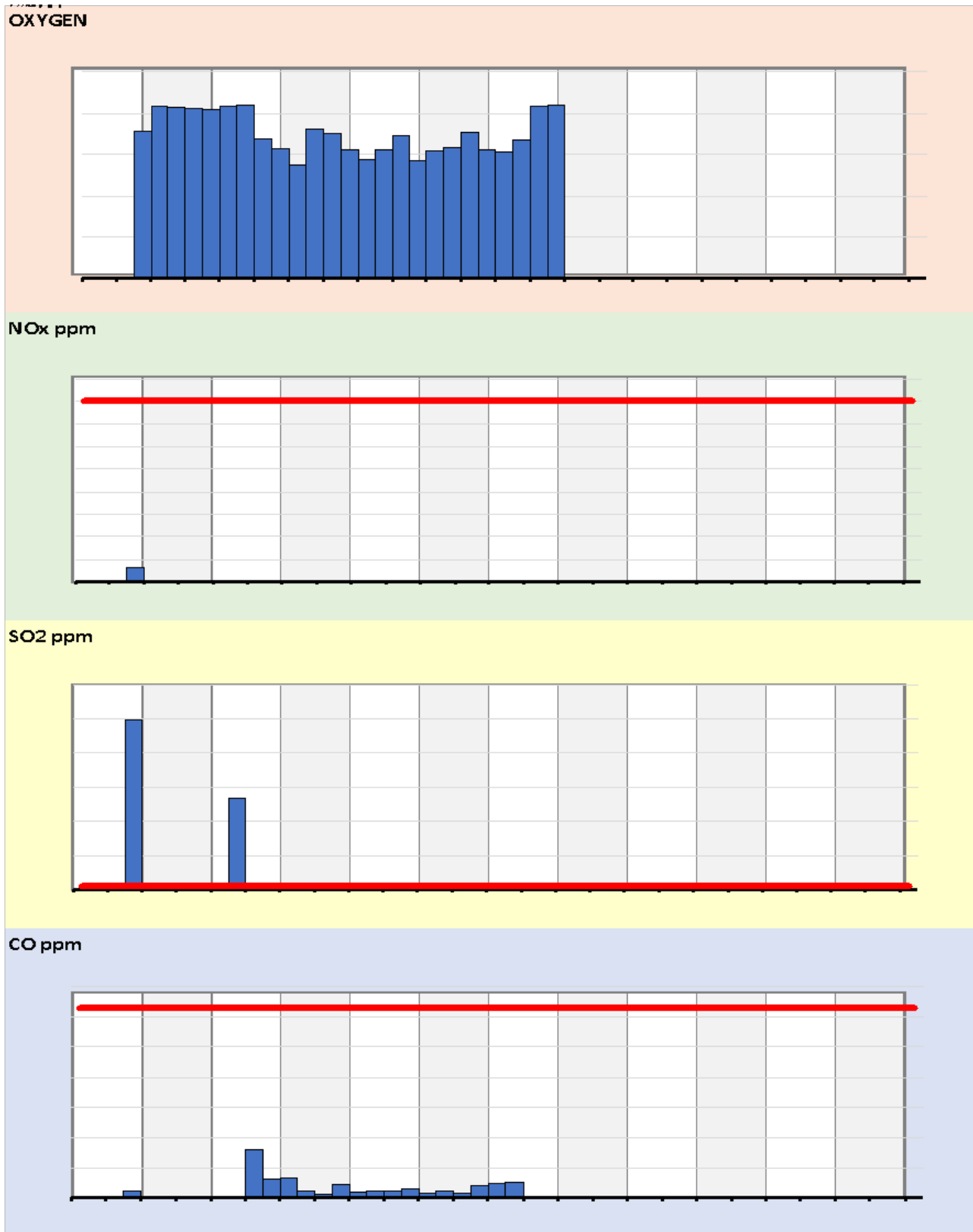
Figure 4-5:   **Run 5: 6-hour run (02/04/2020)**

Run 6 (Figure 4-6) was a longer run on Source 2 biosolids, but demonstrates that on start-up there could be exceedances in the air emissions until the unit has stabilised, which will need to be considered in the scope of the full-scale facility. It also illustrates that the facility can meet the license requirements over a longer period. However, this run was still undertaken at a lower throughput due to the particle sizing of the biosolids.
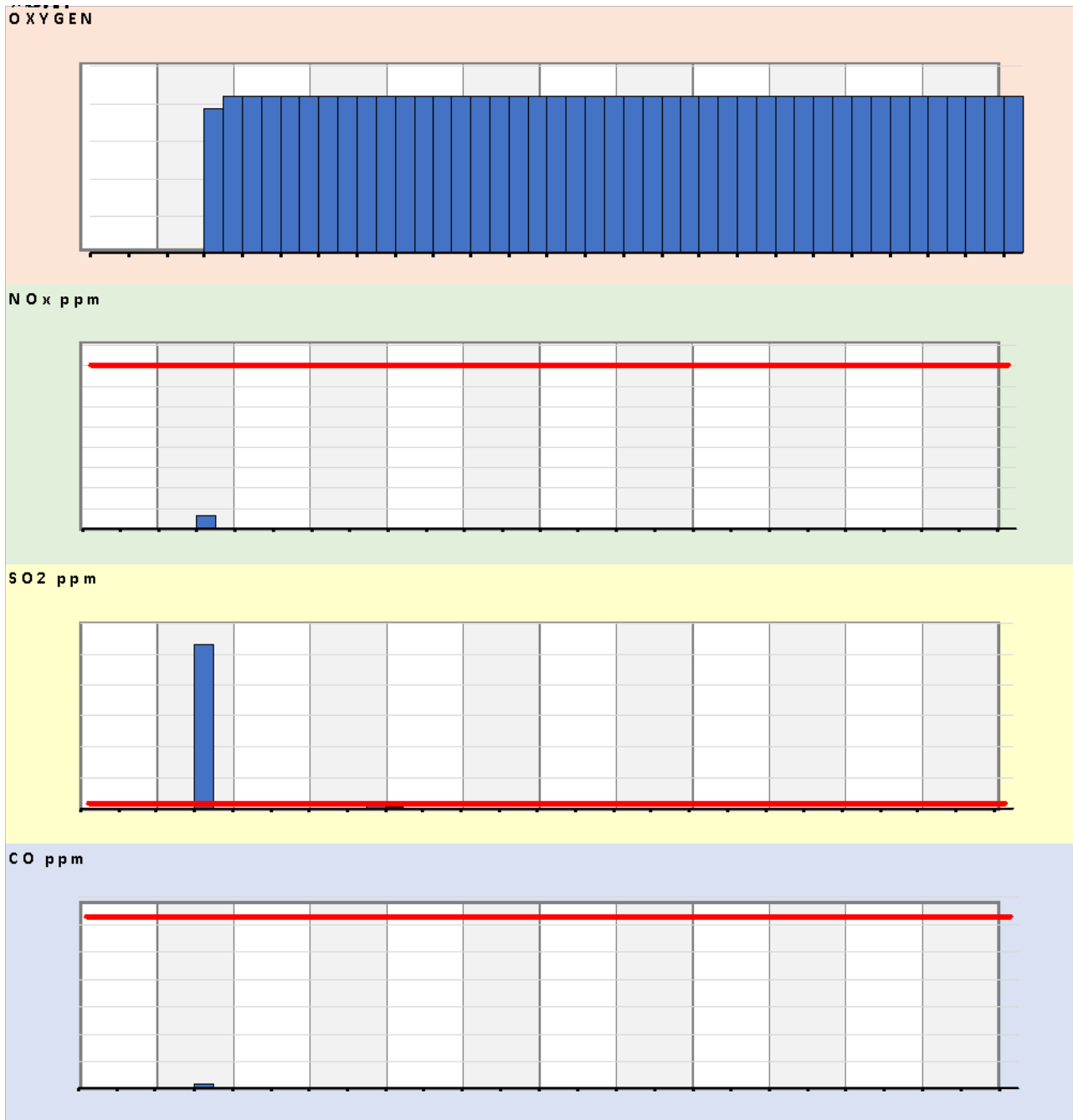
Figure 4-6:   Run 6: 6-hour run (11/06/2020)

Run 7 (Figure 4-7) was completed using the Source 2 biosolids. It shows the presence of NOx, due to the source material being fresher because it had not been stored or stockpiled for the same length of time as the Source 1 material. Therefore, data was available for NOx mitigation and chemical dosage rates that appear to be like the rates estimated for the Loganholme WWTP. In Run 7, the SOx chemical mitigation agent was changed from lime to MgOH. Figure 4-7 shows that using MgOH resulted in no spikes, even during the start-up and shutdown periods.

The oxidisers were changed so that they could maintain increased temperature and retention times due to source material having a higher calorific value (more heat being produced) and the addition of insulating cladding previously installed to mitigate the low calorific value of the Source 1 biosolids material.

The issues with CO become apparent on this run and due to the difference in the biosolids, an increase in dust, and an increase in the temperature of the oxidisers that caused 'ashing out'. These issues became apparent in the full-scale air emission and particulates analysis, discussed in Section 4.7.

Figure 4-7:   **Run 7: 6-hour run (11/08//2020)**

Figure 4-8, Figure 4-9, and Figure 4-10 show the data for the 24-hour run completed supplied by Assured Environmental. Because the CEMS unit was supplying incorrect data, it was considered prudent to obtain results for the 24-hour run by accredited samplers using their online unit to allow for the CEMS unit to be fixed and calibrated.
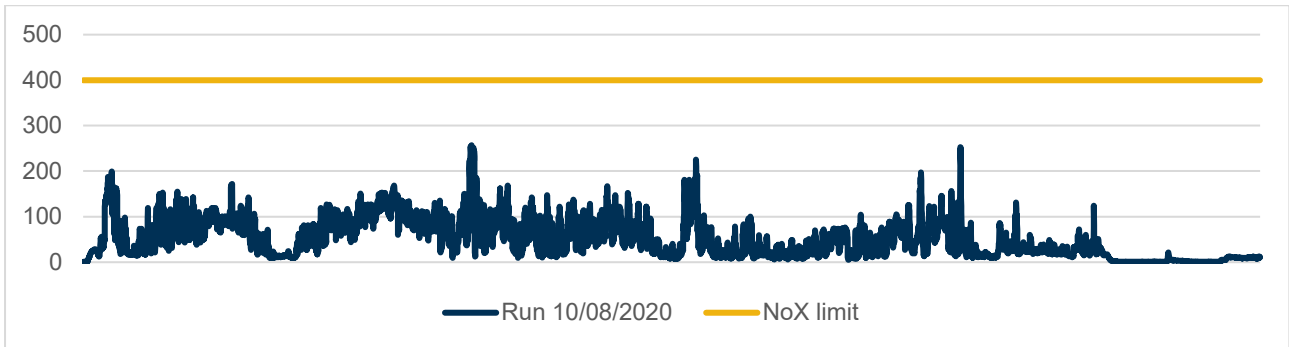
Figure 4-8: **Run 8: 24-hour run NOx results (10/08/2020)**

Figure 4-8 shows the NOx results over the first 24-hour run were within the license limits for the entire run.
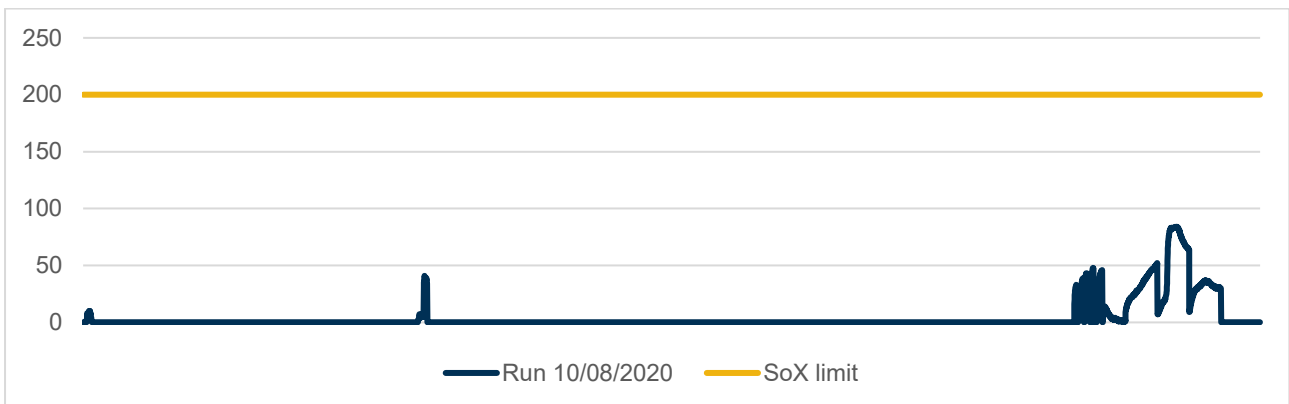
Figure 4-9: **Run 8: 24-hour run SOx results (10/08/2020)**

Figure 4-9 shows the SOx results over the first 24-hour run were within the license limits for the entire run.
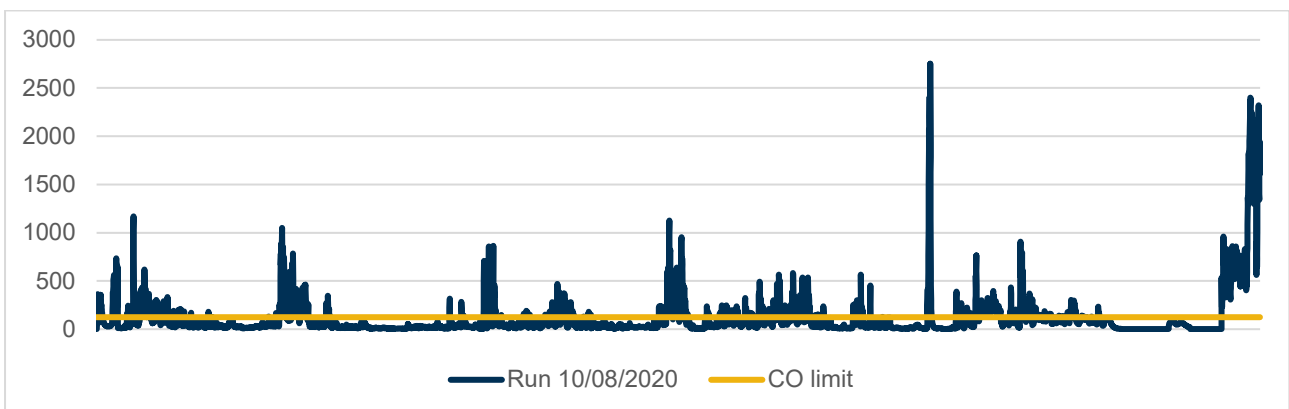
Figure 4-10: **Run 8: 24-hour run CO results (10/08/2020)**

Figure 4-10 shows that the issues with the current unit is the mitigation of CO. Modifications were made to the oxidisers for the next runs. These high CO results may have been carried over from the particulates with the change from Source 1 to Source 2.

CO, hydrocarbons (HC) and particulate matter are associated with incomplete combustion, which occurs in gasification processes compared to incineration. However, this issue can be engineered out by increasing the temperature in the oxidisers to start the process that will control the CO, and then the addition of an ESP to control the particulates. This strategy is supported by data obtained from the demonstration plant about particulates such as ionic characterisation (cation or anions) and sizing. This data has been used to implement the correct strategy for removing the particulates in the design. Installing an ESP in the demonstration plant was not cost or time efficient, but Assured Environment was able to sample and determine the particulates sizing.

Figure 4-11 shows that during Run 9, NOx and SOx had no exceedances. Although the CO limit appears to exceed a significant amount, these intervals were read every minute and the rolling average was 115 mg/m^3 within the limit of the 125 mg/m^3.

