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Valorisation of Composted Organic Fines and Sewage Sludge Using Pyrolysis (OF-PYR)

Authors: Marzena Kwapinska, David A. Agar, Bart Bonsall and James J. Leahy

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Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

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- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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EPA RESEARCH PROGRAMME 2014–2020

Valorisation of Composted Organic Fines and Sewage Sludge Using Pyrolysis (OF-PYR)

(2016-RE-MS-7)

EPA Research Report

Prepared for the Environmental Protection Agency

by

University of Limerick

Authors:

Marzena Kwapinska, David A. Agar, Bart Bonsall and James J. Leahy

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

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Cover image: Pilot scale rotating kiln pyrolysis unit with thermal cracker.

DISCLAIMER

This report is based on research carried out/data from 1 March 2016 to 31 March 2019. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Project Partners

Dr Marzena Kwapinska
Department of Chemical Sciences
Bernal Institute
University of Limerick
Limerick
Ireland
Email: marzena.kwapinska@ul.ie

Dr David A. Agar
Department of Chemical Sciences
Bernal Institute
University of Limerick
Limerick
Ireland
Email: david.agar@ul.ie

Professor James J. Leahy
Department of Chemical Sciences
Bernal Institute
University of Limerick
Limerick
Ireland
Email: j.j.leahy@ul.ie

Mr Bart Bonsall
tcbb RESOURCE
Premier Green Energy Centre
Thurles
Co. Tipperary
Ireland
Email: bart.bonsall@tcbb.ie

Mr Sean O’Grady
Premier Green Energy
Thurles
Co. Tipperary
Ireland
Email: sean.ogrady@pge.ie

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Executive Summary

In Ireland, the organic "fines" residue derived from the separation of municipal solid waste (OF-MSW) and sewage sludge and/or digestates derived from municipal wastewater treatment plants (SS) are currently processed for disposal as wastes, which incurs a significant cost for the material owner.

Pyrolysis is a conversion technology that applies high temperatures to depolymerise organic molecules, resulting in a combustible syngas and solid char, which can potentially be used as a soil conditioner or solid fuel energy carrier. It performs most efficiently when the feedstock is dried and densified into standard particles and sized to enable material flows and rapid penetration of heat.

The OF-PYR project investigated whether pyrolysis could be deployed to recover renewable energy and nutrients (pyroenergy) from OF-MSW and SS to contribute towards a reduction in current disposal costs, as well as towards sustainability objectives, which include a circular, resource-efficient economy, climate change mitigation and maintenance of air/water/soil quality through improved waste management, energy decarbonisation and nutrient recycling.

Laboratory and pilot-scale tests were undertaken to determine feedstock properties, identify optimal process parameters and determine the relative mass and energy balances for the products. The techno-economic viability of pyroenergy was evaluated in the context of current waste management protocols, regulatory regimes and relevant market factors.

It was concluded that SS is a homogeneous, moist, mildly odorous feedstock with a calorific value (CV) ranging from 17 to 20 $\mathrm{MJ/kg_{dry}}$. When properly dried and conditioned it can be pyrolysed to convert 26–51% of the original dry matter to syngas, with heating values (CV) ranging from 16 to 22 $\mathrm{MJ/m^3}$. The balance of the feedstock is converted to liquids and a high-ash char, with a CV of ~13 $\mathrm{MJ/kg_{dry}}$. The mass and energy balance depends on the conditioning and characteristics of the feedstock, as well as pyrolysis process parameters. Syngas generally contains tars and long-chain molecules that can be problematic for use in gas engines, but thermal cracking and water scrubbing can improve the gas quality to enable combustion in internal combustion engines. However, in the OF-PYR pilot-scale tests the conditioning did not achieve a gas standard that met the engine manufacturer's specification. Pyrolysis mineralised and concentrated the phosphorus in the char; however, heavy metals are also concentrated in the char at levels exceeding those specified by the European Biochar Certificate, which precludes its direct use as a soil amendment. Accordingly, char is best suited to valorisation as a solid fuel.

The SS pyroenergy process can make a positive contribution to greenhouse gas emissions mitigation as the syngas and biochar energy carriers are derived from a renewable biomass. It can be techno-economically viable and can contribute toward sustainability objectives provided that:

- An efficient feedstock supply chain evolves, facilitating aggregation of de-watered SS from dispersed wastewater treatment plants for onward supply to processing hubs, adapted to minimise the energy input, capital costs and odorous emissions from feedstock drying/densification. Ideally, SS processing would be co-located with a pyroenergy plant to leverage access to facilities for treatment of process wastewater and minimise feedstock transport requirements.
- The pyroenergy plant is optimised to condition the syngas to meet engine specifications and/or an "end-of-waste" standard such that combustion emissions are no worse than those resulting from combustion of natural gas.
- Market outlets can be identified for valorisation of the biochar solid fuels that are already licensed for waste incineration or alternatively the biochar can achieve "end-of-waste" designation, facilitating on-site combustion regulated under the medium combustion plant regulations rather than the waste incineration regulations, which may otherwise impose onerous emissions monitoring and management requirements on energy recovery.
- Timely access to energy distribution infrastructure is available at reasonable cost to service viable

market outlets offering a continuous thermal energy demand. Suitable energy distribution infrastructure is not widely available in Ireland and may have to be co-developed as part of pyroenergy applications. Transitional market supports will be required to subsidise the cost of supply chain development and customer transition.

- The greenhouse gas mitigation gained from fossil fuel displacement and reduction in transport required to land spread bulky biosolids exceeds the incremental emissions generated during processing; additional greenhouse gas mitigation may be achieved by co-locating SS processing hubs with pyroenergy plants.

Techno-economic viability is dependent on the introduction of a broader, coherent bioenergy framework that finances processing/energy distribution infrastructure and incentivises the transition to renewable energy, with market supports structured as feed-in tariffs, payable to energy generators for renewable energy placed on the market.

Pyrolysis of OF-MSW in laboratory tests converts ~32% of the feedstock to syngas, with a CV ranging from 15.5 to 18.9 MJ/m^3; the balance is converted to liquids and a high-ash char, with a CV of *c.*10 MJ/kg_{dry}. The specific mass and energy balance depends on the specific composition of OF-MSW (e.g. higher plastic content leads to a higher gas yield). Pyroenergy, although technically viable, is unlikely to offer a measurable improvement over current disposal methods such as stabilisation through mechanical biological treatment and land spreading.

OF-MSW is a heterogeneous waste with a high moisture content, as well as high levels of inert metals, glass and rubble, which makes drying/conditioning more complex. The heterogeneity precludes use of technology that might otherwise reduce the conditioning cost. The odour dictates that drying/conditioning may have to be sited remotely from a pyroenergy plant, ideally close to energy market outlets, to optimise energy efficiency. Although the syngas could potentially be conditioned as a clean energy carrier, the char retains the inert contaminants and heavy metals, which render it unsuitable for use as a soil conditioner. Unless the contaminants are removed, it may be difficult to identify markets willing to combust the char as a solid fuel. Heavy metals may preclude its designation as “end of waste”, which means that waste incineration regulations will apply that may impose onerous emissions monitoring and abatement requirements. These factors will increase the pyroenergy cost, meaning that it is unlikely to remunerate the cost of deployment of the technology.

1 Introduction

Two common and widespread difficult waste streams are sewage sludge derived from municipal wastewater treatment plants (SS) and the organic fine component from the mechanical sorting of municipal solid waste (OF-MSW). The utilisation of these waste streams, particularly SS, is undergoing changes. First, societal perceptions of risk and quality assurance schemes in food production have lessened the appeal of spreading treated SS on agricultural land. Second, in Ireland and elsewhere, landfill sites are closing down; therefore, the outlets for SS and OF-MSW are rapidly diminishing and new solutions are being sought for their safe handling and utilisation.

1.1 Current Status of OF-MSW and SS Utilisation in Ireland

Municipal waste comprises non-recyclable waste collected from households and commercial outlets, including paper and cardboard, glass, metals, some plastics, biowaste, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators and bulky waste.

The residual waste is material that cannot be recycled and is extremely heterogeneous, containing food waste, plastics, metals, paper and glass (Buah *et al*., 2007). At waste separation/processing facilities metal and large plastic and paper pieces are removed and the remaining fine material is known as OF-MSW. Sometimes this waste stream undergoes screening. OF-MSW is routinely stabilised through controlled aerobic composting, after which it is used as a cover material at landfill sites (RPS Group, 2014).

The total quantity of wastewater sludge generated in Ireland in 2014 was 53,543 tonnes of dry solids. This is expected to increase to 96,442 tonnes of dry solids by 2040 (Irish Water, 2014). Sludge treatment involves volume reduction (removal of water by separation, thickening and de-watering), quantity reduction (destruction of organic solids by aerobic or anaerobic digestion) and production of “biosolids”. At present, over 98% of wastewater sludge is treated to produce biosolids, which are reused in agriculture. The term “biosolids” applies to fully treated sludge products that are both biologically stable and free of harmful pathogens and reflects the efforts to consider these materials as potential resources (Isaac and Boothroyd, 1996). According to a survey carried out by Irish Water, lime stabilisation, anaerobic digestion and thermal drying are currently the main sludge treatments used for producing biosolids in Ireland. Studies of biosolid treatment options indicated that advanced anaerobic digestion provides the most economically feasible option for treatment of wastewater sludge for reuse or disposal, with overall volumes reduced by up to 30% (anaerobic digestion) or up to 45–50% (anaerobic digestion with hydrolysis). In Ireland, over 50% of all wastewater sludge was anaerobically digested in 2014 (Irish Water, 2014). Anaerobic digestion is very effective at reducing the solid content of primary sludge; however, the level of solid reduction of waste activated sludge is low without pre-treatment.

The agricultural outlet for wastewater sludge is under increasing scrutiny, mainly because of perceptions of contamination risk. There has been a significant reduction in the availability of agricultural outlets because of a tendency to exclude wastewater sludge from lands used for food production under quality assurance schemes (An Bord Bia and the Grain Assurance Scheme). Wastewater sludge in Ireland, subject to appropriate treatment, is primarily reused on land used for animal fodder production. There is also a requirement for storage of sludge being used for land spreading during periods when the application of fertilisers to land is prohibited. Additional sludge storage facilities are required to facilitate the predicted increase in levels of wastewater sludge.

It was pointed out in a recent publication by Healy *et al*. (2017) that, although the application of biosolids in Ireland poses no greater threat to surface water quality than the land application of cattle slurry, there is a possibility that many non-priority elements and emerging contaminants, for which no regulations currently exist, may be applied to the land (e.g. antimony – Sb; tin – Sn; pharmaceutical and personal care products) and may accumulate in soils and enter the food chain. Contaminants that occur in wastewater sludge that pose potential threats to human health and natural ecosystems include metallic nanoparticles (silver – Ag; titanium dioxide – TiO_2; silicon – Si; platinum – Pt; copper – Cu) (Chaudhry and Castle, 2011; Marchesan and Prato, 2012; Westerhoff *et al*., 2013; Fijalkowski *et al*., 2017; Wang *et al*., 2017), micro-plastics (Mahon *et al*., 2017), toxic organic contaminants (Smith, 2009) and pathogenic bacteria and viruses.