Figure 4-11: **Run 9: 24-hour run (11/08/2020)**

Run 11 (Figure 4-12) illustrates that NOx and SOx were controlled. The two exceedances for SOx were during start-up, which attributed to a CEMS blockage from previous runs. Although the CO limit was exceeded during a short period due to the maximum throughput being tested, which increased the particulates going through the oxidisers, the CO was again increased. This issue is being engineered out and will not be an issue with the full-scale facility.
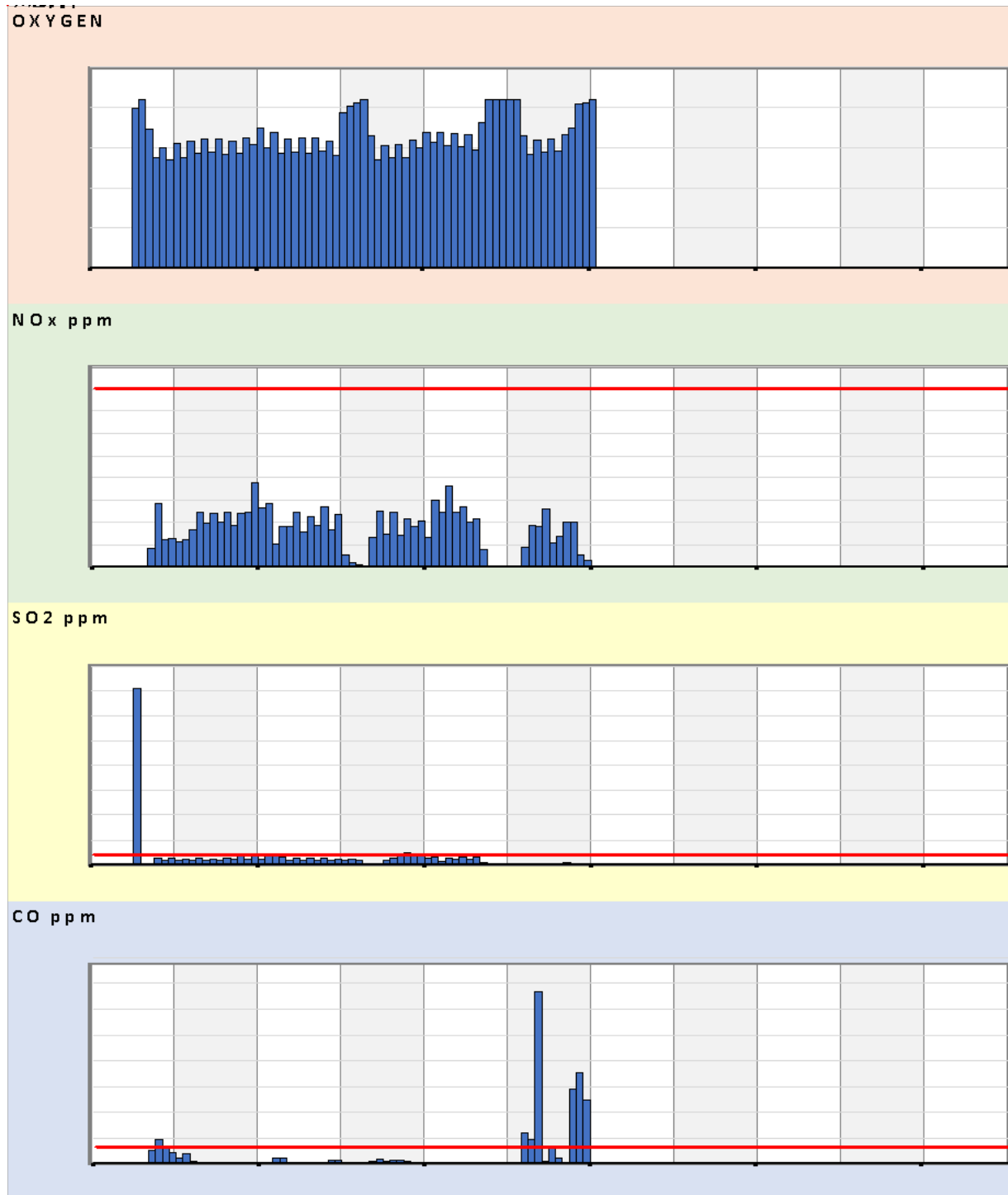
Figure 4-12:   Run 11: 48-hour run (21/07/2020)

Run 12 (Figure 4-13) shows the NOx concentrations where within the limits; however, there were a few exceedances. These exceedances where due to dosing issues (blockages) and issues within the actual CEMS unit. This would not be an issue with the full-scale facility as there would also be limits and alerts set in place to assure this did not occur. The demonstration plant is much more manual then what is to be expected with the full-scale facility design. However, what the above results show is that urea can successful be used to mitigate NOx in a gasification facility.

SOx results demonstrate that MgOH is the best agent for mitigation in the air stream. There were two short exceedances, but this was again to do with manual error and would not be an issue with the full-scale facility.

There were issues with keeping within the limit of the CO. This demonstrates that there will be a requirement to engineer improved particulates capture in the full-scale facility, but it also could be due to the pelletizing of the dried biosolids through the respective dryers, which would not be an issue in the full-scale facility using belt dryers. The drum dryer handling techniques do produce a lot of dust and a high dried pellet density meaning that it is hard to get full combustion. Both factors do contribute to the CO and particulates; therefore, it is believed that by using the belt dryers this will reduce the risk.

The following is the data from the 100-hour run on the 27/07/2020.

Figure 4-13: **Run 12: 100-hour run (27/07/2020)**

4.7   Full air emission results

This section provides a summary of the full air emissions results for three runs: 31/03/2020, 02/04/2020 and 22/07/2020.

As shown in Table 4-1 for the run on the 31 March 2020 there were no exceedances to the target limits set by the conditions of the EA.

Table 4-1:   Air emission results—24-hour run (31/03/2020)

Parameter	< >	Result	Permit	Unit	Reference
Sample date		31/03/2020	-		-
Average source temperature		66	-	°C	-
Flue gas water vapour content		23	-	vol-%	-
Carbon dioxide concentration		7.0	-	vol-%	Sewage Treatment Plant (STP)
Oxygen concentration		12.2	-	vol-%	STP
Flue gas molecular weight—dry		1.3	-	kg/Nm^3	STP
Flue gas velocity		22.8	15 (min)	m/sec	-
Flue gas volume flow		66.8	-	Nm^3/min	STP
Particulate matter		17	-	mg/Nm^3	STP
- at 11% O_2		23	30	mg/Nm^3	
- emission rate		1.1	-	g/min	
Carbon monoxide		55	-	mg/Nm^3	STP
- at 11% O_2		69	125	mg/Nm^3	
- emission rate		3.5	-	g/min	
Oxides of nitrogen (as NO_2)		12	-	mg/Nm^3	STP
- at 11% O_2		16	400	mg/Nm^3	
- emission rate		0.7	-	g/min	
Sulfur dioxide (SO_2)		130	-	mg/Nm^3	STP
- at 11% O_2		160	200	mg/Nm^3	
- emission rate		8.3	-	g/min	
Hydrogen chloride		4.2	-	mg/Nm^3	STP
- at 11% O_2		5.1	60	mg/Nm^3	
- emission rate		0.27	-	g/min	
Hydrogen fluoride	<	0.1	-	mg/Nm^3	STP
- at 11% O_2	<	0.2	4	mg/Nm^3	
- emission rate	<	0.01	-	g/min	
Total VOCs (as n-propane)	<	0.9	-	mg/Nm^3	STP
- at 11% O_2	<	1.1	20	mg/Nm^3	
- emission rate	<	0.059	-	g/min	
Cadmium		0.0075	-	mg/Nm^3	STP
- at 11% O_2		0.010	0.05	mg/Nm^3	

Parameter	< >	Result	Permit	Unit	Reference
- emission rate		0.00048	-	g/min	
Mercury		0.015	-	mg/Nm^3	
- at 11% O$_2$		0.017	0.05	mg/Nm^3	STP
- emission rate		0.00094	-	g/min	
Total heavy metals (medium bound)		0.25	-	mg/Nm^3	
- at 11% O$_2$		0.29	0.50	mg/Nm^3	STP
- emission rate		0.016	-	g/min	
PCDD/F — i-TEQ (medium bound)		0.014	-	ng/Nm^3	
- at 11% O$_2$		0.018	0.10	ng/Nm^3	STP
- emission rate		1.1E-09	-	g/min	
PAHs—BaP (medium bound)		0.51	-	µg/Nm^3	
- at 11% O$_2$		0.64	-	µg/Nm^3	STP
- emission rate		4.0E-05	-	g/min	
Total PFAS (medium bound)		33.7	-	ng/Nm^3	
- at 11% O$_2$		38.5	-	ng/Nm^3	STP
- emission rate		2.6E-06	-	g/min	
Total TOPA (medium bound)		47.2	-	ng/Nm^3	
- at 11% O$_2$		53.9	-	ng/Nm^3	STP
- emission rate		3.6E-06	-	g/min	
Average odour		1,628	-	ou	STP
- emission rate		132,027	-	ou-m^3/min	
Hydrogen sulfide	<	0.8	-	mg/Nm^3	
- at 11% O$_2$	<	0.9	5	mg/Nm^3	STP
- emission rate	<	0.05	-	g/min	
Sulfur trioxide (as H2SO4)		38.7	-	mg/Nm^3	
- at 11% O$_2$		44.1	-	mg/Nm^3	STP
- emission rate		2.434	-	g/min	
Hexavelant chromium	<	0.0072	-	mg/Nm^3	
- at 11% O$_2$	<	0.0089	-	mg/Nm^3	STP
- emission rate	<	0.00046	-	g/min	

As shown in Table 4-2, the particulate matter failed the set limits when the oxygen correction factor was calculated. To mitigate this failure, the easiest and most cost-effective solution was the addition of the venturi as a way of mitigating dust particles. As a precaution, there was a break in runs and extra analysis was added to the schedule to investigate the exceedance and provide a corrective action.

Table 4-2 provides results of the particulate analysis after the addition of the venturi.

Table 4-2:   **Particulate analysis after the addition of a venturi—24-hour run (02/04/2020)**

Parameter	< >	Result	Permit	Unit	Reference
Sample date		2/04/2020	-	dd.mm.yyyy	-
Average source temperature		66	-	°C	-
Flue gas water vapour content		23	-	vol-%	-
Carbon dioxide concentration		6.7	-	vol-%	STP
Oxygen concentration		12.9	-	vol-%	STP
Flue gas molecular weight—dry		1.3	-	kg/Nm^3	STP
Flue gas velocity		21.2	15 (min)	m/sec	-
Flue gas volume flow		61.8	-	Nm^3/min	STP
Particulate matter		28	-	mg/Nm^3	STP
- at 11% O_2		33	30	mg/Nm^3	
- emission rate		1.7	-	g/min	
Carbon monoxide		6	-	mg/Nm^3	STP
- at 11% O_2		7	125	mg/Nm^3	
- emission rate		0.3	-	g/min	
Oxides of nitrogen (as NO_2)		7	-	mg/Nm^3	STP
- at 11% O_2		9	400	mg/Nm^3	
- emission rate		0.5	-	g/min	
Sulfur dioxide (SO_2)		100	-	mg/Nm^3	STP
- at 11% O_2		124	200	mg/Nm^3	
- emission rate		6.1	-	g/min	
Hydrogen chloride		7	-	mg/Nm^3	STP
- at 11% O_2		9	60	mg/Nm^3	
- emission rate		0.4	-	g/min	
Hydrogen fluoride	<	0.1	-	mg/Nm^3	STP
- at 11% O_2	<	0.1	4	mg/Nm^3	
- emission rate	<	0.01	-	g/min	
Total VOCs (as n-propane)	<	1.0	-	mg/Nm^3	STP
- at 11% O_2	<	1.1	20	mg/Nm^3	
- emission rate	<	0.059	-	g/min	
Cadmium		0.0078	-	mg/Nm^3	STP
- at 11% O_2		0.0089	0.05	mg/Nm^3	
- emission rate		0.00049	-	g/min	
Mercury		0.010	-	mg/Nm^3	STP
- at 11% O_2		0.012	0.05	mg/Nm^3	
- emission rate		0.00063	-	g/min	
Total heavy metals (medium bound)		0.160	-	mg/Nm^3	STP

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Parameter	< >	Result	Permit	Unit	Reference
- at 11% O_2		0.183	0.50	mg/Nm^3	
- emission rate		0.010	-	g/min	
PCDD/F—i-TEQ (medium bound)		0.000	-	ng/Nm^3	STP
- at 11% O_2		0.0	0.10	ng/Nm^3	
- emission rate		0.000	-	g/min	
PAHs—BaP (medium bound)		0.000	-	ng/Nm^3	STP
- at 11% O_2		0.0	-	ng/Nm^3	
- emission rate		0.000	-	g/min	
Total PFAS (medium bound)		15.9	-	ng/Nm^3	STP
- at 11% O_2		19.5	-	ng/Nm^3	
- emission rate		9.8E-07	-	g/min	
Total TOPA (medium bound)		19.482	-	ng/Nm^3	STP
- at 11% O_2		24.0	-	ng/Nm^3	
- emission rate		0.000	-	g/min	
Average odour		926	-	ou	STP
- emission rate		76,384	-	ou-m^3/min	
Hydrogen sulfide	<	0.8	-	mg/Nm^3	STP
- at 11% O_2	<	0.9	5	mg/Nm^3	
- emission rate	<	0.05	-	g/min	
Sulfur trioxide (as H2SO4)		37.2	-	mg/Nm^3	STP
- at 11% O_2		45.4	-	mg/Nm^3	
- emission rate		2.373	-	g/min	
Hexavelant chromium	<	0.0052	-	mg/Nm^3	STP
- at 11% O_2	<	0.0064	-	mg/Nm^3	
- emission rate	<	0.00033	-	g/min	

As illustrated in Table 4-3. the corrective action of the addition of the venturi significantly reduced the particulate concentration in the air emissions and therefore the results are all within the set limits

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Table 4-3:   Particulate analysis with inclusion of venturi—Run on 26/05/ 2020

Parameter	Result	Permit	Unit	Reference
Sample date	26/05/2020	-		-
Average source temperature	53	-	°C	-
Flue gas water vapour content	17	-	vol-%	-
Carbon dioxide concentration	2.7	-	vol-%	STP
Oxygen concentration	17.1	-	vol-%	STP
Flue gas molecular weight— dry	1.3	-	kg/Nm^3	STP
Flue gas velocity	19.8	15 (min)	m/sec	-
Flue gas volume flow	64.7	-	Nm^3/min	STP
TEST 1				
Particulate matter	7.6	-	mg/Nm^3	
- at 11% O_2	16	30	mg/Nm^3	STP
- emission rate	0.5	-	g/min	
Sulfur dioxide (SO_2)	4.1	-	mg/Nm^3	
- at 11% O_2	8.6	200	mg/Nm^3	STP
- emission rate	0.25	-	g/min	
Sulfur trioxide (as H2SO4)	0.34	-	mg/Nm^3	
- at 11% O_2	0.71	-	mg/Nm^3	STP
- emission rate	0.021	-	g/min	
Particulate matter	11	-	mg/Nm^3	
- at 11% O_2	25	30	mg/Nm^3	STP
- emission rate	0.71	-	g/min	
Sulfur dioxide (SO_2)	3.3	-	mg/Nm^3	
- at 11% O_2	7.3	200	mg/Nm^3	STP
- emission rate	0.21	-	g/min	
Sulfur trioxide (as H2SO4)	0.33	-	mg/Nm^3	
- at 11% O_2	0.75	-	mg/Nm^3	STP
- emission rate	0.021	-	g/min	

As shown in Table 4-4, the final full air emissions results show that the Loganholme demonstration plant could meet all the conditions set out in the EA. The 100-hour was the ideal run and showed that with the optimisation scheduled in the full-scale facility would be below the targets set in the EA. Table 4-4 also shows that the known issues, such as CO and particulates, can be optimised for the full-scale facility. Although the current EA can be met with current design, the addition of more analysis and determining the particulate sizing and characterisation has been prudent and efficient for making sure that tithe full-scale designs out these known risks.

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Table 4-4: 100-hour run (22/07/2020 and 23/07/2020)

Parameter	< >	Result	Permit	Unit	Reference
Sample date		22/07/2020 & 23/07/2020	-	dd.mm.yyyy	-
Average source temperature		55	-	°C	-
Flue gas water vapour content		15	-	vol-%	-
Carbon dioxide concentration		4.9	-	vol-%	STP
Oxygen concentration		14.4	-	vol-%	STP
Flue gas molecular weight—dry		1.3	-	kg/Nm^3	STP
Flue gas velocity		21.8	15 (min)	m/sec	-
Flue gas volume flow		72.8	-	Nm^3/min	STP
Particulate matter		20	-	mg/Nm^3	
- at 11% O_2		26	30	mg/Nm^3	STP
- emission rate		1.4	-	g/min	
Carbon monoxide		71	-	mg/Nm^3	
- at 11% O_2		109	125	mg/Nm^3	STP
- emission rate		4.5	-	g/min	
Oxides of nitrogen (as NO_2)		140	-	mg/Nm^3	
- at 11% O_2		219	400	mg/Nm^3	STP
- emission rate		10.2	-	g/min	
Sulfur dioxide (SO_2)		119	-	mg/Nm^3	
- at 11% O_2		188	200	mg/Nm^3	STP
- emission rate		0.0	-	g/min	
Hydrogen chloride		2.2	-	mg/Nm^3	
- at 11% O_2		3.3	60	mg/Nm^3	STP
- emission rate		0.15	-	g/min	
Hydrogen fluoride		0.3	-	mg/Nm^3	
- at 11% O_2		0.5	4	mg/Nm^3	STP
- emission rate		0.02	-	g/min	
Total VOCs (as n-propane)	<	0.9	-	mg/Nm^3	
- at 11% O_2	<	1.4	20	mg/Nm^3	STP
- emission rate	<	0.066	-	g/min	
Cadmium		0.0027	-	mg/Nm^3	
- at 11% O_2		0.0045	0.05	mg/Nm^3	STP
- emission rate		0.00019	-	g/min	
Mercury		0.025	-	mg/Nm^3	
- at 11% O_2		0.041	0.05	mg/Nm^3	STP
- emission rate		0.0017	-	g/min	

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Parameter	< >	Result	Permit	Unit	Reference
Total heavy metals (medium bound)		0.19	-	mg/Nm^3	STP
- at 11% O$_2$		0.31	0.50	mg/Nm^3	
- emission rate		0.013	-	g/min	
PCDD/F—i-TEQ (medium bound)		0.0013	-	ng/Nm^3	STP
- at 11% O$_2$		0.0021	0.10	ng/Nm^3	
- emission rate		1.5E-10	-	g/min	
PAHs—BaP (medium bound)		0.30	-	µg/Nm^3	STP
- at 11% O$_2$		0.51	-	µg/Nm^3	
- emission rate		3.6E-05	-	g/min	
Total PFAS (medium bound)		47	-	ng/Nm^3	STP
- at 11% O$_2$		71	-	ng/Nm^3	
- emission rate		5.1E-06	-	g/min	
Total TOPA (medium bound)		74.0	-	ng/Nm^3	STP
- at 11% O$_2$		112.0	-	ng/Nm^3	
- emission rate		8.2E-06	-	g/min	
Average odour		801	-	ou	STP
- emission rate		68,606	-	ou-m^3/min	
Hydrogen sulfide	<	0.8	-	mg/Nm^3	STP
- at 11% O$_2$	<	1.2	5	mg/Nm^3	
- emission rate	<	0.06	-	g/min	
Sulfur trioxide (as H2SO4)		3.6	-	mg/Nm^3	STP
- at 11% O$_2$		4.8	-	mg/Nm^3	
- emission rate		0.253	-	g/min	
Hexavelant chromium	<	0.0063	-	mg/Nm^3	STP
- at 11% O$_2$	<	0.012	-	mg/Nm^3	
- emission rate	<	0.00040	-	g/min	

Design modifications were made to the full-scale facility as part of the value engineering process. Extra analyses were conducted on 03/09/2020 to test these changes. The results show that the carbon monoxide and particulate concentrations were negatively affected by the changes to the oxidisers. The process can be engineered out in the full-scale facility with the addition of an ESP.

5.   Biosolids and Biochar Characterisation

5.1   Biosolids analysis

This section is an in-depth analysis of the biosolids sourced from Victoria, as well as those from Loganholme and Beenleigh WWTPs. For reference, an independent review was undertaken on the Loganholme WWTP and the potential market for biochar using the analytical data from this report, titled *Char characteristics, potential value, and reuse options (Bridle, 2020)* (refer to Appendix A).

Drying concentrates the energy in sludge by removing water and increasing the gross calorific value, transforming the sludge into a combustible material. Several factors such as humidity, air velocity, sludge origin and the physical transformation of the material affect the drying operation, but temperature is the most influential parameter. Temperature affects the drying time, rheological properties, thermal stability, and the physicochemical characteristics of the biosolids, such as calorific value and nutrient content.

Thermal drying removes the moisture from sludge obtained from the Loganholme EETP (14% w/w solids), drying it through the belt filter press, which will change the content to >99% w/w solids. The belt dryers significantly reduce the moisture to below 10% w/w, reducing the cost for handling and transport. Drying biosolids at ≥80 °C also stabilises the material and destroys pathogens.

The potential for energy recovery from biosolids is a function of their composition, which is a mixture of organic (volatile) matter, inorganic matter (inert material) and associated water. The composition of biosolids may vary, and the energy recovery method and corresponding energy products must be compatible with the characteristics of the biosolids. Therefore, the volatile solids are important when considering the heat energy recovery.
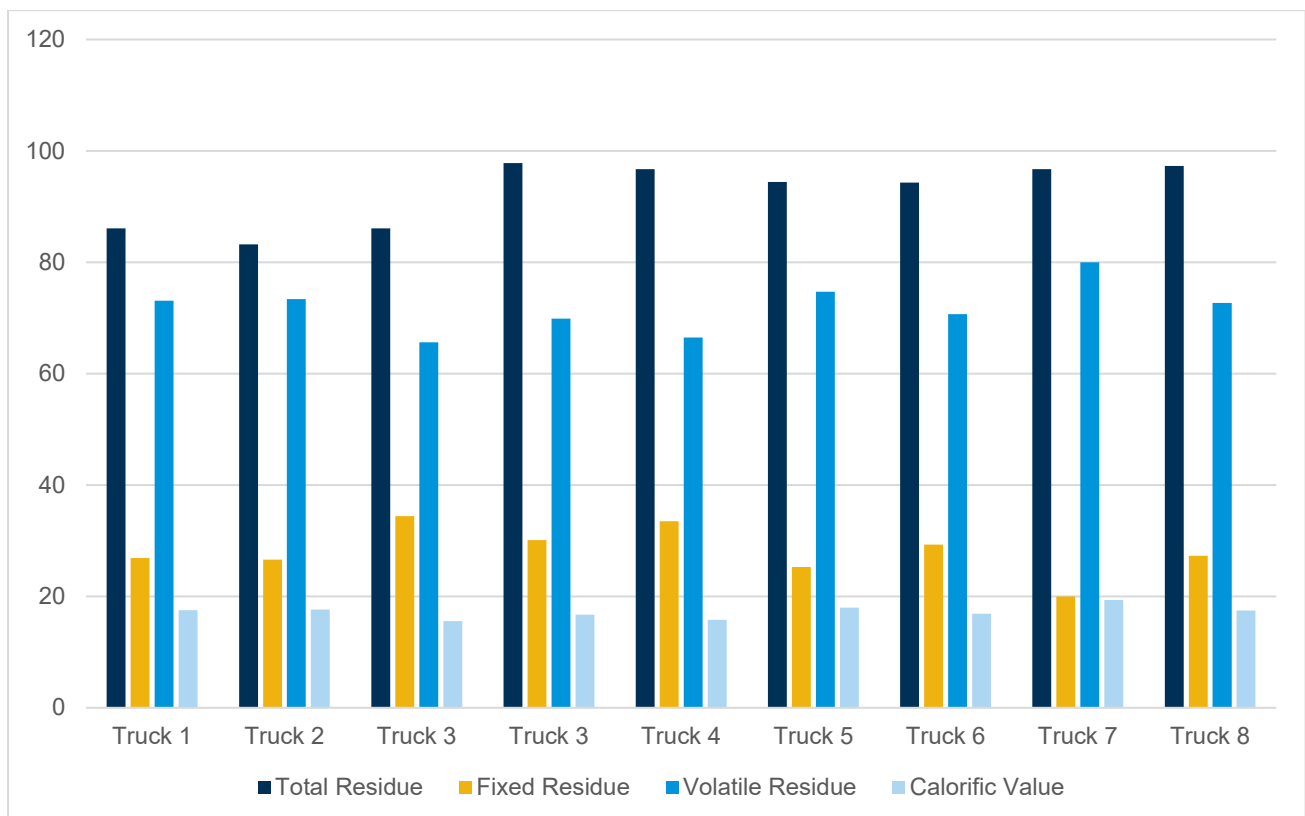

Figure 5-1:   **Biosolids chemical parameters: total residue (%), fixed residue (%), volatile residue (%) and calculated calorific value**

Figure 5-1 shows that the Source 2 biosolids had a higher percentage of total solids and a higher overall percentage of volatile residue, which in turn correlates to a higher calorific value. The Source 1 biosolids had

an average calorific value of 19.26 MJ/kg. Source 2 biosolids had lower calorific values, which is to be expected due to the biosolids degrading while being stockpiled at a third-party storage for many months. This would not be an issue for the Loganholme biosolids gasification facility because it will process all biosolids as they are dried, and no storage will be involved. This is explained in detail in Section 7 Heat balance.

Biosolids are mainly a mix of water and organic matter and may contain:

- Macronutrients, such as nitrogen, phosphorus, potassium, and sulfur

- Micronutrients, such as copper, zinc, calcium, magnesium, iron, boron, molybdenum, and manganese.

Biosolids may also contain traces of synthetic organic compounds and metals, including arsenic, cadmium, chromium, lead, mercury, nickel, and selenium. These trace compounds can limit the uses for biosolids, with all potential uses regulated in Queensland by the *End of Waste Code for Biosolids* (DES,2020).
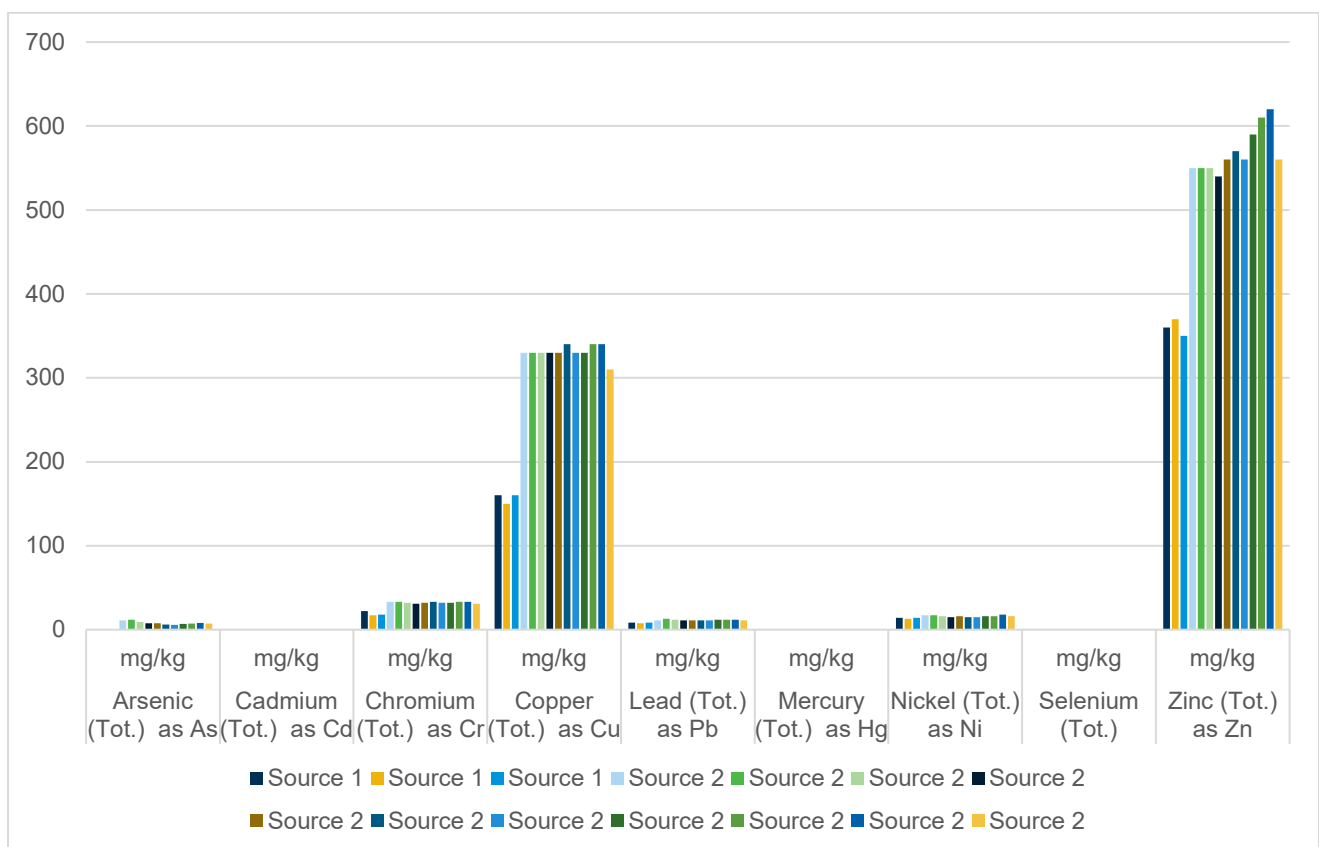
Figure 5-2:   **Comparison of trace metals in biosolids sources**

Figure 5-2 shows the trace metals in the two sources of biosolids. Biosolids from any WWTP will usually have micronutrients such as copper and zinc. These trace metals are of high value in Australia for farmers; this benefit is undervalued in LCC's Biosolids Management Strategy.

The main difference between the two sources of biosolids for detectable heavy metal is that Source 2 has a higher concentration than Source 1, including arsenic, chromium, copper, lead, nickel, mercury, and zinc.

The heavy metal content of biosolids should be taken into consideration, but Source 2 is in a significantly more industrial catchment, which would explain the higher metal concentrations.

Figure 5-2 shows the average of the trace metals in each biosolids source, compared to the average trace metals found in the Loganholme WWTP biosolids.

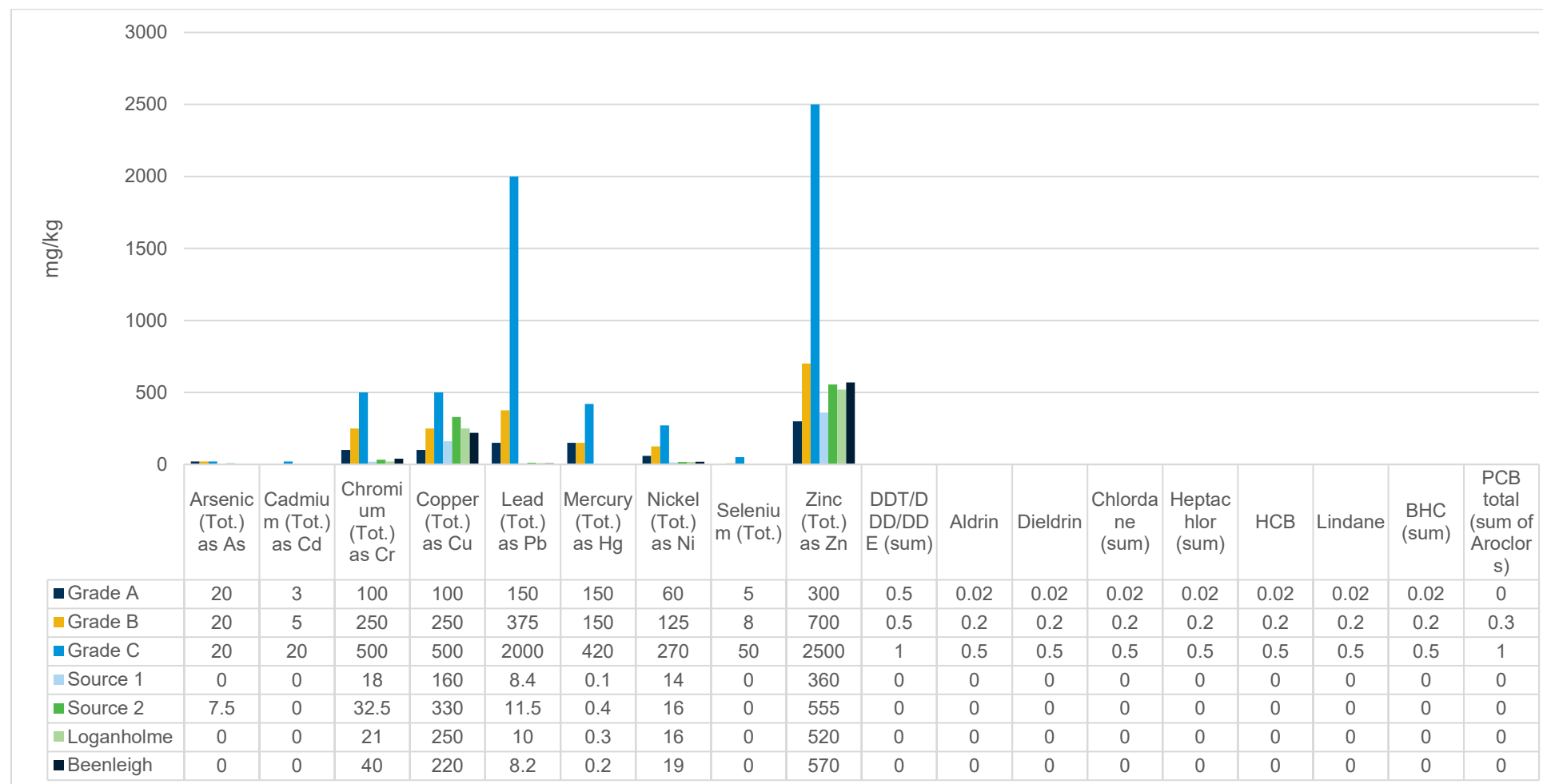|	Arsenic (Tot.) as As	Cadmium (Tot.) as Cd	Chromium (Tot.) as Cr	Copper (Tot.) as Cu	Lead (Tot.) as Pb	Mercury (Tot.) as Hg	Nickel (Tot.) as Ni	Selenium (Tot.)	Zinc (Tot.) as Zn	DDT/DDD/DDE (sum)	Aldrin	Dieldrin	Chlordane (sum)	Heptachlor (sum)	HCB	Lindane	BHC (sum)	PCB total (sum of Aroclors)
Grade A	20	3	100	100	150	150	60	5	300	0.5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0
Grade B	20	5	250	250	375	150	125	8	700	0.5	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Grade C	20	20	500	500	2000	420	270	50	2500	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1
Source 1	0	0	18	160	8.4	0.1	14	0	360	0	0	0	0	0	0	0	0	0
Source 2	7.5	0	32.5	330	11.5	0.4	16	0	555	0	0	0	0	0	0	0	0	0
Loganholme	0	0	21	250	10	0.3	16	0	520	0	0	0	0	0	0	0	0	0
Beenleigh	0	0	40	220	8.2	0.2	19	0	570	0	0	0	0	0	0	0	0	0

Figure 5-3: **Comparison of heavy metals in biosolids**

Figure 5-3 compares the biosolids from interstate sources to samples from Loganholme and Beenleigh WWTPs and the grades in the *End of Waste Code for Biosolids* (DES,2020). Figure 5-3 illustrates that all the sources of biosolids comfortably fall within in the category of Grade B Biosolids.