Because of restrictions on agricultural land spreading arising from quality assurance schemes implemented by the agricultural sector, it is important to explore alternative outlets for wastewater sludge to reduce the risk associated with depending solely on land spreading as an outlet. The main alternative to agricultural land spreading is incineration, with 25% of wastewater sludge in Europe being incinerated in 2012. A recent review by United Utilities in the UK concluded that energy recovery is optimised by using advanced anaerobic digestion upstream of incineration compared with incineration of raw sludge. The techno-economic evaluation performed by tccb RESOURCE (summarised in Chapter 7 below) addressed this point, noting that, given the comparability between the calorific value (CV) of non-digested SS and that of digestate derivatives, thermal applications can be applied either as an alternative to anaerobic digestion or as a supplement.

1.2 Thermal Conversion Technologies

There is growing interest in the use of thermal conversion technologies for waste management (Chen *et al*., 2014; Dussan and Monaghan, 2017; Kumar and Samadder, 2017; Syed-Hassan *et al*., 2017). These generally aim to valorise waste streams while reducing the risks associated with reuse of waste materials. Pyrolysis is of interest in waste management because it can reduce health and environmental risks from problematic wastes (Lindberg *et al*., 2015) (Trinh *et al*., 2013) while providing an avenue for the recovery of energy and nutrients (Buah *et al*., 2007; Song *et al*., 2014).

Pyrolysis is the thermal decomposition of carbonaceous material in an inert atmosphere into gaseous, liquid and solid products. Pyrolysis gas contains non-condensable low-molecular-mass gases such as hydrogen (H_2), carbon monoxide (CO), methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6) and carbon dioxide (CO_2). The liquid product contains condensable volatile compounds (i.e. oils and tars), water and water-soluble organics (Xu and Lancaster, 2009). The solid residue obtained (char) consists mainly of carbon and ash. The fraction of solid gas or liquid product is affected by the processing conditions, including temperature and reactor residence time, as well as the feedstock properties. Slow pyrolysis is generally characterised by relatively mild temperatures (350–700°C) and moderate heating rates (Samolada and Zabaniotou, 2014). The higher the pyrolysis temperature, the higher the yield of gas. One of the main concerns related to all thermal conversion technologies for SS is the release of heavy metals and contaminants such as ammonia (NH_3), hydrogen chloride (HCl), hydrogen cyanide (HCN) and hydrogen sulfide (H_2S) (Zhang *et al*., 2017). The lower temperature associated with pyrolysis compared with incineration is responsible for the absence of heavy metals in the pyrolysis gas; these remain concentrated in the resulting carbonaceous solid product (Menendez *et al*., 2002; Trinh *et al*., 2013). The potential application of the three pyrolysis products depends on the presence of various contaminants. According to Chen *et al*. (2015), the distribution of heavy metals is an important indicator when evaluating pyrolysis as a disposal method and also for determining the final application of the char.

Municipal solid waste pyrolysis is being rolled out in small cities and towns because of the desire to prevent long-distance transportation of waste (Chen *et al*., 2014). Usually, gas and/or char from the pyrolysis of MSW are used as sources of energy (Czajczyńska *et al*., 2017). Moreover, it has been reported that emissions of air pollutants from a MSW pyrolysis plant used for power production were lower than those from a conventional power plant using coal (Baggio *et al*., 2008). Dioxins and furans need sufficient oxygen to form and re-form and the oxygen-deficient atmosphere required for pyrolysis mitigates their formation (Conesa *et al*., 2009; Arena, 2012). Dioxin formation is also catalysed by fine metal particles in the exhaust from incineration facilities and these metals are retained in char during slow pyrolysis.

1.3 Objectives

The purpose of the present study was to investigate the potential of slow pyrolysis as a distributed conversion technology for the treatment of OF-MSW and SS. In this context, pyrolysis was viewed as an alternative to incineration. Two scenarios were tested (Figure 1.1): (1) pyrolysis used as a single-step conversion process to generate a high CV gas as an energy carrier for combustion in a gas boiler to produce heat or in a gas engine to produce electricity and heat, with the char used as a soil amendment, and (2) pyrolysis used as a pre-treatment step prior to combustion for waste with a high loading of mineral matter and high chlorine (Cl), sulfur (S) and nitrogen (N) contents, as frequently encountered in OF-MSW, which are problematic for conventional incineration. Volatile Cl, S and/or N species are released during pyrolysis with the gas phase and are easily scrubbed prior to combustion.

In this study, the following steps were undertaken:

- characterisation of OF-MSW and SS samples from different waste processors;
- pyrolysis at laboratory scale and characterisation of all pyrolysis products;
- pyrolysis at pilot scale for selected waste streams and characterisation of products;
- evaluation of the combustion kinetics of pyrolysis chars;
- vitrification of ash from combustion and investigation of its leaching propensity.

The overall process, presented in Figure 1.1, envisaged densification of the waste to remove any

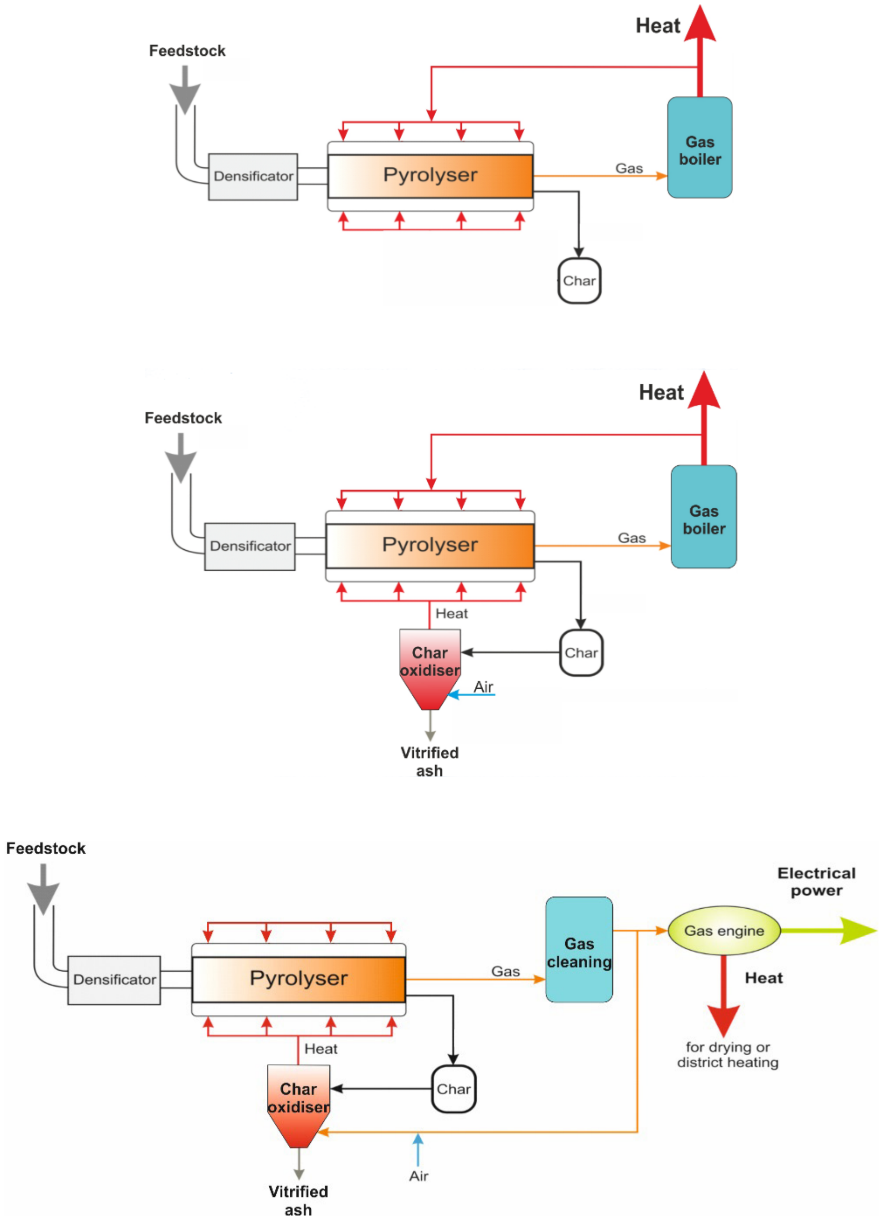

Figure 1.1. Schematic diagram of the proposed process scenarios.

entrapped air before passing to the primary reactor, a rotating kiln where the oxygen content is < 5 wt% volume per volume. The volatile gases released during pyrolysis pass to gas cracking and cleaning, before combustion in a gas engine, whereas the solid carbon-enriched char is used either as a soil amendment or as a fuel for the kiln, producing a vitrified mineral ash.

2 Organic Fines from Municipal Solid Waste

Mixed MSW is a waste material that is not recycled as it is extremely heterogeneous, containing food waste, plastics, metals, paper and glass (Buah *et al*., 2007). Once metals and large plastic and paper pieces have been removed from the mixed MSW stream, the remaining fine material is called OF-MSW. OF-MSW is routinely stabilised through controlled aerobic composting.

2.1 Characterisation of OF-MSW

Samples of OF-MSW from four Irish companies were tested: OF1, OF2, OF3 and OF4. Two of the samples represented uncomposted organic fines (OF2-1, OF3); the other samples were composted and screened. The moisture content of the samples was in the range of 17–63 wt% and reflected the type of processing that the OF-MSW underwent. It was lower for composted OF-MSW, at around 20 wt%, and much higher for fresh, uncomposted OF-MSW, varying from 55 wt% to 63 wt%. All of the samples of OF-MSW were very heterogeneous and contained organic and plastic fractions in addition to glass, metal and stones. Table 2.1 shows that glass constituted the largest fraction of the dried samples, representing from 12.9% to 21.4% of the original mass. The metal content was much lower, ranging from 0.1% to 3.4% weight for weight. Stones were found only in composted fines and accounted for 2.5–4.7% of the dried fines. Photographs of OF-MSW materials are shown in Figure 2.1.

The proximate properties of OF-MSW are presented in Figure 2.2 (see also Table A1.1 in Appendix 1). The ash content of dried OF varied from 39 wt% to 44 wt%, regardless of the type of processing applied, with the exception of one uncomposted sample, OF2-1, which had an ash content of 27 wt%. This may suggest that there is regional and seasonal variation in the ash content of OF-MSW, but it could also be a feature of the storage conditions of the OF-MSW before sampling. The samples were provided by waste processors. Volatile matter content depends on the specific composition of OF-MSW and it varied from 54 wt% to 60 wt% for dried samples; composting reduced it to between 41 wt% and 49 wt%. A fixed carbon content of 2–16 wt% was observed. The higher heating value (HHV) of dried uncomposted OF-MSW was 17.2 MJ/kg, which decreased after composting to between 13.6 and 15.9 MJ/kg. The heating value of a fuel is primarily determined by the carbon content, and this decreases for the OF2 samples after composting, as shown in Figure 2.3 (see also Table A1.2 in Appendix 1). The carbon content in the freshly composted OF2-2 was reduced by 20 wt% compared with the uncomposted OF2-1. A further reduction in the carbon content was observed for the aged composted OF3, with 23 wt% less C than in the original sample.