The contaminate grading for all sources of biosolids is Grade B (the rules for Zn and Cu from the *NSW Biosolids Guideline* is still in place in the *End of Waste Code for Biosolids* (DES,2020). Loganholme WWTP has several unusually high heavy metal results for As, Cr, Ni and Zn due trade-waste contamination.

The organic contaminates such as aldrin, dieldrin, chlordane, heptachlor, HCB, Lindane, BHC, DDT, DDE, DDD, PCB where analysed for the biosolids sourced from Victoria, but the limits were all below the detectable level. One organic contaminant found in biosolids from Beenleigh WWTP is dieldrin. Dieldrin was popular in the 1950s through to the 1970s as a pesticide, but it was banned in Australia in the late 1990s. Therefore, its presence at Beenleigh WWTP, although in low concentrations, should be monitored by the LCC Trade Waste Team.

5.2 Biochar analysis

Biochar is a kind of charcoal created when biomass or organic material is combusted at temperatures of 300–600 °C with limited oxygen. The biochar produced from 100% biosolids source is currently an unverified medium, which means a significant amount of analysis is required to prove the beneficial reuse of this product. However, overall, biochar contains high levels of carbon and nutrients, and a significant cation-exchange capacity. Most of the carbon in the biochar is sequestered (Lehmann, Gaunt, & Rondon, 2006) meaning that it is highly recalcitrant, with carbon turnover on a timescale of millennium, reducing greenhouse gas emissions from soils or from waste management practices. Biochar has significant demonstrated benefits for improving soil properties. The benefits of adding biochar to soil depends on the material used to produce the biochar (feedstock) and the temperatures achieved during gasification (carbonisation).

One study conducted by Bridle (Bridle, Cote, Constable, & Fraser, 1987) determined that biochar produced from biosolids contains low amounts of plant-available N, despite containing a low C:N ratio value of 7 and an elevated amount of total N (6.4%). This study reported that 45% of the initial N was not present in the final biochar, whereas losses of P during pyrolysis were negligible. Lower amounts of N were present, compared to the original biosolids, corroborated by other studies (Dokht, Naeini, Dordipour, De Jong, & Hezarjanbi, 2017). Biochar from biosolids contributes to soil retention of N in the long-term, acting as a slow release fertiliser. Ammonium and nitrate leaching are reduced following biochar amendment.

As part of the demonstration plant, the biochar produced from the two sources has been analysed. Figure 5-4 illustrates the biosolids and biochar analyses from Source 1.
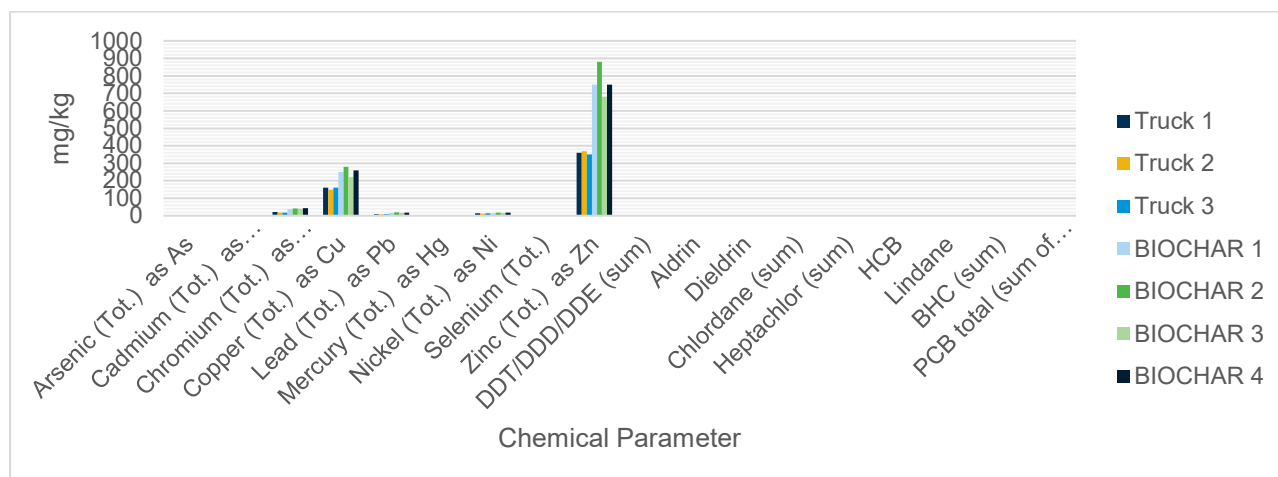

Figure 5-4:   Source 1 biosolids and biochar characterization

Figure 5-4 shows that, as expected, once the biosolids are processed through the gasification unit, the concentrations of trace metals increase. Table 5-1 shows the difference in the material after it was treated through the gasification facility and how the biochar compares to the contaminant grading under the *End of Waste Code for Biosolids (*DES, 2020).

Table 5-1:　　Source 1 analysis of biosolids and biochar processed through the demonstration plant

	Biosolids	Biochar	Difference	Limit set in the EoW Code for Biosolids (Queensland)		
				GRADE A	**GRADE B**	**GRADE C**
Arsenic (Tot.) as	<5.0	<5.0		20	20	20
Cadmium (Tot.) as Cd	<0.50	<0.50		3	5	20
Chromium (Tot.) as Cr	19	40	53	100	250	500
Copper (Tot.) as Cu	157	253	38	100	250	500
Lead (Tot.) as Pb	8.2	17	53	150	375	2000
Mercury (Tot.) as Hg	0.1	<0.1		150	150	420
Nickel (Tot.) as Ni	14	16	15	60	125	270
Selenium (Tot.)	<5.0	<5.0		5	8	50
Zinc (Tot.) as Zn	360	765	53	300	700	2500
DDT/DDD/DDE (sum)	<0.02	<0.02		0.5	0.5	1
Aldrin	<0.02	<0.02		0.02	0.2	0.5
Dieldrin	<0.02	<0.02		0.02	0.2	0.5
Chlordane (sum)	<0.02	<0.02		0.02	0.2	0.5
Heptachlor (sum)	<0.02	<0.02		0.02	0.2	0.5
HCB	<0.02	<0.02		0.02	0.2	0.5
Lindane	<0.02	<0.02		0.02	0.2	0.5
BHC (sum)	<0.02	<0.02		0.02	0.2	0.5
PCB total (sum of Aroclors)	<0.1	<0.1		<0.1	0.3	1

Table 5-1 also shows the differences in trace metal concentration. As expected, the metals present in the biosolids, such as Cr, Pb and Zn, increased by ~50%. The other contaminant to note is mercury, which was present in the biosolids, but not in the biochar. Metals such as mercury, cadmium and arsenic have low boiling points; when they are processed through the hearth, they become volatile and become part of the biogas.

Under the *End of Waste Code for Biosolids* (DES,2020)*,* the biochar produced from the Source 1 biosolids would be classified as a Grade C rather than a Grade B contaminate, because of the Zn and Cu levels. The biochar would be classified as Restricted Use 2, as the pathogen reduction is by thermal treatment and the contaminate limits would be graded Grade C. This would mean that the biochar could be used for:

- Agriculture
- Forestry
- Soil and site rehabilitation.

These applications fit the current view that biochar would make a useful soil ameliorant (Hossain, Strezov, Chan, & Nelson, 2010) especially as the increased levels of Zn and Cu, which are typically low in Australian soils, would be sought after by farmers, making the biochar more valuable as a product.

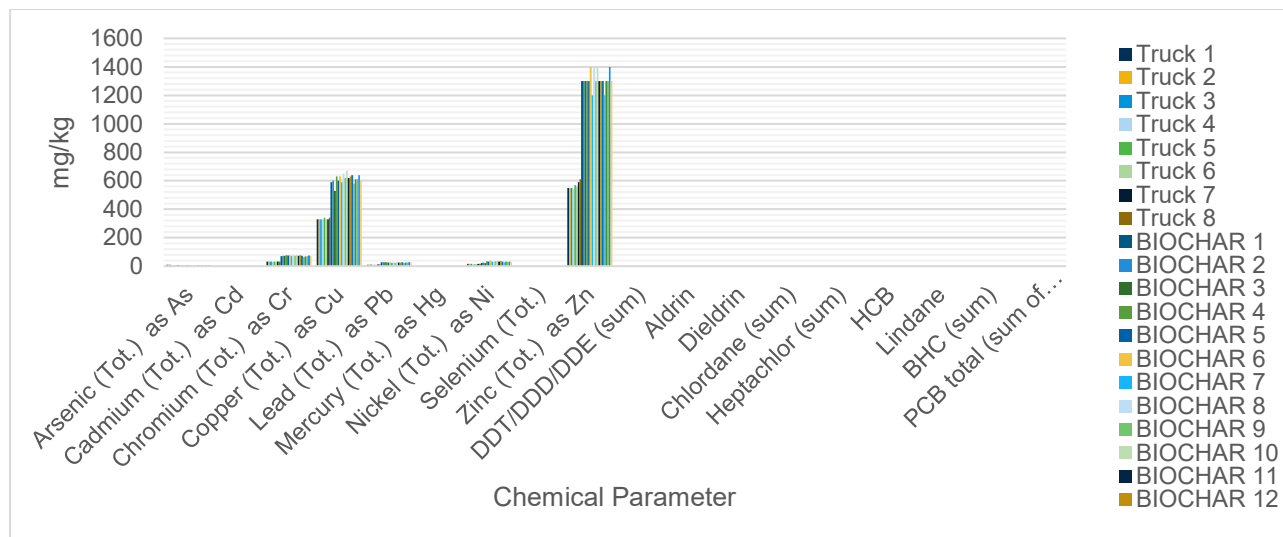Figure 5-5 shows the biosolids and biochar analysis for Source 2.

Figure 5-5:   **Source 2 biosolids and biochar characterisation**

Like the biosolids from Source 1, when the biosolids from Source 2 were processed through gasification, the trace metals present were more concentrated in the biochar.

Table 5-2 shows the differences in the Source 2 after it was treated through the gasification facility and how the biochar compares to the contaminant grading under the *End of Waste Code for Biosolids* (DES,2020).

Table 5-2:   **Source 2 analysis of biosolids and biochar processed through the demonstration plant**

	Biosolids	Biochar	Difference	Limit set in the EoW code for Biosolids (QLD)		
				GRADE A	**GRADE B**	**GRADE C**
Arsenic (Tot.) as	8.21	4.4		20	20	20
Cadmium (Tot.) as Cd	<1.0	1.4		3	5	20
Chromium (Tot.) as Cr	32.	73	56	100	250	500
Copper (Tot.) as Cu	333	613	46	100	250	500
Lead (Tot.) as Pb	12	26	56	150	375	2000
Mercury (Tot.) as Hg	0.39	<0.1		150	150	420
Nickel (Tot.) as Ni	16	31.	50	60	125	270
Selenium (Tot.)	<5.0	<5.0		5	8	50
Zinc (Tot.) as Zn	565	1312	57	300	700	2500
DDT/DDD/DDE (sum)	<0.02	<0.02		0.5	0.5	1
Aldrin	<0.02	<0.02		0.02	0.2	0.5
Dieldrin	<0.02	<0.02		0.02	0.2	0.5
Chlordane (sum)	<0.02	<0.02		0.02	0.2	0.5
Heptachlor (sum)	<0.02	<0.02		0.02	0.2	0.5
HCB	<0.02	<0.02		0.02	0.2	0.5
Lindane	<0.02	<0.02		0.02	0.2	0.5
BHC (sum)	<0.02	<0.02		0.02	0.2	0.5
PCB total (sum of Aroclors)	<0.1	<0.1		<0.1	0.3	1

Table 5-2 shows that after the biosolids are treated through gasification process, the trace metals present are more concentrated with an ~50% increase in the biochar, except for As and Hg (Yanjun, Guanyi, Wenchao, Mi, & Long, 2016). This result is expected because metals such as and Hg will decrease due to their boiling point because, after being processed through the gasification unit, they become volatile and part of the biogas stream. Therefore, it is recommended that when monitoring it would be prudent to characterise the biosolids before they are processed by the gasifier annually.

Under the *End of Waste Code for Biosolids* (DES,2020), the biochar produced from the Source 2 biosolids would be classified a Grade C rather than Grade B contaminate because of the Zn and Cu levels. The levels increase the value of the product as a soil ameliorant for farmers in the agricultural sector. The bioavailability of Cu and Zn are not usually valued; however, farmers use CU and zinc sulfate as well as a range of other trace metals to aid plant growth. Based on the main micronutrients present in biosolids, that is copper and zinc, the value of biosolids can be derived from the market price for CU and zinc sulfate, given they are the most used metals applied to land.

Comparing the Loganholme WWTP biosolids to those from Source 1 and Source 2, although useful, cannot be a direct comparison because the Source 1 and Source 2 biosolids have already been through a dewatering and drying process; therefore, the biosolids characterisation would be different, although there should not be a change in the metal concentration as mg/kg dry. This illustrates that because of the Zn and Cu values, the same results are expected from the Loganholme biosolids; therefore, they would also be classified as a Grade C contaminant, requiring thermal treatment to be classified as a Restricted Use 2.

Therefore, in a worst-case scenario, biochar from the Loganholme WWTP would be classified as Restricted Use 2 under the *End of Waste Code for Biosolids* (DES,2020) (no change to current classification), which means it can be used for:

- Agriculture

- Forestry

- Soil and site rehabilitation.

Provided that the biosolids meet the contaminant and pathogen reduction requirements specified in the *End of Waste Code for Biosolids* (DES, 2020)*,* the biosolids are not considered to be waste, but rather a resource that can be reused in agriculture. However, to open other areas of marketability for biochar (Martin & Craggs, 2010) would be a key driver to develop an End of Waste Code for Biochar.

6. Emerging Contaminates of Concern

This section is an overview of how the demonstration plant addresses its objective of the quality of the biochar product and confirming destruction of Persistent Organic Pollutants (POPs) and contaminates of concern.

6.1 Perfluoroalkyl substances

PFAS is a POP found in biosolids (Latimer, 2016). PFAS are manufactured chemicals that have been used in everyday household items. PFAS make products non-stick; water repellent; and fire, weather, and stain resistant and are used in a range of consumer products, such as carpets, clothes, and paper, and have also been used in firefighting foams, pesticides, and stain repellents.

The chemical structure of PFAS, including variations in chemical structure between different types of PFAS, is an important consideration for understanding the behaviour of PFAS in the environment. The high solubility of PFAS in water means that PFAS may readily leach from soil to surface water and groundwater, where they can move long distances to enter creeks, rivers and lakes and become part of the food chain, being transferred from organism to organism (Rutludge, Cole, & Prasad) (USEPA, 2017).

In Queensland, PFAS monitoring has been included in the *End of Waste Code for Biosolids* (DES, 2020). This is the only regulatory standard for biosolids in Australia to date and the methodology for monitoring for PFAS is still being developed. As of January 2020, the application of biosolids to agricultural land is subject to the following PFAS-specific trigger values (Table 6-1), which apply after the application of biosolids to land.

Table 6-1: Trigger values for PFAS in soil after the application to land

Sum of PFOS and PFHxS	PFOA	Land use
0.01 mg/kg	0.1 mg/kg	Residential with garden/accessible soil (HIL A)
2 mg/kg	20 mg/kg	Residential with minimal opportunities for soil access (HIL B)
1 mg/kg	10 mg/kg	Public open space (HIL C)
20 mg/kg	50 mg/kg	Industrial/ commercial (HIL D)

Table 6-1 shows the trigger limits are in addition to other maximum allowable soil contaminant concentrations specified in the code. Sampling of the biosolids for PFOS, PFHxS and PFOA must be undertaken for every 120 tonnes of biosolids applied, in addition to post-application sampling to assess against the trigger values (Taylor & Yamada, 2003). TOPA analysis should be used to determine the PFAS concentrations in the soil prior to application of biosolids.

As PFAS analysis is a rapidly evolving field, there are recent advances in analytical systems and techniques. Therefore, PFAS were monitored by three different methods in the demonstration plant: TOP ASSAY, USEPA Method, and TOP Assay EWi (HPLC/MS). Table 6-2 is an extract from the PFAS NEMP 2.0 (Department of Agriculture, Water, and the Environment, 2020), which explains the different analytical methods and the limitations of these methods.

Table 6-2: PFAS standard methods of analysis

Method	Use	Sample matrices	Limitations	Analytes
USEPA Method EPA-821-R-11-007 Draft Procedure for Analysis of Perfluorinated Carboxylic Acids and Sulfonic Acids in Sewage Sludge and Biosolids by HPLC/MS/MS December 2011	To analyse for specific analytes in sewage sludge and biosolids	Sewage sludge and biosolids	**Only analyses for specific PFAS** Further details in the reference	PFBA, PFPA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTriDA, PFTeDA, PFBS, PFHxS, PFHpS, PFOS, PFOSA, NMeFOSA, NEtFOSA, NMeFOSE, NEtFOSE

Method	Use	Sample matrices	Limitations	Analytes
Total Oxidisable Precursor Assay (TOP Assay)	**Can be used in conjunction with a USEPA method to estimate the total PFAS, and sometimes the approximate end point PFAS.** Can help inform risk assessment	Water samples and extracts including soil, biota, firefighting foam products and wastes	**Cannot be used to target exact PFAS precursors, as it is a semi-quantitiveP69FP69F1PP method. Allows for some inferences as to precursor chain length**	Total PFAS chains (C4-C14)
Total Organic Fluorine Assay (TOF Assay) as combustion ion chromatography (the most common method available)	Can be used in conjunction with a USEPA method to understand the total presence of organic fluorine in a sample and compare this to the organic fluorine equivalent detected by the USEPA method	Water samples and extracts including soil, biota, firefighting foam products and wastes	**Cannot be used to target exact PFAS precursor compounds**	Total organic fluoride corrected to remove inorganic forms

All of the biosolids data analysed in the following section used the accredited method TOP assay, originally published by Houtz and Sedlak (Hossain, Strezov, Chan, & Nelson, 2010), which is widely used as an estimate of the total perfluoro alkyl acids (PFAA) content of a sample, particularly in wastewater and biosolid matrices.

The laboratory contracted to undertake the PFAS analysis is developing an experimental method, which is still TOP assay, but uses a different set of analysis parameters that provide for a more robust oxidation of the precursor substances that yield a higher extraction value. This method is still under development and peer review; however, the current parameters for extraction of samples via this method are consistent. It is believed that:

> '…the Houtz and Sedlak (Houtz, Sutton, Park, & Sedlak, 2016) method significantly underestimated the levels of PFAS compared with the modified method, which showed a 10-fold increase in the measured PFAS after digestion'. (Hutchinson, Rieck, & Wu, 2020).

Each biosolid or biochar sample was analysed via the complementary methods to gain a wholistic understanding of the biosolids and biochar characteristics. However, only data from the accredited method was used in statistical analysis.
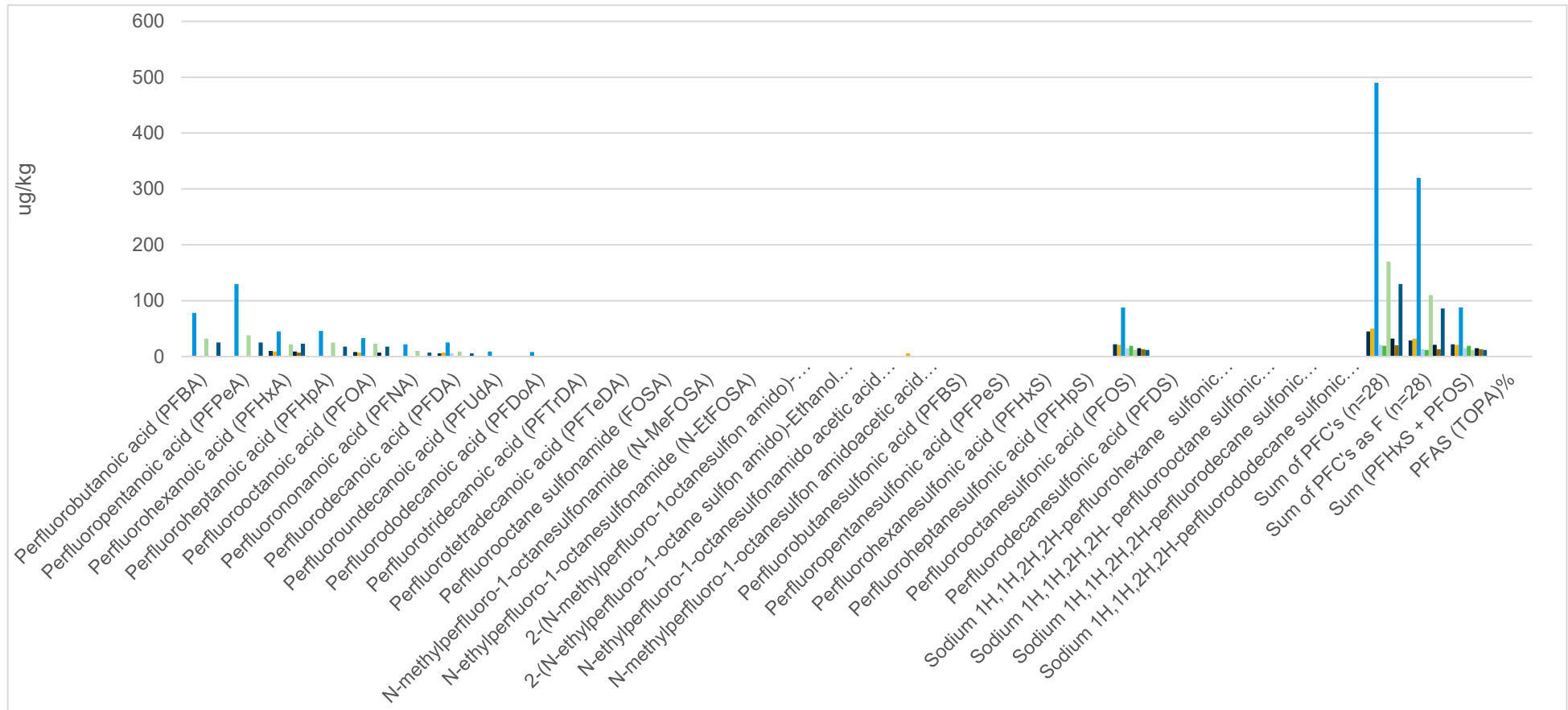
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Figure 6-1:   Source 1 PFAS concentrations

Figure 6-1 is an overview of the PFAS concentrations found in the biosolids from Source 1. The PFAS concentration found in these biosolids would not meet the criteria to apply to residential land with garden-accessible soil. The Source 1 biosolids average sum of PFHxS + PFOS was 17ug/kg and PFOA was 5ug/kg. Therefore, the PFAS concentration exceeds the trigger values for the use in residential areas and would need to be closely regulated.

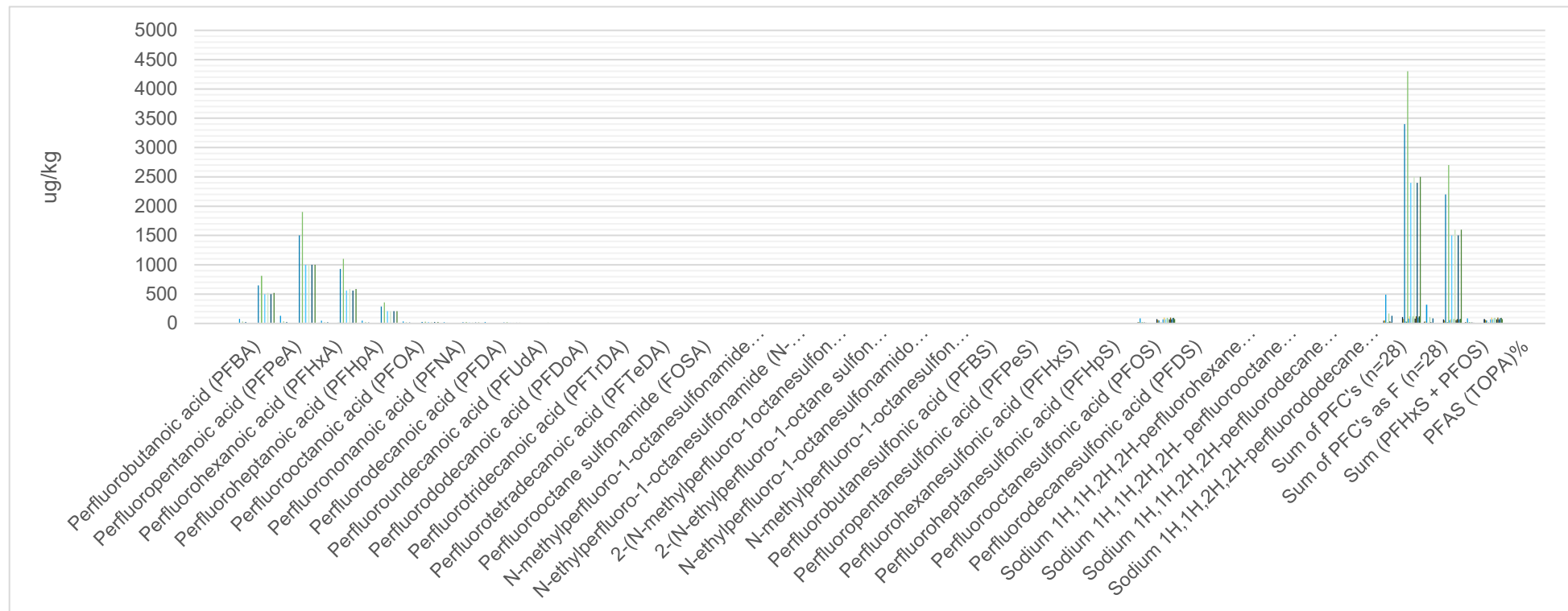Figure 6-2 is an overview of the PFAS concentrations found in the biosolids from Source 2.

Figure 6-2: **Source 2 PFAS concentration**

Figure 6-2 is an overview of the PFAS concentrations found in the biosolids from Source 2. The PFAS concentration found in these biosolids would not meet the criteria to apply to residential land with garden-accessible soil. The PFAS concentrations for Source 2 biosolids are even higher than Source 1 and would not be meet the criteria to apply to public open spaces. Source 2 biosolids average sum of PFHxS + PFOS was 38ug/kg and PFOA the was <5ug/kg. Therefore, the PFAS concentration exceeds the trigger values for the use in residential areas and public open spaces and would need to be closely regulated.

6.2   Loganholme and Beenleigh WWTP PFAS concentrations

Figure 6-3 illustrates a direct comparison of biosolid samples from Loganholme and Beenleigh WWTPs.
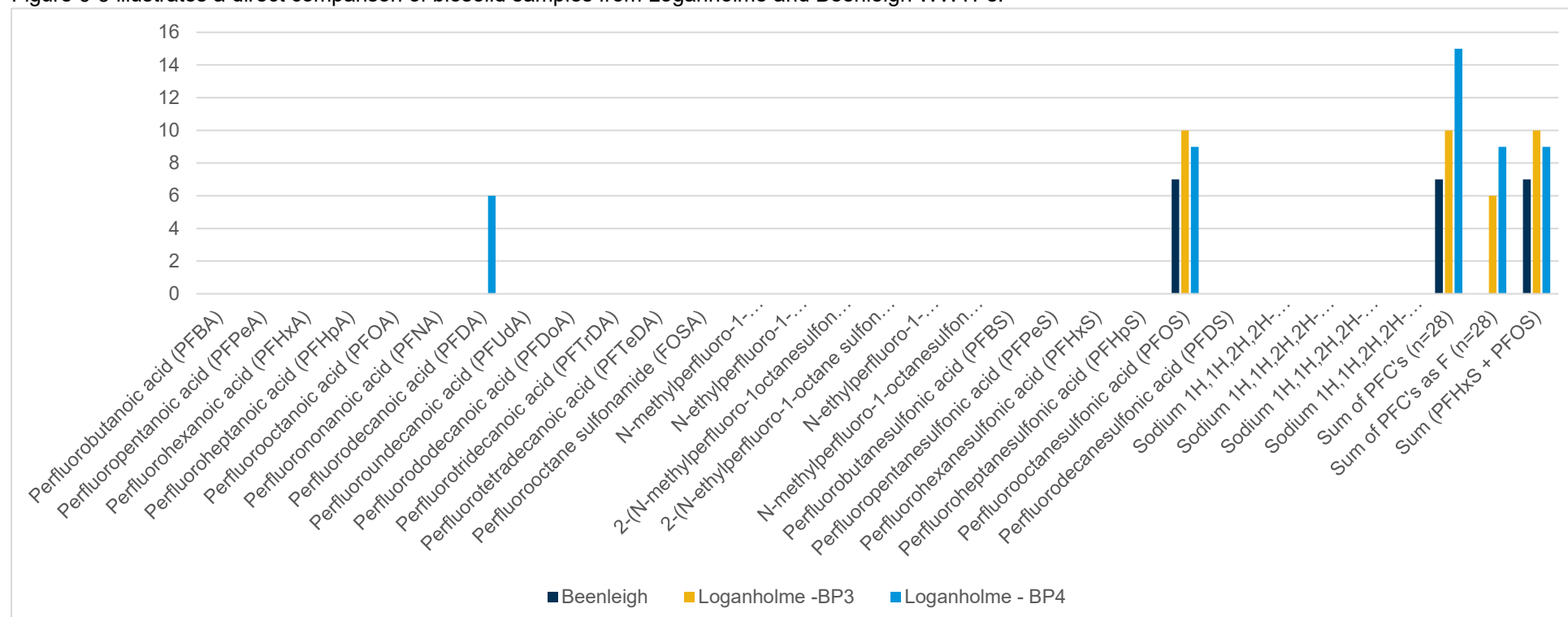

Figure 6-3:   **Loganholme and Beenleigh WWTP PFAS concentrations**

Figure 6-3 is an overview of the PFAS concentrations found in the Loganholme and Beenleigh WWTP biosolids. The sum of PFHxS + PFOS for Loganholme WWTP belt press 3 (BP3) was 10 ug/kg and for belt press 4 (BP4) 9 ug/kg and PFOA was <5ug/kg for both sets of samples. For Beenleigh WWTP, the sum of PFHxS + PFOS was 7 ug/kg and PFOA was also <5 ug/kg. Therefore, the PFAS concentration, although within the detection levels, does not exceed the trigger values for soil application and, in its current form, is within the range for residential use.

6.3 Biochar and PFAS

Once the biochar was processed through the demonstration plant, the sum of all (PFHxS + PFOS) or PFAS TOPA% for Source 1 biosolids was <0.5ug/kg or not detectable (in four samples in total).

For Source 2, 24 biochar samples were analysed for the TOP assay method and PFHxS + PFOS was 2ug/kg and PFOA was also <0.5ug/kg. It is assumed that one of the reasons for the detection of PFAS in the biochar samples is that characteristics of the Source 2. Being processed thorough a 'pelletiser' dryer means that the biosolids are produced as spherical pellets, which are quite dense and, in some cases, have quite large particle sizes. This size is not conducive to being able to be processed and fully charred through the hearth. Sampling from the system was also difficult; however, Figure 6-4 are photos of the samples were received by the laboratory.