The composition of the mineral matter of OF-MSW was measured and is presented in Figures 2.4 and 2.5. Figure 2.4 shows that the content of silica (Si) was the highest among the major elements for all OF samples, at 70 g/kg, followed by calcium (Ca), at 34–53 g/kg. The contents of aluminium (Al), iron (Fe) and potassium (K) ranged from 10 to 20 g/kg, whereas those of magnesium (Mg), sodium (Na) and S were about 10 g/kg. OF-MSW did not contain high levels of phosphorus (P); the content of P ranged from 1.4 to 4.1 g/kg.

Table 2.1. Fractions of glass, metal and stones in dried OF-MSW

OF-MSW	Sample after drying, g	Glass, g (%)	Metal, g (%)	Stones, g (%)
OF2-1: unprocessed, unscreened	593.3	76.3 (12.9)	5.4 (0.9)	–
OF2-2: freshly composted, screened	642.3	133.3 (20.7)	15.3 (2.4)	8.2 (2.5)
OF2-3: old composted, screened	1026.4	177.2 (17.3)	7.9 (0.8)	35.3 (3.4)
OF3: uncomposted	1165.1	249.1 (21.4)	1.6 (0.1)	–
OF4: composted, screened (30 mm)	947.3	161.0 (17.0)	31.8 (3.4)	44.1 (4.7)

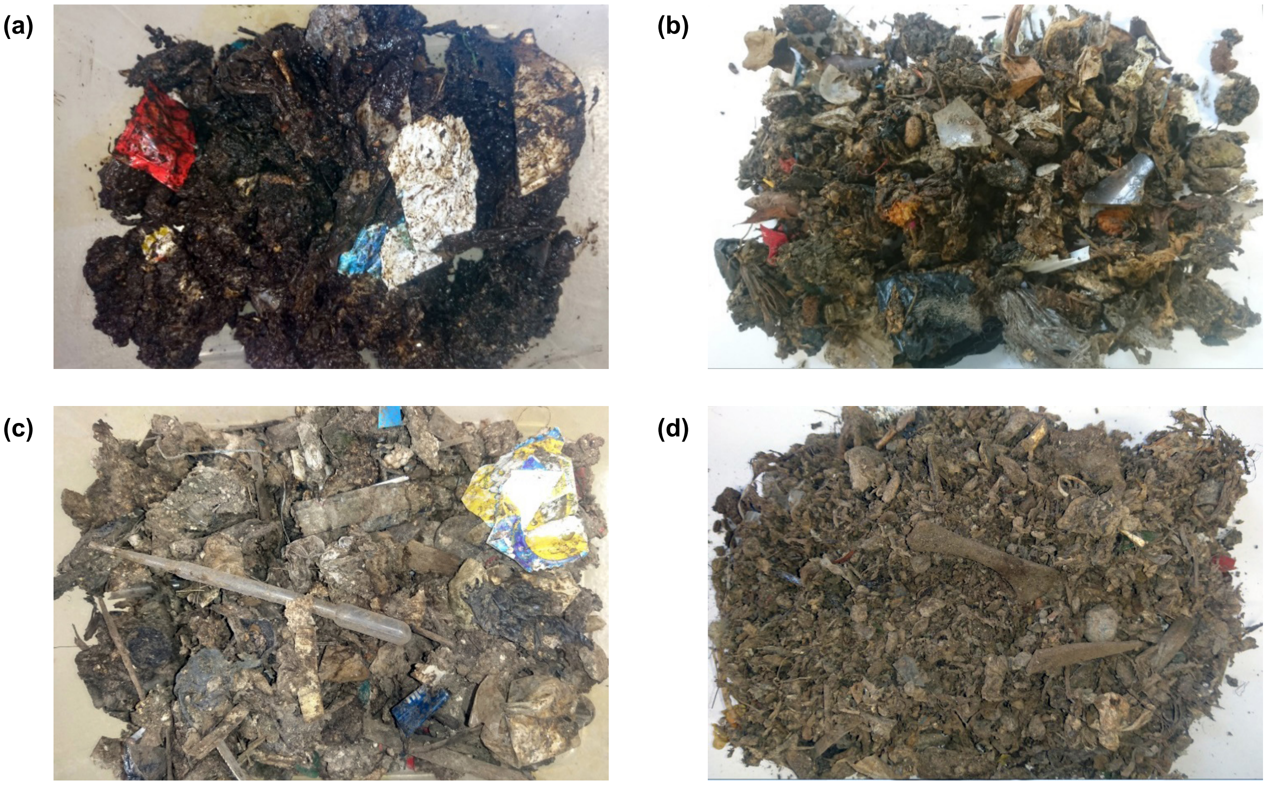

Figure 2.1. Photographs of OF-MSW: (a) unprocessed OF-MSW; (b) composted OF-MSW; (c) dried, unprocessed OF-MSW; and (d) dried, composted and screened OF-MSW.

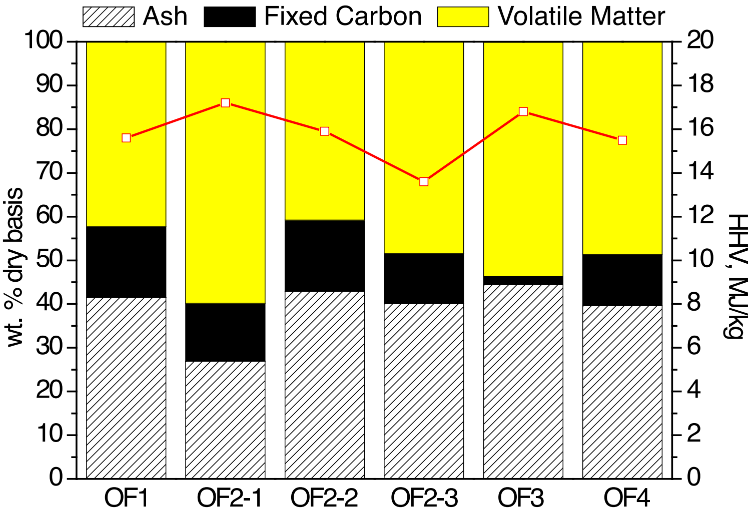

Figure 2.2. Proximate properties of OF-MSW on a dry basis. The fixed carbon content was determined by difference (OF1, composted; OF2-1, unprocessed; OF2-2, freshly composted; OF2-3, ages composted).

Figure 2.5 shows that, of the minor elements, titanium (Ti) was present at the highest concentration for all OF samples. Particularly high levels were found in OF1, OF3 and OF4, ranging between 3.4 and 4.3 g/kg, with lower levels found in OF2 samples, ranging from 1.1 to 1.8 g/kg. Titanium dioxide is a common additive in many food, personal care and other consumer products. In general, there were significant differences between the OF samples in concentrations of chromium (Cr), nickel (Ni) and zinc (Zn). The Cr concentration varied between 65 and 1500 mg/kg, Ni between 250 and 1100 mg/kg and Zn between 340 and 2400 mg/kg. The highest concentrations of Zn, Ni and Cr were observed in OF2-2. The

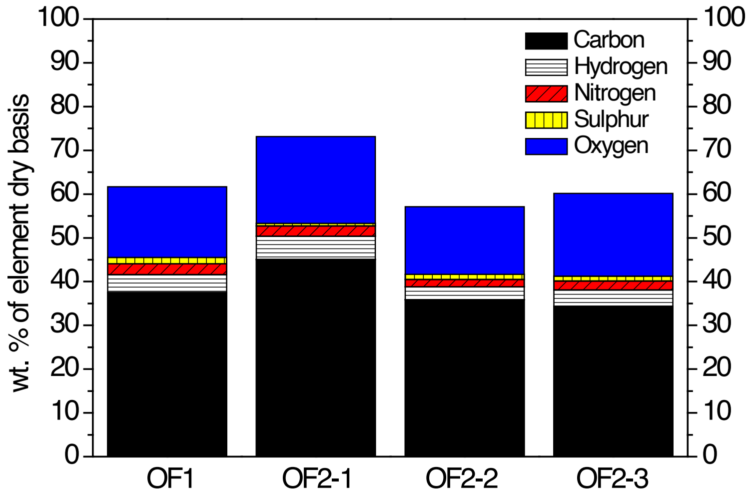

Figure 2.3. Ultimate properties of OF-MSW on a dry basis (OF1, composted; OF2-1, unprocessed; OF2-2, freshly composted; OF2-3, aged composted).

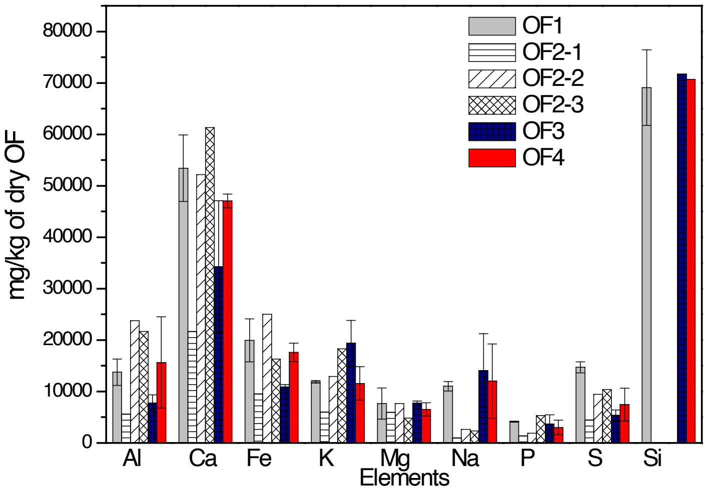

Figure 2.4. Major elements in dried OF-MSW samples.

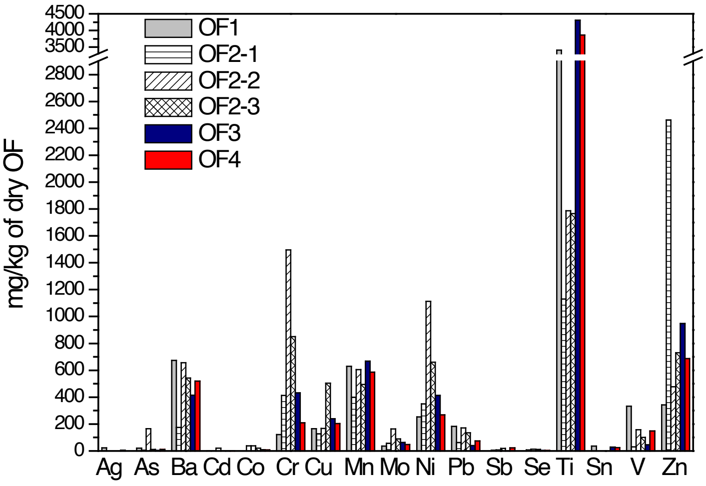

Figure 2.5. Minor and trace elements in dried OF-MSW samples.

concentration of copper (Cu) was about 200 mg/kg in all samples except for OF2-3, in which a concentration of 500 mg/kg was observed. The content of barium (Ba) was in the range from 200 to 600 mg/kg, except for OF2-1, in which it fell to 170 mg/kg. Lead (Pb), vanadium (V) and molybdenum (Mo) were present in all OF-MSW samples at different concentrations, in general below 200 mg/kg. The contents of other heavy metals, e.g. cadmium (Cd), cobalt (Co), Sn, Sb and arsenic (As), were low (always below 40 mg/kg).

2.1.1 Conclusions

The OF-MSW samples are highly variable, particularly with respect to the quantity and composition of mineral matter. Heavy metal content was high, especially for Ti, Cr, Zn and Ni.

2.2 Pyrolysis of OF-MSW at Laboratory Scale

All OF-MSW samples were bench dried at ambient temperature and pyrolysed in a laboratory-scale fixed-bed reactor. The pyrolysis set-up consisted of a quartz tube heated reactor coupled with a condenser cooler and a twin-neck round-bottom receiving flask where the pyrolysis liquid was collected. The condenser outer jacket was cooled by circulation of a refrigerated liquid at −5°C. The outlet of the receiving flask was connected to a rubber tube fitted with a connector, which enabled gas sampling or connection to an extraction unit, where the permanent combustible gases were discharged. The quartz reactor was wrapped with heating tape, which was enclosed with two layers of woven high-temperature insulation. An electro-thermal power regulator was used to supply the heating tape with electrical current, enabling precise temperature control. A schematic diagram of the experimental set-up is presented in Figure 2.6 and a detailed description is provided in Agar *et al.* (2018).

The relative distribution of the pyrolysis products was determined by the principle of conservation of mass, whereby the combined mass of pyrolysis products is equal to that of the initial sample feedstock. The primary assumption was that no liquids exit the apparatus in the vapour phase and all condensable products are collected. A batch (50 g) of dried feedstock contained in a steel-mesh basket was placed in the reactor, heated to 700°C and kept at this temperature for 10 minutes, during which the OF-MSW was pyrolysed. The product gas generated was cooled to below room temperature while passing through the condenser and samples of gas were collected in Tedlar bags. After 10 minutes, the heating jacket was turned off and the char was cooled to room temperature while still in the reactor under a flow of N to prevent combustion. The char yield was calculated as the ratio of the mass of the solid char after pyrolysis to the initial

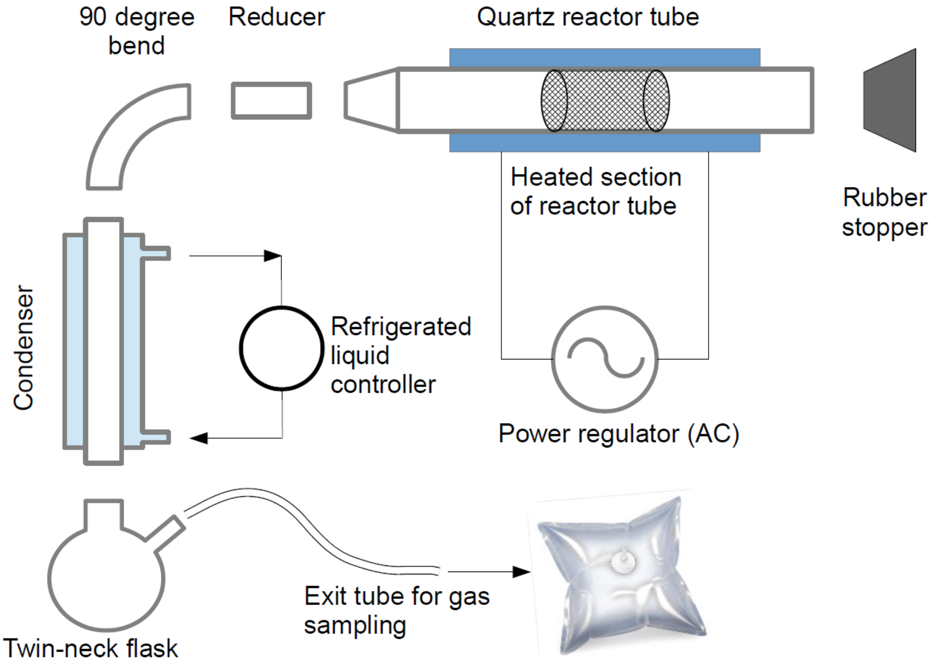

Figure 2.6. Exploded view of the laboratory pyrolysis apparatus (not to scale).

sample mass. The vast majority of the pyrolysis liquid was collected in the receiving flask; however, some of the oil/tar condensed on the cooler parts of the experimental apparatus. Therefore, to account for this fraction, before and after each series of pyrolysis runs, the reactor, along with the heating tape, insulation, receiving flask, dry condenser, rubber stopper and all of the connected glassware, were weighed and the mass of the liquid fraction estimated. The gas yield was calculated as the difference between the initial sample mass and the combined mass of the char and pyrolysis liquid. The pyrolysis gas composition (CO, CO_2, H_2, CH_4, C_2H_4, C_2H_6, N_2 and oxygen – O_2) was determined by gas chromatography (Micro GC, Agilent 3000) and was used to calculate its heating value.

The distribution of pyrolysis products is shown in Figure 2.7 and Table A1.3 (see Appendix 1); the pyrolysis products are shown visually in Figure 2.8. The results represent an average of five separate pyrolysis runs, with 50 g of feedstock per run. Given the small sample size, large, obvious glass and metal components were removed from the feedstock before pyrolysis. The char yield for OF-MSW ranged from 39% to 57%. There were differences in the yield of char between the composted and the uncomposted OF-MSW; the yield was higher for composted samples at 52–57%. The liquid yield varied significantly between samples, from 7% to 32%, which seems to suggest that yield depends on the specific composition of the OF-MSW rather than the type of pre-treatment undertaken. The average gas yield from OF-MSW was 32 ± 7% and there was no clear indication that composting lowers the yield of gas obtained during pyrolysis. The scientific literature confirms that the heterogeneity of OF-MSW plays a vital role in

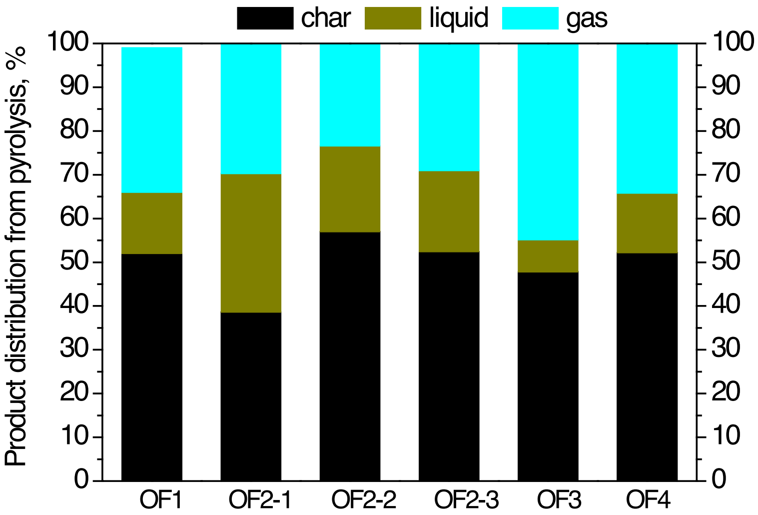

Figure 2.7. Average product distribution from pyrolysis of OF-MSW samples at 700°C for 10 minutes.

Figure 2.8. Solid (char) and liquid products from pyrolysis of OF-MSW at 700°C for 10 minutes (char with glass and metal pieces).

determining the yield of individual products (Sipra *et al.*, 2018).

The results of the proximate analysis of the chars are presented in Figure 2.9 and Table A1.4 (see Appendix 1). The chars from OF-MSW consisted mainly of ash, at about 58–82 wt%. The volatile matter content of the chars from OF1, OF3 and OF4 was between 3.5 wt% and 5.3 wt%, implying that almost complete decomposition of the organic matter occurred in the fixed-bed reactor after 10 minutes at 700°C. The volatile matter content of the OF2 samples, on the other hand, was 10–13 wt%, suggesting that decomposition of these samples was not complete at 700°C and a fraction of the organic matter was not released from the solid matrix, again implying that the extent of decomposition depends on the specific composition of the OF-MSW. The HHV of OF-MSW chars varied from 8.8 to 13.2 MJ/kg.

As a waste material, OF-MSW and their chars contain significant amounts of N (0.7–2.5 wt%) and S (0.8–2.4 wt%) (Figure 2.3 and Figure 2.10, as well as Tables A1.2 and A1.5 in Appendix 1). Less than half of the original N is preserved in the OF-MSW char after pyrolysis. For OF1 and OF2-3 chars, the S was conserved during pyrolysis and concentrated in the char, an observation consistent with results from other studies (Zhang *et al.*, 2017), with 55 wt% and 65 wt% of the S retained in the char for OF2-1 and OF2-2 respectively. Given the heterogeneous nature of the OF-MSW feedstock, the limited number of samples and the small sample size used in elemental analysis, some inconsistencies were observed. Moreover, the

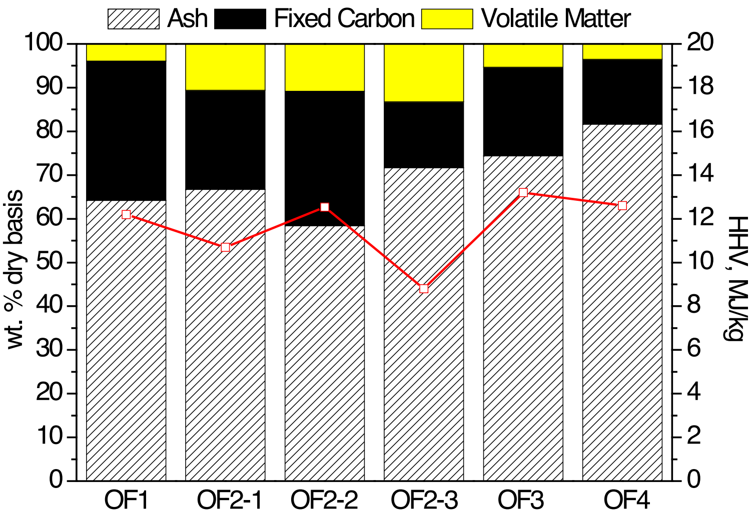

Figure 2.9. Proximate properties of chars from pyrolysis of OF-MSW at 700°C for 10 minutes (dry basis).

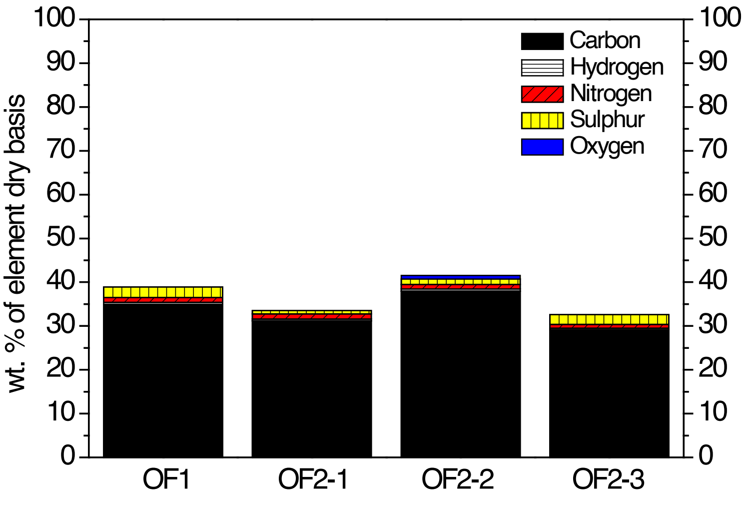

Figure 2.10. Ultimate properties of OF-MSW chars (dry basis).

mass balance of elements from the analysis did not always sum up to 100 wt%, as oxygen was determined by difference rather than actual measurement. Consequently, this sometimes gave rise to negative values for oxygen in the results.