Figure 6-4:   Source 2 pellets sizes produce biochar that is not fully charred

This is not the process that would occur in the full-scale facility due the use of the belt dryers, which produces more of a crumb rather than a pellet. All particle sizes would be within the range of 3–10mm. For corrective action, the bags of biochar were resampled two weeks later, which is out of holding time. However, but all these samples produced lower results and the average of sum was 1 ug/kg, which illustrates the importance of particle size consistency.

During the gasification process, all the PFAS compounds are made volatile in the hearth and then they progress through to the oxidiser. Therefore, the biochar does not contain PFAS at concentrations that would trigger the soil application limits and is a better overall product that will stop the bioaccumulation process in the environment.

6.4 Mass valance for PFAS

Table 6-3 is a mass balance that incorporates all data from all the sources: biosolids samples from both Source 1 and Source 2; the scrubber water (in the full-scale facility this water will return to the inlet works or be used as quenching water); and the stack (three full air emissions analyses). The oxidisers were incorporated in the air emissions analysis to give guidance on whether one or two oxidisers were required in the full-scale facility. The results show that only one oxidiser is required for each gasifier.

Table 6-3: PFAS mass balance

Analytes	Biosolids		Biochar		Oxidisers		Scrubber		Stack		% Destruction
	µg/kg	µg/hour	µg/kg	µg/hour	g/min	µg/hour	µg/L	µg/hour	g/min	µg/hour	
Perfluorobutanesulfonic acid	0	0	0	0	0.00000008	0.001	0	0	0.000000019	1.1259	
Perfluoropentane sulfonic acid (PFPeS)	0	0	0	0	0.00000008	0.001	0	0	0.000000011	0.6803	
Perfluorohexane sulfonate (PFHxS)	9	3654	0	0	0.00000008	0.001	0	0	0.000000021	1.2324	**100**
Perfluoroheptane sulfonate (PFHpS)	0	0	0	0	0.00000008	0.001	0	0	0.000000011	0.6803	
Perfluorooctane sulfonate (PFOS)	32.1	13482	2.8	1176	0.00000012	0.002	0	0	0.000000064	3.8578	**91**
Perfluorodecanesulfonic acid (PFDS)	1.2	504	0	0	0.00000016	0.003	0	0	0.000000023	1.3606	**100**
Perfluorobutanoic acid	1.3	546	0	0	0.00000048	0.008	0	0	0.000000284	17.0355	**97**
Perfluoropentanoic acid (PFPeA)	0	0	0.2	84	0.00000038	0.006	0.0022	2.42	0.000000384	23.0351	
Perfluorohexanoic acid (PFHxA)	8.7	3654	0	0	0.00000044	0.007	0.0008	0.88	0.000000077	4.6219	**100**
Perfluoroheptanoic acid (PFHpA)	0	0	0	0	0.00000027	0.005	0	0	0.000000104	6.2117	
Perfluorooctanoic acid (PFOA)	1.5	630	0	0	0.00000122	0.020	0	0	0.000000957	57.4321	**91**
Perfluorononanoic acid (PFNA)	0	0	0	0	0.00000024	0.004	0	0	0.000000060	3.6136	
Perfluorodecanoic acid	5.3	2226	0	0	0.00000049	0.008	0	0	0.000000071	4.2316	**100**
Perfluoroundecanoic acid (PFUnA)	0	0	0	0	0.00000052	0.009	0	0	0.000000071	4.2316	
Perfluorododecanoic acid (PFDoA)	0	0	0	0	0.00000047	0.008	0	0	0.000000057	3.4016	

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Perfluorotridecanoic acid (PFTrDA)	0	0	0	0	0.00000044	0.007	0	0	0.000000057	3.4016	
Perfluorotetradecanoic acid (PFTeDA)	0	0	0	0	0.00000203	0.034	0	0	0.000000283	17.0079	
4:2 Flurotelomersulphonate	0	0	0	0	0.00000008	0.001	0	0	0.000000011	0.6803	
6:2 Fluorotelomersulphonate	0	0	0	0	0.00000011	0.002	0	0	0.000000180	10.7836	
8:2 Fluorotelomersulphonate	0	0	0	0	0.00000010	0.002	0.0056	6.16	0.000000134	8.0422	
10:2 Fluorotelomersulphonate	0	0	0	0	0.00000008	0.001	0	0	0.000000043	2.5596	
Perfluorooctane sulfonamide	0	0	0	0	0.00000039	0.007	0	0	0.000000057	3.4016	
N-Methyl-heptadecafluorooctane sulphonamide	0	0	0	0	0.00000039	0.007	0	0	0.000000057	3.4016	
N-Ethyl-heptadecafluorooctane sulphonamide	0	0	0	0	0.00000039	0.007	0	0	0.000000057	3.4016	
N-Me perfluorooctanesulfonamid oethanol	0	0	0	0	0.00000039	0.007	0	0	0.000000057	3.4016	
	0	0	0	0	0.00000197	0.033	0	0	0.000000283	17.0079	**94**

Table 6-3 shows that the overall mass balance for PFAS destruction through the process of gasification facility, which is 94% destruction of this persistent organic pollutant. This verifies that the gasification process when carbonisation occurs of the biosolids PFAS becomes volatile and is transferred to the off gas and is then destroyed in the thermal oxidisers. There was cross contamination seen when the biosolids particles sizes were too large and dense to fully carbonise and this carry over is not expected when processed through the belt dryers in the full-scale facility.

6.5 Microplastics

Microplastics are plastics smaller than 5 mm and they fall into two broad types:

- Primary-intentionally produced plastics, for example microbeads from toothpaste or glitter from cosmetics

- Secondary-resulting plastics from the weathering of larger plastics such as microfibres, that may cause adverse effects in organisms and ecosystems.

In Australia, between 2800 and 19,000 tonnes of microplastics are applied to agro-ecosystems each year through biosolids. Figure 6-5 shows examples of microplastics found in biosolids.
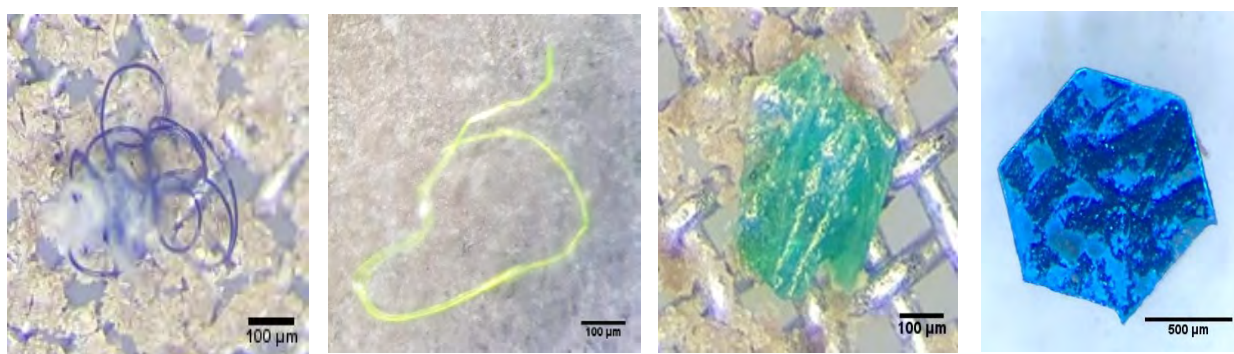
Figure 6-5:   **Micro and nano-plastics: microfibers, fragment (100µm), glitter (500µm)**

The Source 1 biosolids contained a high proportion of microplastics. On average, the biosolids contained 8.8 particles/gram. Figure 6-6 shows the size of microplastics found in the biosolids and after they had been treated through the gasification process.
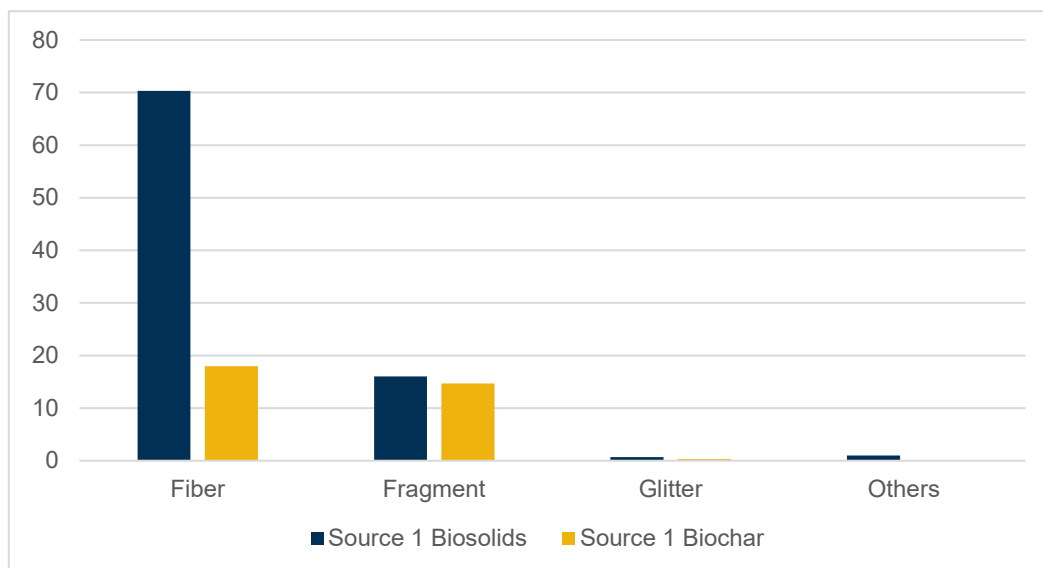

Figure 6-6:   **Source 1 types of microplastics in the biosolids and biochar**

Figure 6-7 illustrates the particle types found in the Source 1 WWTP samples and after the treatment through the gasification system. It shows the gasification process reduces the microplastic plastic concentration; 1mm (81% less), 250µm (72% less), 150µm (60% less) and 63µm (35% less).
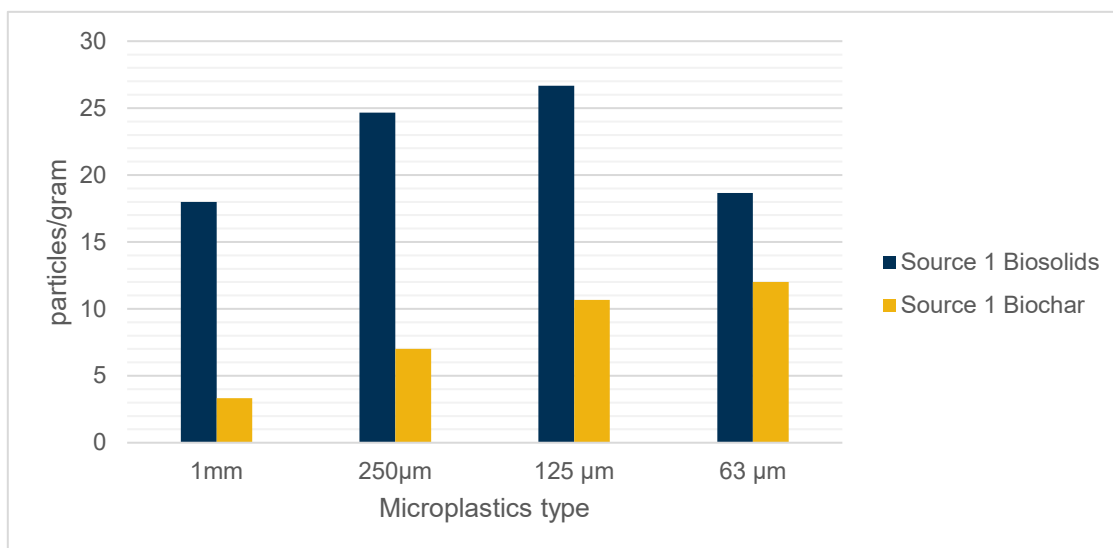
Figure 6-7:   **Source 1 microplastic types in the biosolids and biochar**

Figure 6-7 shows that the gasification process destroys more of the fibre type microplastics with a 74% destruction rate compared with fragment (8%), glitter (50%) and others (100%). This emerging contaminate of concern can be significantly reduced through the gasification process.
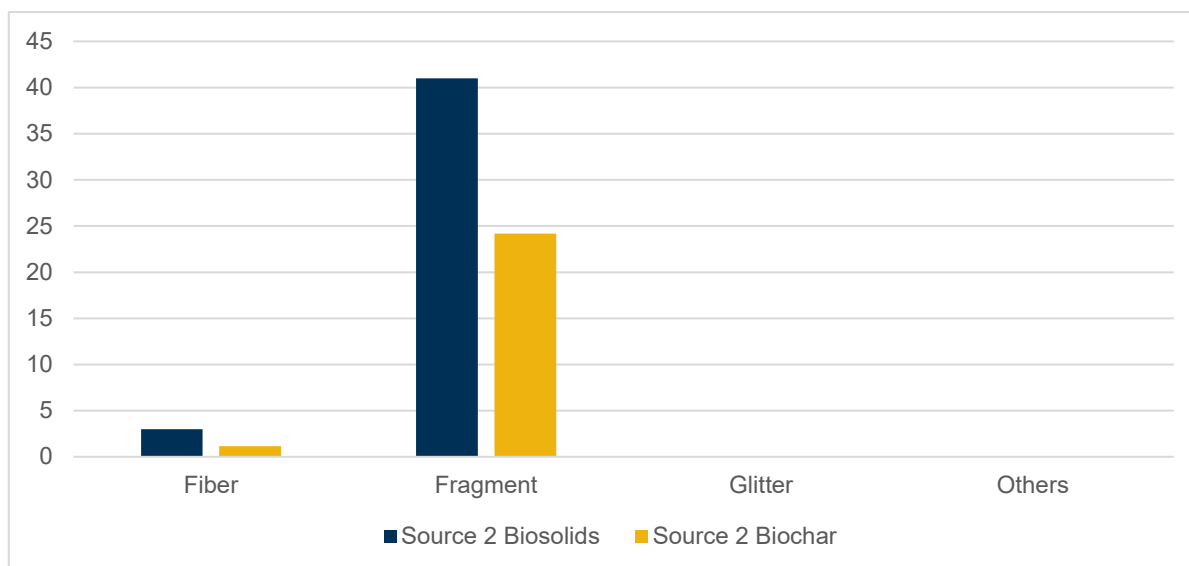

Figure 6-8:   **Source 2 particle size of microplastics in the biosolids and biochar**

Figure 6-8 illustrates the particle types found in the Source 2 biosolid samples and after treatment through the gasification process. It shows the gasification process reduces the microplastic plastic concentration: 1mm (39% less); 250µm (48% less); 150µm (29% less); and 63µm (36% less). These destruction limits are less then Source 1, but these results are to be expected given the larger, denser particle size of Source 2 biosolids.
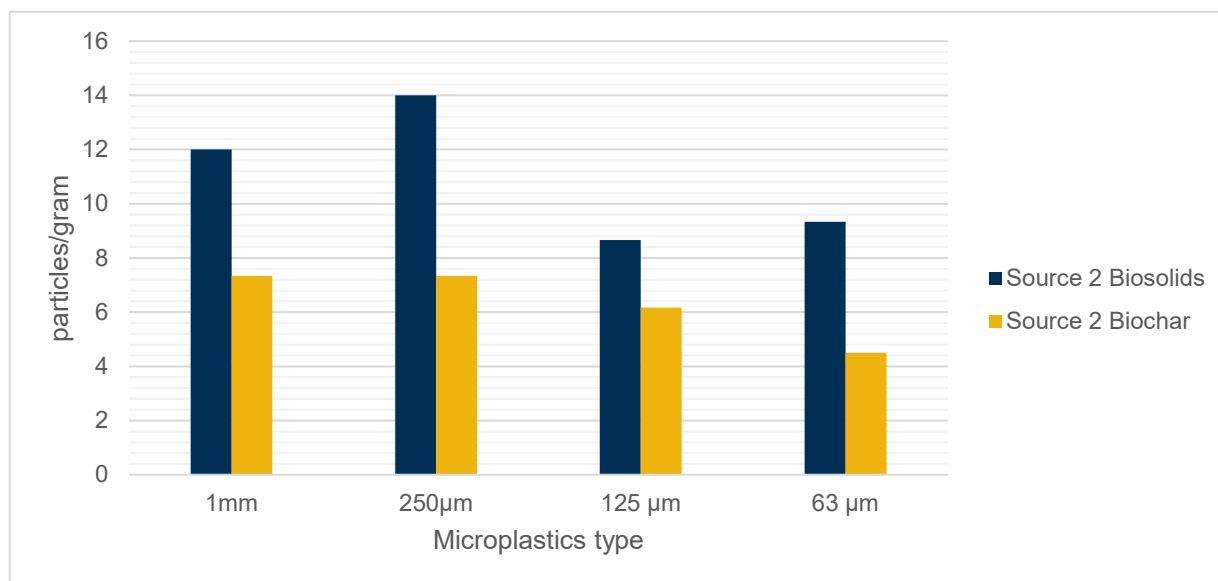
Figure 6-9: **Source 2 microplastic types in the biosolids and biochar**

Source 2 biosolids was small and dense because it is pelletised and not what is expected out of full-scale facility design of the belt dryers, which is more of a uniformed crumb. Also, even though the Source 2 biosolids is pelletised, they are not as dense and tightly bound and far easier to be crushed and more representative of what would be expected in the Loganholme WWTP full-scale facility. Therefore, it is expected that the microplastic destruction would be greater when processed through the belt dryer than what is illustrated in the Source 1 and 2 biosolids. Figure 6-9 shows that the gasification process does seem to destroy more of the fibre type microplastics with a 61% destruction rate compared with 41% fragment types.