The composition of the mineral matter in the OF2 chars was measured and is presented in Figures 2.11 and 2.12. All of the major elements and most of the minor elements were concentrated in the char samples. The content of Zn, Cd, selenium (Se), Co and Pb was lower in the OF chars, indicating that these elements were released from the solid matrix during pyrolysis at 700°C and will need to be scrubbed from the gas. Concentrations of Pb, Cu, Ni, Zn and Cr in OF chars were higher than the maximum allowable limits (As 13 mg/kg, Cd 1.5 mg/kg, Cr 90 mg/kg, Cu 100 mg/kg, mercury – Hg – 1 mg/kg, Ni 50 mg/kg, Pb 150 mg/kg), as set by the European Biochar Certificate (EBC) (2012); therefore, the OF-MSW char is limited to being used as a solid fuel.

The results of the gas analysis of OF-MSW samples are shown in Figure 2.13 and Table A1.6 (see Appendix 1). The combustible gas fractions, whose combined volume fraction ranged from 70% to 86% of the observed gases, were predominantly CO, CH_4, H_2, C_2H_4 and C_2H_6. The calculated lower heating value (LHV) ranged from 15.5 to 23.5 MJ/m^3. The differences in gas composition and CV depend mainly on the original sample composition (heterogeneity), but it was also observed for OF2 that the LHV of the pyrolysis gas was lower for the composted samples OF2-2 and

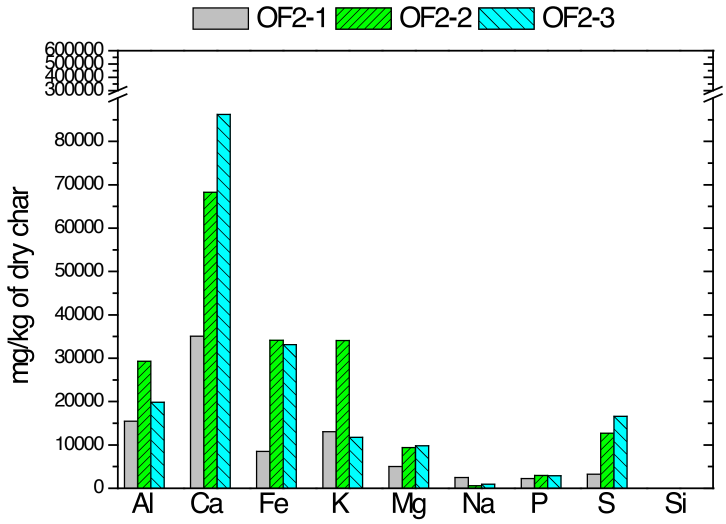

Figure 2.11. Major elements in OF2 char samples.

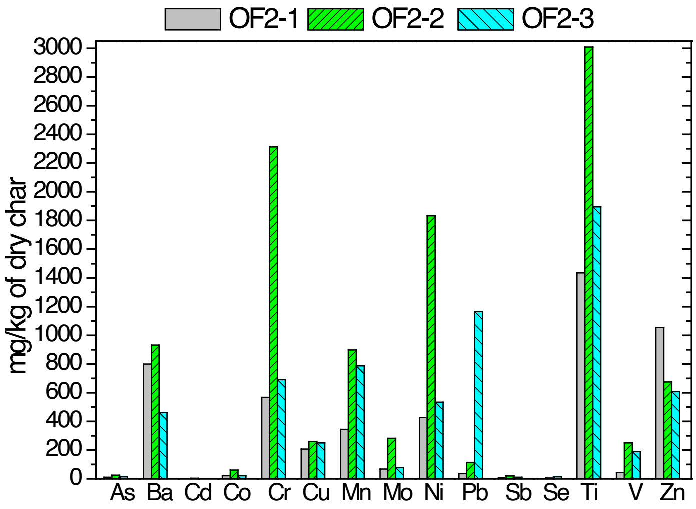

Figure 2.12. Minor elements in OF2 char samples.

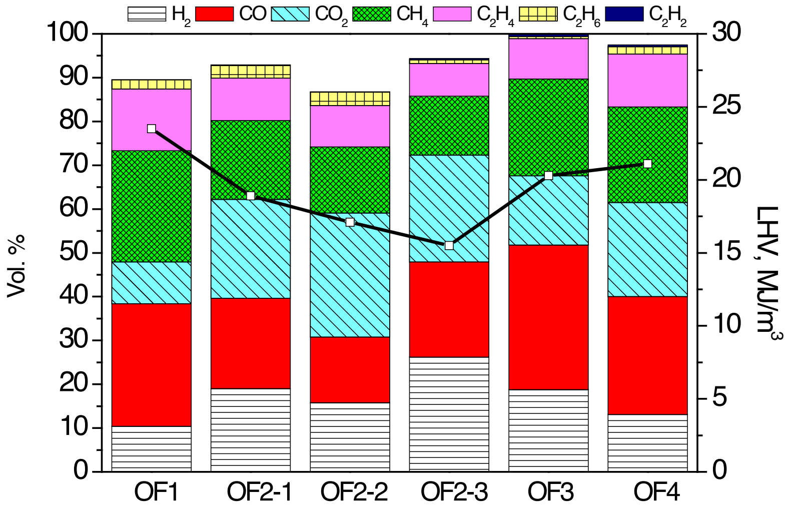

Figure 2.13. Pyrolysis gas composition (N_2-free basis).

OF2-3 (17.1 and 15.5 MJ/m^3, respectively) than for the uncomposted sample OF2-1 (18.9 MJ/m^3).

Some N_2 and O_2 were present in the gas samples collected during pyrolysis because the reactor tube contained air at the start of the experiment. However, the fraction of N_2 and O_2 declined significantly when the apparatus was filled with pyrolysis gas. The gas composition presented in Table A1.6 is on an N_2-free basis.

Observations on pyrolysis gases were limited to relative volumes. The absolute amounts of each gas species produced from the feedstock cannot be determined without information on gas flow rates from the reactor during the pyrolysis run. Nonetheless, flow from the reactor was observed to be greatest during the first few minutes of pyrolysis.

The liquid fraction obtained from pyrolysis was dark brown in colour and consisted of two visible phases, an oil fraction and an aqueous fraction, as shown in Figure 2.8. The two phases were easy to separate. The lower fraction contained water and certain hydrosoluble organic compounds whereas the oil fraction contained the organic fraction. Table A1.7 (see Appendix 1) contains a list of 20 compounds detected in the aqueous fraction of pyrolysis liquids from OF-MSW samples, with the most abundant compounds being pyridine, pentanoic acid, pyridine-2-methyl,2,4-imidazolidinedione and 5,5-dimethyl-5-ethyl-5-methyl-2,4-imidazolidinedione. Table A1.8 (see Appendix 1) contains a list of 25 compounds detected in the oil fraction, with the most abundant compounds being styrene, ethylbenzene, toluene, naphthalene and α-methylstyrene.

A reduced fraction of liquid product is expected at pilot-scale level as the residence time of the vapours will be longer than in the laboratory-scale experiments, in which the vapours were cooled immediately after release from the solid residue structure. A longer residence time allows for cracking of higher molecular weight molecules, such as those found in oils and tars, liberating gases, such as CO, CH_4, C_2H_4 and H_2, and oxygenated species.

2.2.1 Conclusions

Pyrolysis of OF-MSW enables recovery of energy in the form of a high CV gas; however, the quantity of gas was variable, depending on the specific composition of the feedstock, (e.g. higher plastic content leads to a higher gas yield). The presence of metal and glass pieces makes the material unsuitable for use as a soil amendment. More importantly, the concentrations of Pb, Cu, Ni, Zn and Cr in OF chars were higher than the maximum allowable limits set by the EBC; therefore, the OF char can be used only as a fuel for combustion.

3 Sewage Sludge

3.1 Sewage Sludge Characterisation

Samples of SS from three wastewater treatment plants were collected. These included one sample of SS after anaerobic digestion and a mixture of SS with forest residue (FR) (consisting of thinnings of conifer trees, sometimes referred to as brash). Over a period of 1 year, nine samples of SS from one of the wastewater treatment plants were collected at regular intervals to assess seasonal variation in properties. Proximate and ultimate properties of all of the samples were analysed and are presented in Figures 3.1 and 3.2 and Tables A1.9 and A1.10 (see Appendix 1). The moisture content varied depending on the type of processing that the original SS had undergone. Sludge granules (SS2 and SS3) and pellets (SS1) had moisture contents ranging from 6 wt% to 10 wt%, whereas belt pressed cake (SS4) showed values between 85 wt% and 90 wt%. When granules of SS2 were mixed with FR (SS2 + FR), the moisture content increased from 6 wt% to 14 wt%. The ash content was slightly higher in granules (SS2) and pellets (SS1), at 29 wt% and

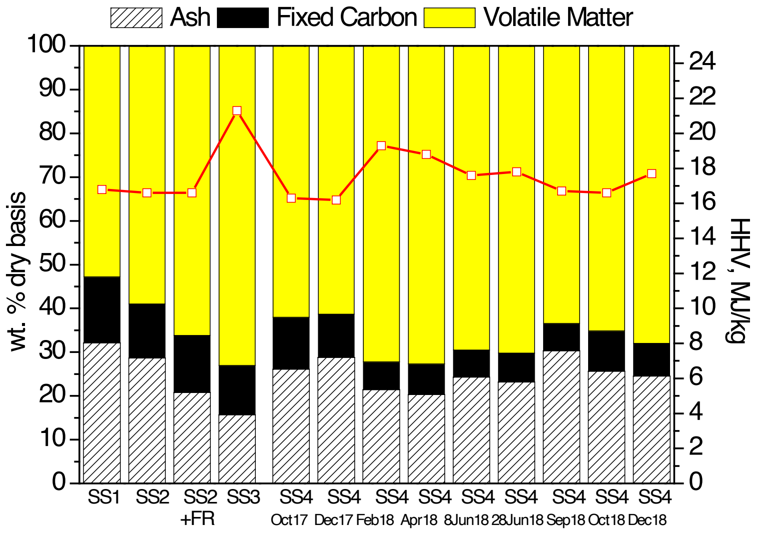

Figure 3.1. Proximate properties of SS samples (dry basis).

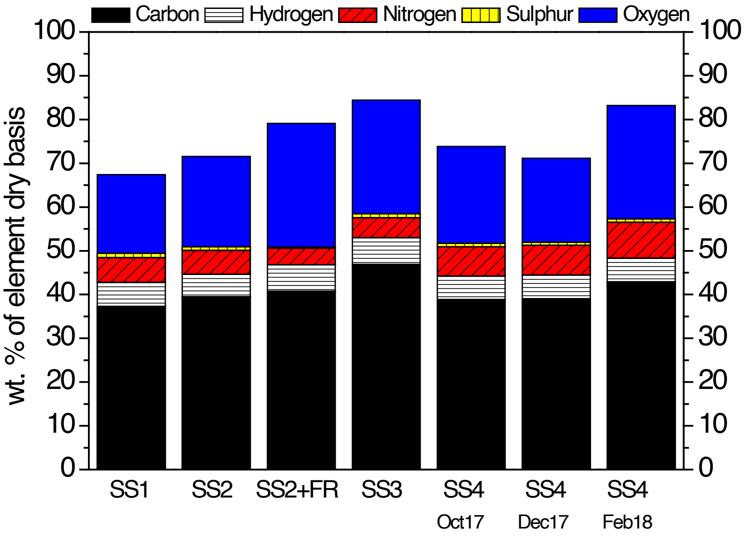

Figure 3.2. Ultimate properties of SS samples (dry basis).

32 wt%, respectively, than in belt press cake (SS4), which had an ash content ranging from 20 wt% to 30 wt%. The volatile matter content was slightly lower in granules and pellets, at 53 wt% and 59 wt% for SS1 and SS2, respectively, than in belt press cake, which had a volatile matter content ranging from 61 wt% to 73 wt%. Mixing SS2 granules with FR increased the volatile matter content from 59 wt% to 66 wt%. The HHV of SS samples on a dry basis varied from 16 to 19 MJ/kg.

A report on 32 samples of SS collected from 18 studies showed an average HHV of 16 MJ/kg (dry basis), a volatile matter content of 48.4 wt%, a fixed carbon content of 7.6 wt% and an ash content of 44 wt% (Syed-Hassan *et al.*, 2017). The SS samples investigated in the current study had a lower ash content and a higher volatile matter content than these SS samples.

The proximate properties of SS4 (belt press cake) changed over the 12-month sampling period. The moisture content was relatively stable at 86.9 ± 2.1 wt%, whereas the average ash content was 24.9 ± 3.4 wt% but changed according to the weather conditions. There was slight variation in the ash content, with the highest ash content observed in the sample collected in September 2018, following a dry summer, and the lowest ash content observed in samples from February and April 2018, during a wet cold spring (with snowfall and temperatures around freezing). The HHV ranged from 16 to 19 MJ/kg, reflecting the volatile matter and ash contents. The highest CV was for samples with the lowest ash content and the highest volatile matter content, collected in February and April 2018. The lowest HHV was for samples with a high ash content and a low volatile matter content, collected in October and December 2017 and October 2018. The average HHV for SS4 was 17.4 ± 2.1 MJ/kg.

In terms of the ultimate properties, all samples had high N and S contents. The N content varied between 5 wt% and 8 wt% and was highest for SS4 collected in February 2018. The N content was reduced from 5.4 wt% to 3.8 wt% when SS2 was mixed with FR. The S content ranged from 0.7 wt% to 1 wt% and was reduced to 0.2 wt% by mixing SS2 with FR. The SS samples used in this study were similar to those investigated elsewhere. Typical SS has a N content of 7.15 wt% (dry basis) and a S content of 1.4 wt% (Syed-Hassan *et al.*, 2017; Ronda *et al.*, 2019).

The composition of the mineral matter of the SS samples was measured and is presented in Figures 3.3 and 3.4. Figure 3.3 shows that Si was the most abundant of the major elements for all SS samples, ranging in concentration from 150 to 240 g/kg (dry basis), whereas Ca and P were present in concentrations of around 25 g/kg. The Al concentration ranged from 15 to 60 g/kg and was highest in SS2, whereas the Fe concentration varied from 7 to 45 g/kg and was highest in SS4, probably reflecting the different types of coagulants or flocculants (mostly Al or ferric salts) used in the wastewater treatment plants (Lee *et al.*, 2014). Mg and Na concentrations differed between the SS samples, varying from 3.6 to 14 g/kg and 0.3 to 17 g/kg,

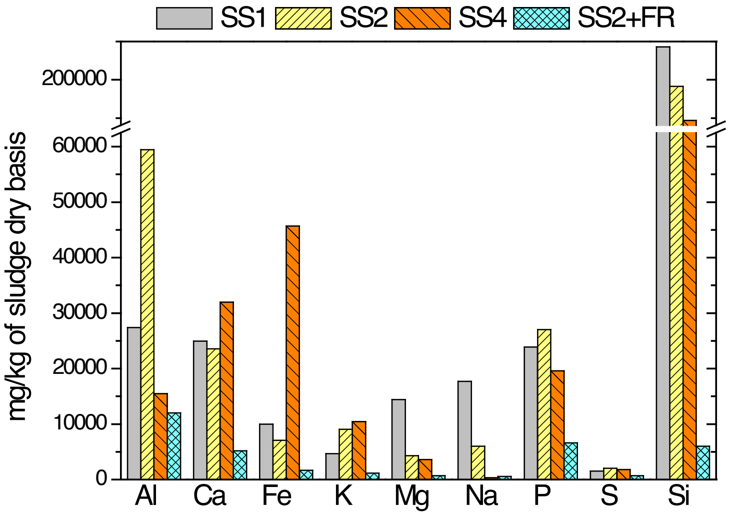

Figure 3.3. Major elements in SS samples (dry basis).

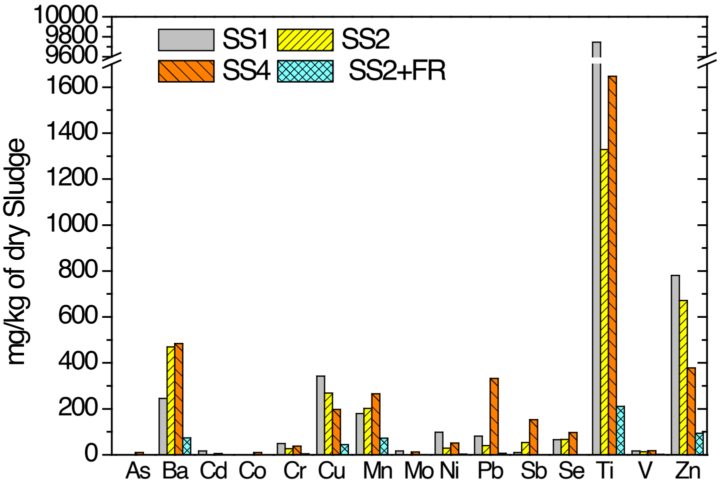

Figure 3.4. Minor and trace elements in SS samples (dry basis).

respectively. The concentration of K varied between 5 and 10 g/kg, whereas the S concentration was always below 2000 mg/kg. The concentrations of all of these major elements were reduced in the blended mixture of SS2 and FR.

Figure 3.4 shows that Ti had the highest concentration of the minor elements for all SS samples. It was particularly high in SS1 (9.7 g/kg), with concentrations in SS2 and SS4 of 1.2 and 1.6 g/kg, respectively. The concentration of Zn varied from 360 mg/kg in SS4 to 760 mg/kg in SS1, whereas the concentration of Ba in SS2 and SS4 was twice that in SS1 (500 mg/kg vs 250 mg/kg, respectively). The concentrations of Cu and manganese (Mn) were similar, ranging from 200 to 300 mg/kg. The concentration of Pb was much higher in SS4 (330 mg/kg) than in SS1 and SS2 (80 and 40 mg/kg, respectively). In addition, the concentration of Sb was highest in SS4 (150 mg/kg vs 10 and 50 mg/kg in SS1 and SS2, respectively). The Se concentration was similar in all SS samples, at 70–90 mg/kg. The concentrations of other heavy metals, such as Cd, Co, Cr, Mo, Ni and As, were low (less than 50 mg/kg).

The high concentrations of Ti and Zn in all SS samples reflects the abundance of titania and zinc oxide nanoparticles in consumer products. Overall, the concentrations of heavy metals in the SS samples were in the range reported by Healy *et al*. (2017) and Ronda *et al*. (2019).

The metal content of sludge ash post incineration has been evaluated by Krüger *et al*. (2014). In Germany nearly half of the ash was composed of Si, Ca, Fe, P and Al. All of these elements were also abundant in the current sludge samples. The most abundant of the rarer elements in Germany were Zn, Ba, Mn, Cu, Sr, Cr and Pb. Typical German wastewater treatment plants receive industrial effluent, which can contain heavy metals, whereas the Irish wastewater treatment plants in the current investigation treat almost exclusively domestic/commercial effluent.

Seasonal variation in the composition of the mineral matter of SS4 samples is presented in Figures 3.5 and 3.6. Figure 3.5 shows that iron (Fe) was the most abundant major element and varied between 50 and 80 g/kg (dry basis) during the sampling period. A similar trend was observed for P, with the P concentration varying from 21 to 35 g/kg. This probably reflected the dose of ferric salts used to remove P from wastewater. Ca and Si varied from 15 to 30 g/kg and from 17 to 43 g/kg, respectively, with the highest concentration observed in the SS4 sample collected in December 2017. The concentration of Al was generally below 5 g/kg, except for the sample from December 2017, which contained a concentration of Al of 9 g/kg. The concentrations of K, Mg and Na were consistent throughout the year, at 4.6 ± 0.7 g/kg, 3.5 ± 0.4 g/kg and 1.8 ± 0.4 g/kg, respectively. The concentration of S ranged from 2 to 6 g/kg, with an average concentration of 3.5 ± 1.3 g/kg.

Titanium dioxide (TiO_2) is the most extensively used nanoparticle and its fate in the soil environment has been investigated by Kim *et al*. (2012), who found that TiO_2 nanoparticles from biosolids can interact with toxic trace metals such as Ag and enter the soil environment. Figure 3.6 shows that the concentration

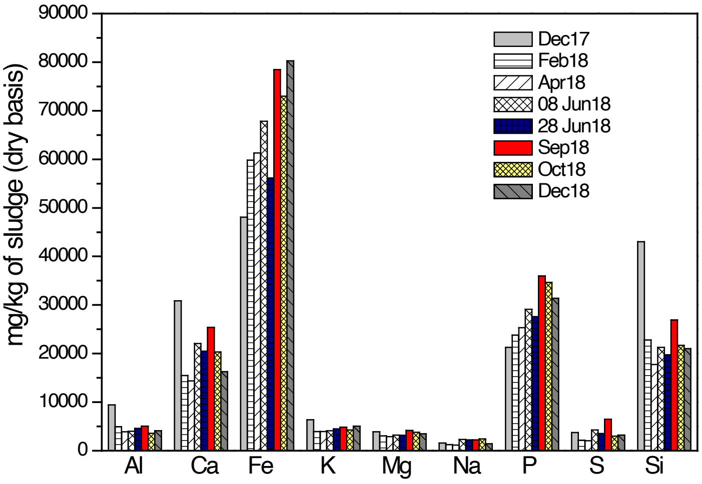

Figure 3.5. Major elements in SS4 samples over a 12-month period (dry basis).