The Loganholme WWTP biosolids have microplastics of around 3.3 particles/gram. Figure 6-10 shows the size and type of microplastics found in the Loganholme WWTP sludge.
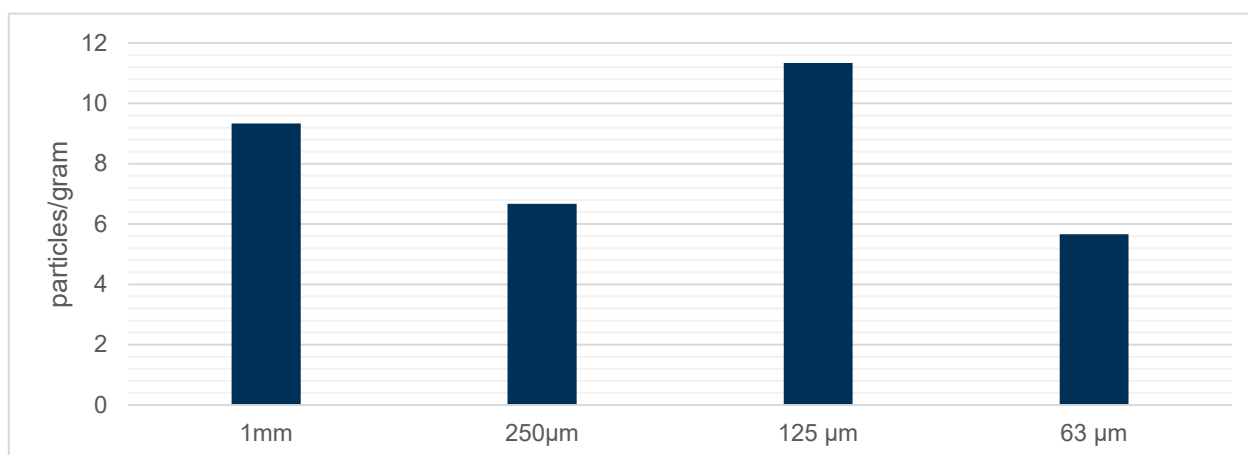

Figure 6-10: **Loganholme WWTP particle size of microplastics in the biosolids and biochar**

Figure 6-11 show a representative sample of biosolids from the Loganholme WWTP illustrating the types of microplastics found.
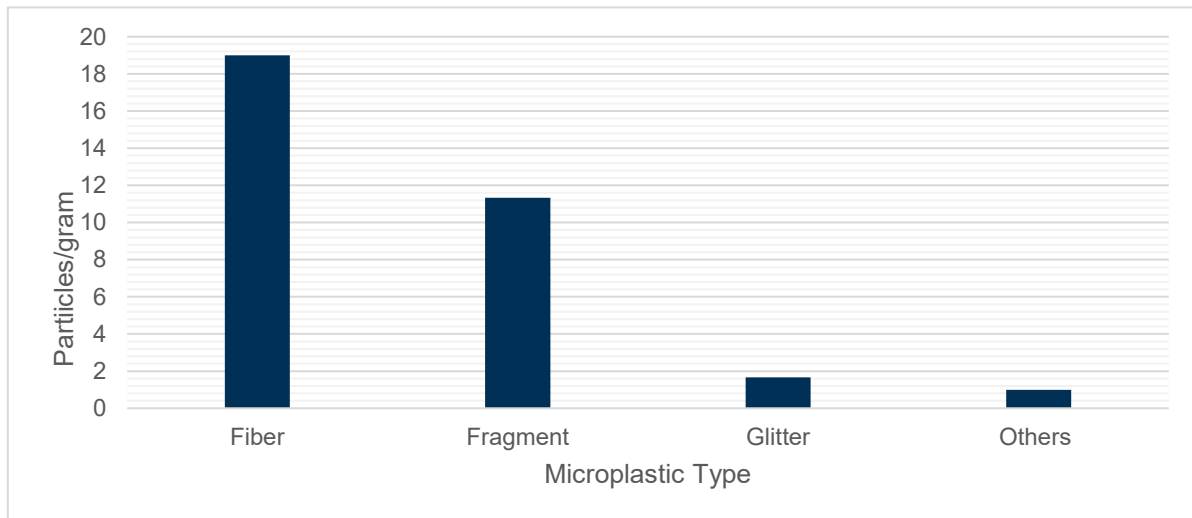

Figure 6-11:   **Loganholme WWTP microplastic types in the biosolids and biochar**

As shown in Figure 6-11, Loganholme WWTP biosolids, like Source 1 biosolids, mostly contained fibre and fragment types of microplastic, as well as glitter. Overall, Loganholme WWTP biosolids had 63% less plastics than Source 1. This could be due to the dry concentration of the Source 1 biosolids.
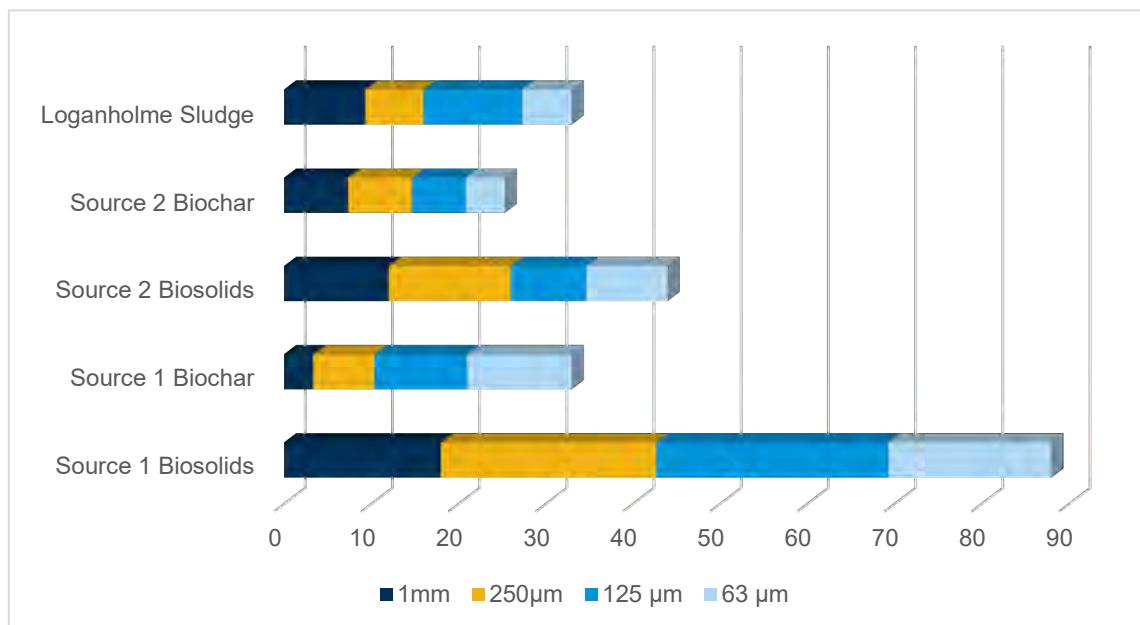

Figure 6-12:   **Microplastics particle size comparison across all sources of biosolids**

Figure 6-12 shows that microplastics are present in the biosolids from all WWTPs; however, it also shows that Source 1 has a significant proportion compared to Loganholme WWTP and Source 2. Overall, the destruction of microplastics through the gasification process is around 60% when the source material has been through a pelletising drying process. Therefore, processing biosolids through a belt dryer that produces a less condensed source material would potentially mean a higher destruction rate of microplastics. This is an area to investigate once the full-scale facility is implemented in the Loganholme WWTP to determine the destruction rates.

7. Heat Balance

This section is an overview of how the demonstration plant addresses its objective for the heat balance for an integrated drying facility.

7.1 Background

The unit supplied for the demonstration plant incorporated a steam boiler and condensing unit to capture and measure heat generation and recovery (Pipatmonomai, Kaewluan, & Vitidsant, 2009) (Solarte-Toro, Chacon-Perez, & Cardona-Alzate, 2018). Hot flue gases from the thermal oxidiser passed through a steam boiler before being discharged to a wet scrubber.

For the demonstration plant, the steam was re-condensed via a heating coil submerged in a water bath to allow the recovered heat to be measured. Condensate was returned to the steam boiler. Plant service water used for the water bath drained back to the treatment plant. This was a controlled exercise and the scrubber water. In the full-scale facility, the flue gas will be used to heat a water circuit in a hot water generator rather than a steam boiler. The hot water set at 90–95 °C will exchange heat into a separate dryer water circuit that returns at 70–75 °C.

A key objective of the integration of dewatering, drying and gasification is that the overall process is heat-energy neutral. This effectively means that sufficient heat needs to be recovered from that produced in the gasification process to operate the dryer without the need for an additional fuel source during normal operation. The heat balance of the overall integrated drying–gasification process is mostly influenced by four parameters:

1. **Calorific value of the biosolids:** This is related to the volatile solids content of the biosolids and is inherent to the treatment plant and, therefore, not able to be adjusted in design or operation.

2. **Biosolids dewatering performance:** Mechanical removal of water via centrifugal dewatering is more efficient than evaporation and significantly impacts the heat required for drying. The initial dewatering step is designed to achieve 20% w/w dry solids (target) with 18% w/w minimum.

3. **Thermal efficiency of the dryer:** Measured as kW of heat input per tonne of water evaporated, a lower figure represents higher efficiency. This is a fundamental characteristic of the type of dryer.

4. **Operating temperature of the dryer:** A lower operating temperature allows for greater heat recovery from the gasification process flue gas as the final flue gas temperature can be reduced. The operating temperature range is inherent to the type of dryer.

Table 7-1: Calorific values for Source 2 and Loganholme and Beenleigh WWTPs

Calorific value	Unit	Loganholme WWTP	Beenleigh WWTP	Source 2
Net	MJ/kg DM	18.80	18.4	19.26
Gross	MJ/kg (calc)	2.25	2.20	2.23

Table 7-1 compares the calorific value of Source 2 biosolids to those from Loganholme WWTP and Beenleigh WWTP. Although Beenleigh WWTP is lower than Loganholme WWTP, once the sewage diversion is in place Beenleigh WWTP will be closer in value to the Loganholme WWTP values as calorific value is determined by the process stream. This shows that the Loganholme WWTP biosolids calorific value is 98% to that of Source 2 and therefore very similar results in heat energy recovery are expected. Table 7-2 is the calculated energy recovery based on the Source 2 biosolids passing through the gasification facility.

The heat balance on the Source 1 biosolids was inadequate to the extent that the radiant heat exchanger on the thermal oxidiser had to be partially disabled to allow adequate oxidiser temperatures to be maintained. The heat balance on Source 2 biosolids is outlined in Table 7-2.

Table 7-2: **Summary of unit operations performance of the demonstration plant**

Parameter	Value	Notes
Biosolids feed rate	480 kg/hr	85% of design feed rate (565 kg/hr) 74% of maximum continuous feed rate (650 kg/hr)
Heat recovered at radiant heat exchanger (integrated with the Thermal Oxidiser)	350 kW	Median value at 800–820 °C oxidiser temperature. Scales upwards with oxidiser temperature.
(a) Heat recovered by radiant heat exchanger scaled from 85% feed rate to 100%	0.4 MW	350 kW x 100/85
Heat recovered from flue gas heat recovery steam generator	780 kW declining to 600 kW	Median value at 540 °C inlet temperature. Declining heat transfer efficiency over 48 hours.
Flue gas heat exchanger outlet temperature (T_{out})	185 °C to 265 °C	Higher temperature reflects loss of heat transfer efficiency. Much of the loss of heat transfer efficiency occurred over a period of 24–48 hours, with a slow ongoing decline after that.
Heat recovery steam generator efficiency	66% declining to 51%	Calculated from (Tin-Tout)/Tin. Tin = 540 °C.
Heat recovered from flue gas scaled to 80% heat recovery.	941 kW	Heat recovered @ 80% = HR @ 51% efficiency x 80/51 This is a prediction based on implementation of a flue gas to hot water heat exchanger in the permanent plant with on-line soot blowing provisions to maintain performance.
(b) Heat recovered from flue gas scaled from 85% rate to 100%	1.1 MW	941 kW x 100/85
Forecast heat recovery in permanent system at design rate (565 kg/hr)	1.5MW	(a) + (b). The nominal requirement is 1.4MW per processing train. The expected performance exceeds the requirement; however, the design margin is minimal (less than 10%) and sensitive to the dewatering performance. Therefore, Pyrocal recommends the implementation of a condensing heat exchanger, located downstream of the main flue gas heat exchanger. The heat/temperature available at this point should be suitable for 150-200 kW of pre-heating for the water to the main flue gas heat exchanger. This would raise the design margin for the heat balance to 20%.

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8.   Operating Costs

The operating costs of the plant are dominated by the consumption of process additives for equipment protection and emissions control, and electrical consumption. The chemical additions required are an alkali such as magnesium hydroxide ($(Mg(OH)_2)$) for hot corrosion control and SOx/metals capture and an ammonia source such as urea for NOx reduction.

Electrical consumption was measured at 42–45 kW, at a power factor of -0.9 and a rate of 480 kg/hr, scaling directly with throughput at rates exceeding 33% of design throughput. This equates to 94kWh per tonne of biosolids feed.

Initially, hydrated lime ($Ca(OH)_2$) was used as the alkaline chemical additive. While this solution worked, the reliability of handling was poor in a weather-exposed environment. Hold-ups in the metering hopper were experienced. Lime powders are well known for this behaviour. In addition, accumulation of insoluble calcium compounds was observed in the scrubber and while the accumulation did not cause an operational issue, the issue could be foreseen. Therefore, a high concentration sodium hydroxide solution was trialed and then a magnesium hydroxide ($Mg(OH)_2$) slurry. Of the two, magnesium hydroxide was considered the best option because it caused no accumulation of precipitates in the wet scrubber and is safer to handle than sodium hydroxide.

A 50% urea solution was injected into the gas stream as a source of ammonia for NOx reduction. Two different addition points were trialed, with addition after the oxidiser providing the best performance.

The demonstration plant not only allowed optimisation of the choice of chemicals but also the ability to determine the final consumption rates.

8.1   Urea

When starting the demonstration plant, the urea dosing rates were around 40 L/tonne of dry biosolids of 50% w/w urea solution, subject to increases up to 180 L/tonne of biosolids if high carbonisation temperatures were used (greater than 700 °C). This was significantly optimised throughout the demonstration and Table 8-1 shows dosing rates expected for the full-scale facility.

Table 8-1:   Urea dosing rates

	1 unit	**2 units**
Throughput	575 kg/h	1150 kg/h
Urea concentration	0.4%	0.4%
Dosing rate	2.3 kg/h	4.6kg/h
	12L/h	24 L/h
Dosing location	Spear of the inlet of the oxidisers	

Table 8-1 shows that the dosing rate has been optimised from 40–180 L/dry tonne to around 20L/dry tonne. This is a significant decrease in the amount of urea required for mitigation of NOx. Table 8-1 also shows the calculated dose rates for ultimate design capacity.

8.2   Magnesium hydroxide

Initially, the demonstration plant was consuming up to 30 litres per tonne of dry biosolids of $Mg(OH)_2$ 55% w/w slurry. This was primarily influenced by dust release rate (system throughput), i.e. higher dust rates resulted in lower alkali requirement, because the carbon dust captured in the scrubber was mildly alkaline with a pH in water of approximately 8.5. Table 8-2 calculates the dosing for ultimate design capacity.

Table 8-2:   **Magnesium hydroxide dosing rates**

	1 unit	2 units
Throughput	575 kg/h	1150 kg/h
$Mg(OH)_2$ concentration	1.20%	1.20%
Dosing rate	6.9 kg/h	13.8kg/h
	4.5 L/h	9L/h
Dosing location	Suction of wet scrubber recirc pump (75%) Screw feeding the Hearth (25%)	

Table 8-2 illustrates that the dosing rate has been optimised from 30 L/dry tonne to around 4.5L per dry tonne. This is a significant decrease in the amount of urea required for mitigation of NOx.