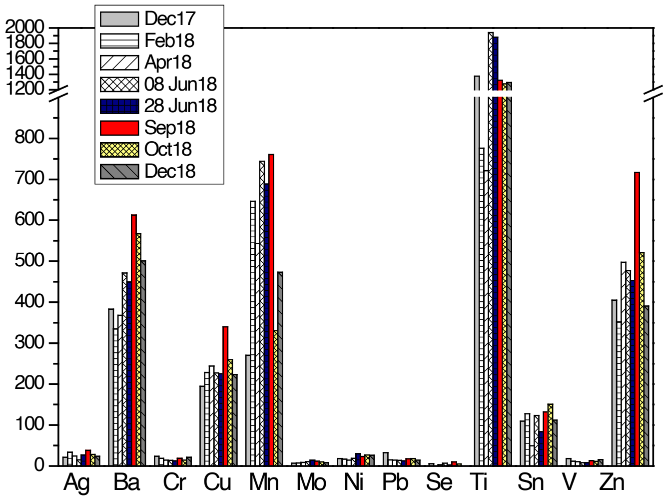

Figure 3.6. Minor elements in SS4 samples over a 12-month period (dry basis).

of Ti in SS4 varied significantly over the sampling period, from 700 to 1900 mg/kg. The highest concentration of Ti was found in samples collected in June 2018, with the lowest concentrations found in February and April 2018. The average Ti concentration was 1300 ± 440 mg/kg. Titania is one of the most abundant ingredients in suncreams, whose usage peaked during June 2018. Concentrations of Ba and Zn varied from 300 to 610 mg/kg and from 350 to 720 mg/kg, respectively, whereas the concentration of Cu was usually observed to be around 200 mg/kg, except for the sample from September 2018, when it was 340 mg/kg. The concentration of Mn was higher from February to September 2018 than in October and December 2018, at 680 mg/kg versus 360 mg/kg, respectively. The concentration of Sn was consistent throughout the year, with an average of 110 mg/kg. Concentrations of Cr, Mo, Ni, Pb, Se and V did not vary significantly and were below 20 mg/kg. The other heavy metals, such as Cd, Co, As, Sb and Hg, were present in some SS4 samples but at a very low concentrations (below 5 mg/kg). Silver (Ag) was present in each SS4 sample tested at an average concentration of 26 ± 7 mg/kg, which is higher than that observed in sludge ash from German wastewater treatment plants (Krüger *et al*., 2014). The concentration of Sn in SS4 samples (110 mg/kg) was higher than that reported by Healy *et al*. (2016) and much higher than its baseline concentrations in soils.

Overall, the concentrations of the metals that are regulated in the European Union (EU) (Cu, Ni, Pb, Cd, Zn and Hg) were well below the EU regulatory limits for biosolids in all of the SS samples tested.

3.1.1 Conclusions

The SS samples tested had a moderate ash content (20–32 wt%) and a high volatile matter content (53–73 wt%) on a dry basis, and a LHV of 16–19 MJ/kg, which makes them a potentially attractive fuel for pyrolysis, with the aim of energy recovery in the form of a high CV gas. There was seasonal variation in the ash content, volatile matter content and calorific value, reflecting weather conditions (higher ash content in hot summers, with the lowest ash content in the cold spring). The composition of mineral matter varied between SS samples. Generally, the concentrations of the heavy metals that are regulated in the EU were below the EU regulatory limits for biosolids in all SS samples. There was slight seasonal variation in the concentrations of P and Fe, probably related to the dose of ferric salts used for P removal. Although the sample size was small, the concentrations of some non-regulated elements, such as Ag, Sn and Ti, were relatively high in the SS samples that were tested.

3.2 Pyrolysis of Sewage Sludge at Laboratory Scale

All SS samples were bench dried at ambient temperature and then pyrolysed in a laboratory-scale fixed-bed reactor. The distribution of pyrolysis products is shown in Figure 3.7 and Table A1.11 (see Appendix 1). The results represent an average of five separate pyrolysis runs, with 50 g of feedstock per run. The char yield from SS ranged from 30 wt% to 48 wt%; the wide variation was the result of the different types of treatment undergone during the wastewater treatment process. In general, higher char yields (43–45 wt%) were obtained for pelleted or granulated SS samples (SS1 and SS2), with lower yields obtained for belt press cake, which had an average char yield of 37.7 wt%. Mixing granules of SS2 with FR reduced the char yield from 42.6 wt% to 37.8 wt%. The average liquid fraction was 28 wt% but it varied significantly between samples, from 15 wt% to 45 wt%, which suggests that it depends on the specific composition of SS as well as the type of pre-treatment undergone. The gas fraction from pelleted or granulated SS samples was lower, at 26.0 wt% and 29.5 wt% for SS2 and SS1, respectively, than that from samples from belt press cake, which had an average gas yield of 34.2 wt%. Mixing SS2 with FR increased the gas yield from 26.0 wt% to 36.2 wt%.

The distribution of pyrolysis products primarily depends on the proximate properties of the SS. Seasonal variation in the ash and volatile matter content (see Figure 3.1 and Table A1.9 in Appendix 1) was reflected in the distribution of the pyrolysis products from SS4. The highest char yield was observed for the sample collected in September 2018, which followed the dry summer. A lower char yield, from 30 wt% to 35 wt%, was observed in the samples of SS4 between February and June 2018. The lowest fraction of liquid, at 15 wt%, was found in the sample collected in September 2018, whereas the highest, at 45 wt%, was found in the sample from February 2018. Weather conditions had an influence on the properties

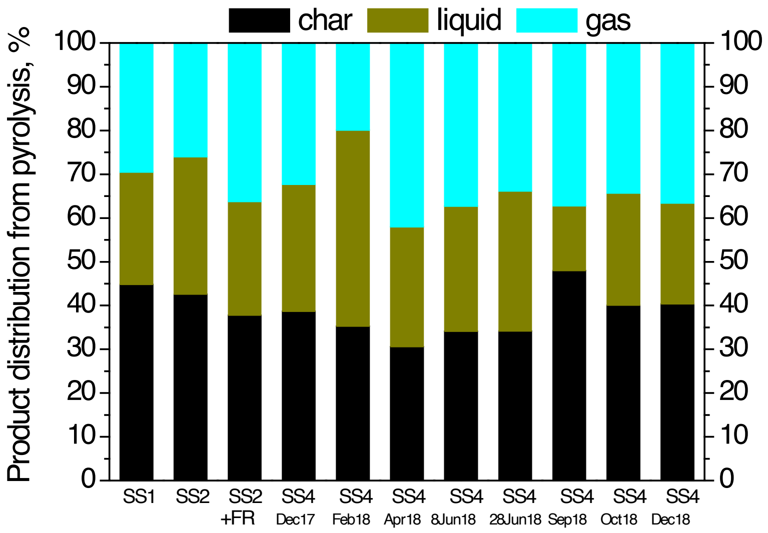

Figure 3.7. Average product distribution from pyrolysis of SS samples at 700°C for 10 minutes.

of SS4; the lowest gas yield of 20 wt% was obtained from sample collected in February 2018 after a cold wet season, whereas the average gas yield for SS4 samples was 34 wt%.

The proximate properties of the SS chars are presented in Figure 3.8 and Table A1.13 (Appendix 1). The chars consisted mainly of ash, which represented 54–71 wt% of the recovered solid. These ash values are lower than those reported elsewhere (Trinh *et al*., 2013) The volatile matter content of most of the chars was below 12 wt%, implying that almost complete decomposition of the organic matter occurred in the fixed-bed reactor at 700°C and a residence time of 10 minutes; the exceptions were the SS4 December 2017 and SS2 + FR samples, for which the observed volatile matter content was 16 wt% and 24 wt%, suggesting that decomposition of these samples was not complete and a fraction of organic matter was still un-released from the solid matrix, probably because of the very large particle size of the dried SS4 lumps. The HHV of SS chars varied from 9 to 16 MJ/kg.

With regard to the seasonal variation of the results for the SS4 samples, the volatile matter content (average 9.4 ± 3.5 wt%) and fixed carbon content (average 24.4 ± 5.4 wt%) varied slightly over the sampling period but this could be related to the non-uniform particle size of the dried SS4 (pyrolysis of bigger particles was probably incomplete). The ash content was 66.2 ± 3.3 wt% whereas the HHV was 12.8 ± 2.0 MJ/kg.

Sewage sludge has a significant N and S content (see Tables A1.10 and Table A1.12 in Appendix 1). Less than 20 wt% of the original N and 20–30 wt% of the original S was preserved in the char following pyrolysis; these values are similar to those reported by others (Trinh *et al*., 2013).

The composition of the mineral matter of SS chars is shown in Figures 3.9 and 3.10. All of the major elements and most of the minor elements were concentrated in the char samples, as observed in other studies (Zielińska and Oleszczuk, 2015; Ronda *et al*., 2019). The concentrations of Cr, Pb, Se, Sn, Cd and Co were lower in the SS chars, suggesting that these volatile elements were released from the sludge during pyrolysis at 700°C. Volatilisation of some heavy metals is typically observed during pyrolysis (Trinh *et al*., 2013; Chen *et al*., 2015; Dong *et al*., 2015; Han *et al*., 2017; Chanaka Udayanga *et al*., 2018).

The concentrations of Cu, Ni and Zn in SS chars were higher than the allowable limits set by the EBC, suggesting that the SS char could be used as a fuel either for combustion or for land spreading, similar to SS, under the agriculture regulations. Mancinelli *et al*. (2016) reported that SS char generated at 700°C exceeded the limit set in the EBC for Cu (100 mg/kg), Cr (90 mg/kg) and Zn (400 mg/kg) by 6.1 times, 1.2 times and 5 times, respectively.

The composition of the gas released during pyrolysis of the SS samples is presented in Figure 3.11 and Table A1.14 (see Appendix 1). The combustible gas fraction comprised predominantly CO, CH_4, H_2, C_2H_4 and C_2H_6. The combined volumetric fraction of the combustible gases was 57–88% of that of the

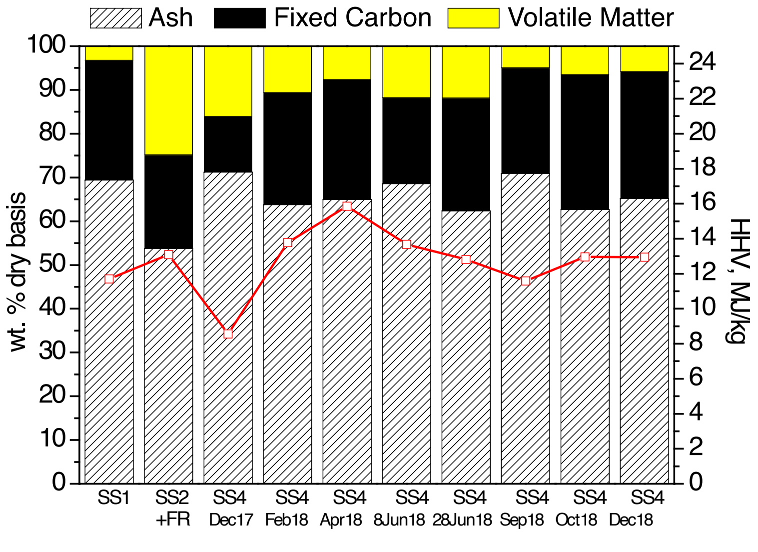

Figure 3.8. Proximate properties of SS char samples (dry basis). The red line represents the HHV (MJ/kg).