8.3   Diesel

Diesel should also be accounted for in the operational. At start-up, each hearth requires around 100L per train—two gasifiers would require 200L of diesel each start-up. Overall, the full-scale facility requires continuous running for two weeks with two days shutdown. Therefore, the diesel consumption would be around 400L per month.

8.4   Boiler shield

The boiler shield is a required chemical that is used in a closed loop. However, every two weeks, 25L would have to be dosed as a top-up as part of the maintenance scheduled shutdown periods.

9.   Conclusion

The Loganholme WWTP Biosolids Gasification Demonstration Plant has proven to be an innovative solution to a problem facing WWTPs that are managing biosolids: increasing energy costs, haulages rates and emerging contaminants of concern. The demonstration plant confirmed that gasification of biosolids is a reliable process that can be incorporated into a WWTP.

Each of the objectives set for the demonstration plant in terms of reliability, air emissions, persistent organic pollutants, heat balance and operating costs were achieved.

Therefore, it is recommended to proceed with the full-scale Biosolids Gasification Facility at Loganholme WWTP.

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Appendix A: Char Characteristics, Potential Value and Reuse Options

TO WHOM IT MAY CONCERN

I Trevor Bridle, of Bridle Consulting, confirm that I am the author of the report, "Task 2, Char Characteristics, Potential Value and Reuse Options", dated October 2020, prepared to Logan City Council.

Signed:

Trevor Bridle

Date: 8th December, 2020

TASK 2: CHAR CHARACTERISTICS, POTENTIAL VALUE AND REUSE OPTIONS

VALUE AND REUSE OPTIONS

Prepared for

**Water Infrastructure
Logan City Council**

Prepared by

BRIDLE CONSULTING

October 2020

LIST OF ACRONYMS

BoD	Basis of Design
DS	Dry Solids
Dry tpa	Dry tonnes per annum
Dry tpd	Dry tonnes per day
GCV	Gross Calorific Value
HM	Heavy Metal
K	Potassium
N	Nitrogen
P	Phosphorous
PFAS	Poly Fluoro Active Substance
PFC	Per Fluoro Compounds
TS	Total Solids
VS	Volatile Solids
Wet tpd	Wet tonnes per day
WWTP	Wastewater Treatment Plant

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1.   Introduction

After the successful full-scale demonstration of the Pyrocal gasification process earlier this year Logan City Council is now proceeding with a commercial gasification facility at their Loganholme WWTP. The Basis of Design (BoD) for this facility, which includes Mass and Energy Balances, has been developed by Logan Water. The full-scale demonstration work was done using dried sewage sludge from Source 1 and Source 2 WWTPs since no dried sludge was available from any of the Logan Water WWTPs. Bridle Consulting was contracted by Logan City Council to estimate char characteristics that would be generated from Loganholme biosolids, based on the data generated from the demonstration trials and comment on the potential value and uses of the char.

2.   Information Provided

Logan City Water provided the following documents to Bridle Consulting to conduct this Char Reuse Review:

1. DT 007 Loganholme Biosolids Treatment Process Mass Balance, Rev 3 xlsx.

2. Excel Spreadsheet named "Copy of Merge". This spreadsheet included analytical data of the Loganholme, Source 1, and Source 2 biosolids as well as char analytical results from the Source 1 and Source 2 gasification trials.

3.   Estimation of Loganholme Char Quality

The quality of the char that will be produced from gasification of Loganholme biosolids has been estimated based on the following information:

*   Loganholme biosolids analytical data provided by Logan Water,

*   The design char yield of 35% as reported by Logan Water,

*   The classification of NPK from biosolids to char, based on published data,

*   The classification of heavy metals from biosolids to char, based on results reported by Logan Water from the gasification trials, and,

*   The destruction of PFCs as reported via the gasification trials. Estimates of PFAS destruction is by Bridle Consulting.

A summary of the average gasification trial results for the four runs using Source 1 biosolids and the eighteen runs using Source 2 biosolids are shown in Table 3-1.

Table 3-1:   **Average gasification trial results**

Parameter	Units	Source 1		Source 2	
		Biosolids	Char	Biosolids	Char
VS	%	70.7	36.3	72.3	38.3
Ash	%	29.3	63.7	27.7	61.7
Calculated char yield	%		46.00		44.9
As	mg/kg	<5	<5	8.1	4.4
Cd	mg/kg	<1	<1	<1	1.4
Cr	mg/kg	19	40.3	32.3	73.1
Cu	mg/kg	157	252.5	331	613
Pb	mg/kg	8.2	17.3	11.5	26.4
Hg	mg/kg	0.1	<0.1	0.4	<0.1
Ni	mg/kg	13.7	16	16.1	31.3
Se	mg/kg	<5	<5	<5	<5
Zn	mg/kg	360	765	569	1311
PFAS	ug/kg	22			
Total PFCs	ug/kg	32.7	<5	57	<5

The average char yield for the Source 1 and Source 2 runs are calculated because all the ash in the biosolids is conservative and is classified (transferred) to the char.

A wealth of information on the fate of heavy metals in biosolids during gasification and pyrolysis has indicated that volatile and semi-volatile metals such as mercury, arsenic and cadmium are vaporised during the process. All the mercury is vaporised and much of the cadmium and a lesser amount of arsenic are also vaporised and transferred to the syngas. All the other heavy metals are completely retained in the char.[1]

Based on this fact the theoretical char concentrations of the non-volatile heavy metals have been calculated, based on measured char yields for the Source 1 and Source 2 gasification trials and these are reported, together with measured metal values, in Table 3-2.

Table 3-2:   **Calculated and measured char heavy metal values**

Heavy Metal	Units	Measured/Theoretical Char HM Value			
		Source 1		Source 2	
		Measured	Theoretical	Measured	Theoretical
Cr	mg/kg	40.3	41.3	73.1	71.9
Cu	mg/kg	252.5	341.3	613	737.3
Pb	mg/kg	17.3	17.8	26.4	25.6
Ni	mg/kg	16	29.8	31.3	35.9
Zn	mg/kg	765.0	782.7	1311	1267.4

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[1] Bridle, T.R, Hammerton, I.F and Hertle, C.K, "Control of Heavy Metals and Organochlorines using the Oil-from-Sludge Process", Proceedings of the IAWPRC Sludge Management Conference, Los Angeles, January 1990.

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As can be seen there is very good agreement between the measured and theoretical char HM values. Consequently, to estimate the expected char heavy metal concentrations from the full-scale Loganholme gasification facility the theoretical approach has been adopted.

The predicted char characteristics from the full-scale Loganholme gasification facility are shown in Table 3. These predicted char characteristics are based on the Logan Water Loganholme biosolids characteristics provided to Bridle Consulting and the following assumptions:

- A char yield of 35%, as provided by Logan Water,

- That about 55% of the biosolids N and all the P and K is classified to the char[2], and,

- Metal and contaminant classification and PFC/PFAS destruction as noted above.

It is recommended that Logan Water use these char characteristics when discussing char reuse options with Regulatory Agencies and potential char users.

Table 3-3:   **Predicted Loganholme Gasification Facility char characteristics.**

Parameter	Units	Loganholme Biosolids	Char
VS	%	81	47.2
Ash	%	19	52.8
Nitrogen	%	5	7.9
Phosphorus	%	2.3	6.6
Potassium	%	0.67	1.9
Estimated char yield	%		35
As	mg/kg	2.6	1.5
Cd	mg/kg	0.7	2.0
Cr	mg/kg	48	137
Cu	mg/kg	260	743
Pb	mg/kg	13	37
Hg	mg/kg	0.5	<0.05
Ni	mg/kg	210	600
Se	mg/kg	4.2	12
Zn	mg/kg	626	1789
PFAS	ug/kg	22	<0.2
Total PFCs	ug/kg	44.9	<0.45

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[2] Bridle, T.R and Prichard, D., "Energy and Nutrient Recovery from Sewage Sludge via Pyrolysis", Proceedings of the IWA Conference, Resources from Sludge, Forging New Frontiers, Singapore, March 2004.

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4. Potential Value of the Char

The char from biosolids gasification contains many valuable components, the major valuable constituents being the following:

- Phosphorus and Potassium (P and K). These macro plant nutrients are 100% bio-available and have been speciated in a slow-release form by the thermal gasification process[3]

- Fixed Carbonised Carbon that significantly enhances soil fertility. Research by the NSW Department of Agriculture has demonstrated up to a 30% increase in broad acre crop yields when char is applied at a rate of 10 tonnes per hectare on agricultural soil

- Minor nutrients and Trace Elements such as Sulphur, Boron, Iron, Molybdenum, Zinc, Cobalt and Copper that are vital for crop growth, and,

- Energy.

The Nitrogen in the char is not plant available and thus has no agronomic value.

The most valuable components in the char are the nutrients P and K. Based on the current prices for the fertiliser's urea ($450/t), mono-ammonium-phosphate ($800/t) and potassium chloride ($380/t) the current value of P is $2,900/t and the value of K is $199/t. Based on the predicted concentrations of P and K in the Loganholme char, the value of these two nutrients is $211/t char. The estimated Fixed Carbon content of the char is 36%. It is difficult to put a value on this fixed carbon, but it is likely to be in the range of $100 to $200/t. At a value of $150/t the value of fixed carbon in the char is thus $54/t char. **Thus, the overall value of the char, for reuse in agriculture, is likely to be, at minimum, $265/t.**

The other major valuable component in char is energy. It is estimated that the Loganholme char will have and energy content of 20 GJ/t. Based on the current Australian price for coal ($56/t), with an energy content of 28GJ/t, the energy value of coal is $2/GJ. **Thus, the overall value of the char, for reuse as an energy source, is likely to be $40/t.**

This analysis strongly indicates that maximum returns from char sales will be in the agricultural sector. This reuse option also provides the best environmental outcomes.

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[3] Pritchard, D, Curtin University of Technology, "Nutrient Properties of Char", Research Report prepared for Environmental Solutions International Ltd, Perth, WA, September 2003.

5.   Potential Uses for the Char

A number of potential uses for char from gasification and pyrolysis of biosolids have been previously identified and these are summarised below[4]:

1.   Use in agriculture as a fertiliser supplement

2.   Use as a fuel in boilers, power plants and other industrial combustors

3.   Use as a fuel and feedstock in cement kilns

4.   Use as an ingredient to produce lightweight/insulating bricks and pavers

5.   Use as an industrial adsorbent in place of Activated Carbon

6.   Use as a low-grade Activated Carbon for odour control, and

7.   Use as a metallurgical reductant.

Use in Agriculture as a Fertiliser/Soil Supplement

This reuse option has the highest potential economic return for Logan City Council with the best environmental outcomes. There is sufficient scientific evidence of the significant benefit that is achieved by applying char as a fertiliser supplement to agricultural soils.

The major issue for Logan City Council will be in obtaining the necessary regulatory approvals for this reuse option. The current Queensland "End of Waste Code – Biosolids" (ENEW 07359617, December 2019) stipulates the quality of biosolids that can be applied to agricultural land. Provided that the biosolids meet contaminant and pathogen reduction requirements specified in the code the biosolids are not considered as waste but rather a resource which can be reused in agriculture. There are 3 grades of quality prescribed for the 3 reuse options, namely Unrestricted Use, Restricted Use 1, and Restricted Use 2. Based on the predicted char quality as shown in Table 3, the char would not meet the Nickel quality requirement of 270 mg/kg to allow Restricted Use 2 category. Consequently, broad acre agricultural reuse for the char would NOT be permitted in Queensland. It must however be noted that the Code only applies to biosolids and thus char is unlikely to be managed by the Code. However, this should be confirmed by Logan City Council.

Thus, the most likely option for agricultural reuse would be to blend the char with other components to produce a blended or compounded fertiliser/soil supplement, like the many commercially produced and bagged products currently available at gardening centers and hardware stores. This option should be explored by Logan City Council.

Use as a Boiler/Combustor Fuel

Many industrial boilers/combustors in Queensland use fuels other than coal, oil, or gas as their primary fuel. The char would be a very suitable alternate fuel for many of these industrial boiler/combustors. As mentioned previously, the potential value of this fuel would be $40/t char. The only issue regarding this reuse option would be obtaining environmental approval from the EPA. The issue would likely be the controls required to meet heavy metal, SOx, and NOx emission limits for the facility.

Use as a Fuel/Feedstock in Cement Kilns

The char has significant inorganic constituents (Si, Al, Ca etc.) that would add to clinker formation in the kiln. This would be an added benefit of using the char to supplement the kiln energy requirements. The value of char to cement manufacturing would be at least $40/t char. Due to the likely small contribution the char would make to kiln fuel requirements it is unlikely that any emission issues would be raised. Char has been used as a kiln feedstock in Europe.

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[4] Bridle, T.R, "Sludge Pyrolysis: Has its Time Arrived". Presented at the Bioenergy Australia Conference, Fremantle, December 2006.

Feedstock for Lightweight/Insulating Bricks and Pavers

This reuse option has been demonstrated and is in use in Europe where light weight/insulating bricks are routinely used in the construction industry. The char is mixed with clay and then fired in the kilns. The organics in the char are combusted leaving small pores in the finished bricks, providing the lightweight and insulating properties. Traditionally Styrofoam pellets are used, but they are now being replaced by char.

A full-scale production trial run of light-weight brick manufacture was undertaken in Germany using 1 tonne of char produced from a demonstration sludge pyrolysis unit[4]. This trail produced bricks of essentially the same quality as when using Styrofoam pellets. A picture of a brick from this manufacturing run is shown in Figure 1.
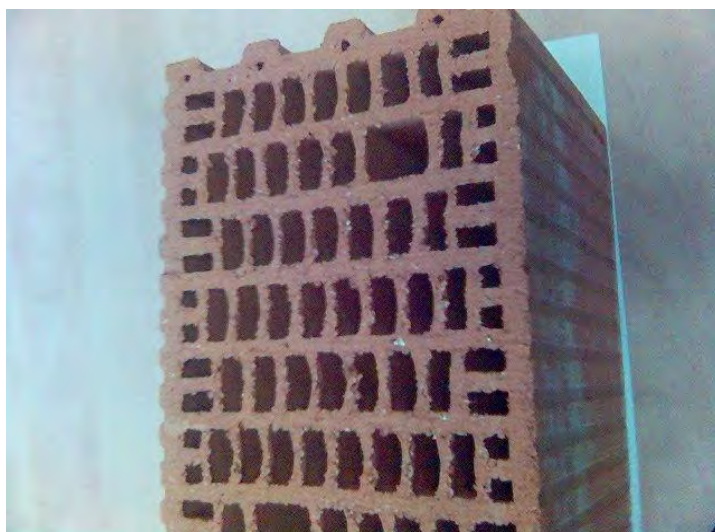

Figure 5-1:   Light-weight clay brick made with char addition

Dried sludge has also been used in South Africa for the production of light-weight bricks. There is, as yet, no market for this in Australia but this reuse option is worthy of consideration by Logan City Council.

Use as a Low-grade Adsorbent to Replace Activated Carbon

Char from biosolids pyrolysis or gasification has significant adsorptive capacity and is equivalent to a low-grade activated carbon. Test-work in Germany has shown that char has a very good adsorptive capacity for heavy metals[5]. When the char was activated it had much superior adsorptive capacity for heavy metals than conventional Activate Carbon. This may be a very good use for the char, especially for treating heavy metal contaminated ground water and mining/industrial effluents.

Use as a Low-grade Activate Carbon for Odour Control

Due to its high adsorptive capacity the char would be a good alternative to conventional activated carbon for odour control applications. It would also me a good media to use in biological odour control filters commonly used in the sewage and industrial wastewater treatment industries.

Use as a Metallurgical Reductant

Char, with its relatively high carbon content could be used to replace commercial reductants used in the metallurgical processing industry. To Bridle Consulting's knowledge this, reuse option has not yet been evaluated.

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[5] Skrypski-Maentele, S and T.R Bridle, "Environmentally Sound Disposal of Tannery Sludge", Wat. Res. Volume 29, No 4, 1995

6. Recommendations

Bridle Consulting recommends that Logan City Council evaluates, in more detail, the potential char reuse options identified in this report.

Reuse in the agricultural sector, as a blended soil supplement offers the maximum financial returns and also the best environmental outcomes. It is thus recommended that Logan City Council engages with the relevant Queensland Government Departments to identify any constraints on this reuse option. In addition, Logan City Council should contact the many commercial companies that operate in the blended fertiliser/soil markets to assess their interest in using char as one of the ingredients in their blended products.