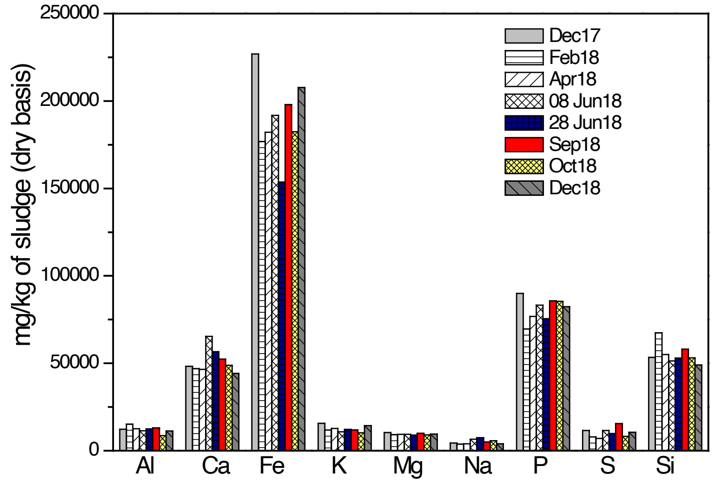

Figure 3.9. Major elements in SS4 char samples (dry basis).

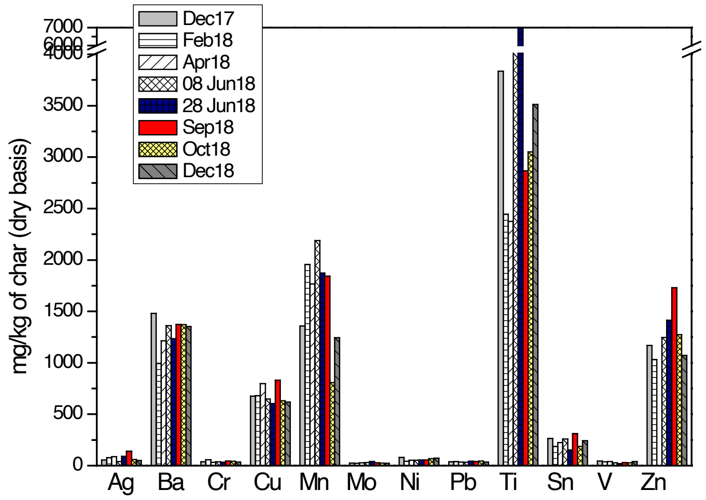

Figure 3.10. Minor elements in SS4 char samples (dry basis).

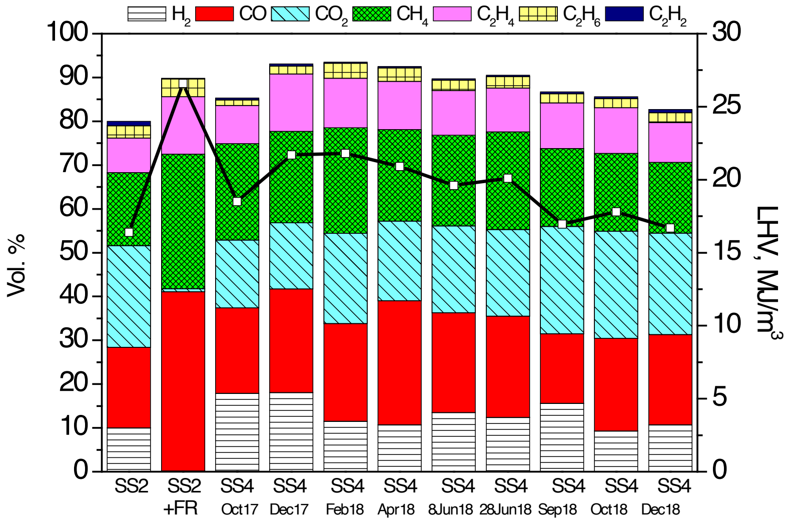

Figure 3.11. Pyrolysis gas composition (N_2-free basis).

observed gases. The calculated LHV ranged from 16 to 22 MJ/m^3. The differences in gas composition and LHV depend mainly on the original sample composition. Mixing SS2 with FR resulted in a significant increase in the LHV of the gas, from 16 to 27 MJ/m^3. Although all of the SS samples contained S, H_2S was not always detected in the pyrolysis gas.

Figure 3.11 shows the variation in the pyrolysis gas composition for SS4 during the sampling period. There was a wide variation in the volumetric fraction of CO, H_2 and CO_2. The average calculated LHV was 19 ± 2 MJ/m^3.

The liquid fraction obtained from pyrolysis was dark brown in colour and consisted of two visible and easy to separate phases, comprising an oil and an aqueous fraction. The heavier aqueous fraction contained water and certain hydrosoluble organic compounds whereas the oil fraction contained the organic fraction. Table A1.7 in Appendix 1 lists 20 compounds detected in the aqueous fraction of the pyrolysis liquid from SS4 samples, with the most abundant compounds being acetamide; 2,4-imidazolidinedione,5,5-dimethyl-; pyridine; 2,4-imidazolidinedione, 5-methyl-; and pyridine 2-methyl. Table A1.8 in Appendix 1 lists 24 compounds detected in the oil fraction of the pyrolysis liquid from SS4 samples, with the most abundant compounds being toluene, styrene, indole, naphthalene and phenol. Nine out of 18 compounds reported in Table A1.8 were also measured in the pyrolysis oil from SS by Chen *et al*. (2018).

3.2.1 Conclusions

The distribution of pyrolysis products depends on the specific properties of SS but also reflects the types of treatment that the SS undergoes. A higher char yield was obtained for granulated and pelleted SS than for belt press cake SS, whereas the opposite trend was observed for gas yield. Seasonal variation in SS properties was observed in the distribution of pyrolysis products. The lowest gas yield of 20 wt% (desirable) and the highest liquid yield of 45 wt% (undesirable) were obtained for the sample collected in February 2018.

The LHV of pyrolysis gas ranged from 16 to 19 MJ/m^3 and was mainly influenced by the specific SS composition. Slight seasonal variation in the gas composition was observed.

The concentration of Cu, Ni and Zn in SS chars was too high for their use as a soil amendment according to the EBC.

4 Pyrolysis of Sewage Sludge at Pilot Scale

The objective of this part of the project was to determine if pyrolysis of a mixture of anaerobically digested sewage sludge (AD-SS) and wood could provide a gas of sufficient quality for use in a gas engine, with the char offering the potential to be used for combustion.

The AD-SS was obtained in the form of granular dry material. Before pyrolysis it was mixed with wood chips in a 70:30 ratio by weight and subsequently pelletised. Photographs of AD-SS and AD-SS mixed with wood pellets (AD-SS + FR) are shown in Figure 4.1. The bulk density of the pellets was 662 kg/m^3.

The proximate properties of AD-SS and AD-SS + FR are presented in Table 4.1.

For the AD-SS + FR pellets tested, a volatile matter content of 74.3 wt% and an ash content of 13.8 wt% were observed (dry basis), indicating that, during high-temperature decomposition, most of the organic content of the dried sludge forms vapour-phase products (non-condensable permanent gases and condensable compounds). A high volatile matter content is advantageous when the pyrolysis gas is the desired product. A fixed C content of 11.9 wt% indicates the amount of unconverted C that potentially will remain in the char after pyrolysis. The N content was 4.0 wt%, which is one of the typical characteristics of SS. A S content of 0.76 wt% was observed.

Mixing AD-SS with FR slightly reduced the ash, N and S contents in the feedstock.

Figure 4.1. AD-SS (left) and pellets of AD-SS mixed with wood (right).

Table 4.1. Proximate and ultimate properties of AD-SS and AD-SS + FR

Properties, wt%	AD-SS before pelleting	AD-SS + FR (70:30)
Moisture, a.r.	6.68	8.03
Ash content, d.b.	15.72	13.75
Volatile matter, d.b.	73.03	74.33
Fixed carbon, d.b.	11.26	11.92
LHV, MJ/kg, d.b.	21.30	20.60
C, d.b.	46.85	47.36
H, d.b.	6.16	6.05
N, d.b.	4.59	4.00
S, d.b.	0.87	0.76
O, d.b. (by difference)	25.97	27.96

a.r., as received basis; d.b., dry basis.

The composition of the mineral matter of AD-SS + FR pellets is presented in Table A1.17 in Appendix 1. Si (21.7 g/kg of dry matter) was the most abundant element, followed by Ca (17.7 g/kg), P (12.1 g/kg), Fe (6.2 g/kg) and Al (5.6 g/kg). Ti showed the highest concentration among all minor elements (1061 mg/kg), followed by Ba (444 mg/kg) and Cu (415 mg/kg). Silver was present at a concentration of 35 mg/kg.

The experimental tests were carried out in a pilot-scale facility at Premier Green Energy, Thurles, used predominantly for pyrolysis of FR chips. A schematic diagram of the experimental facility with sampling points is shown in Figure 4.2. The pilot facility consists of four main sections: a feeding system, a pyrolysis reactor with a char and gas separation section, a gas conditioning section and a gas engine or flare. The feeding system comprises two hoppers, a series of augers and interlocking gate valves to ensure uniform input of feedstock and that a minimal amount of air enters into the pyrolysis reactor. In order to prevent pyrolysis of the feedstock prior to its entry into the reactor, the feeding pipe is cooled using a water jacket. The pyrolysis reactor is a stationary muffle furnace with a refractory lined SS253 MA steel rotating retort. The pyrolysis temperature was the average temperature measured at the entrance and the outlet of the reaction chamber (retort). At the beginning of each test, before the feedstock was fed into the conversion chamber, an oxygen-deficient environment was created by purging the retort with N until the oxygen content was below 3 vol.%. The feedstock residence time in the retort was about 10 minutes whereas the residence time of the gas was about 7 seconds. The majority of the char leaving the reactor was gravity separated and collected in a storage vessel. Fine char particles were separated from the pyrolysis gas in a hot cyclone. Subsequently, the gas was ducted into a cracking reactor, where it was mixed with air that had been pre-heated to about 400–450°C in the recuperator. The residence time of the gas in the cracking reactor was about 3 seconds. The gas leaving the cracker was ducted into a recuperator to reduce its temperature to 150 ± 50°C prior to wet gas scrubbing while pre-heating the air for the cracking reaction. The cooled gas was further conditioned in a water scrubber, passed through an activated carbon filter, treated in a de-humidifier and, finally, reheated to 30–45°C before being sent to the gas engine. The pilot plant operates at a slightly negative pressure; the pyrolysis gas was extracted from the system using a gas booster.

The operating process conditions for the pyrolysis pilot tests were as follow: feeding rate of AD-SS + FR pellets of ~60 kg/hour, pyrolysis temperature of ~800°C, cracking reactor temperature of 880°C and flow rate of air for cracking of 30.75 Nm^3/hour. During the experiment the following physical properties were measured: mass of feedstock fed in, mass of char produced, and volumetric flow of pyrolysis gas and air for the cracking reactor. The gas composition was measured in-line by gas chromatography (Micro GC) at the third sampling port whereas off-line gas samples were collected in Tedlar bags at the first and second sampling ports. Samples of gas were taken at all sampling points for determination of solid phase adsorption (SPA) tar content, moisture content and NH_3 concentration. The set-up for NH_3 sampling and SPA tar sampling at the second sampling port is presented in Figure 4.3.

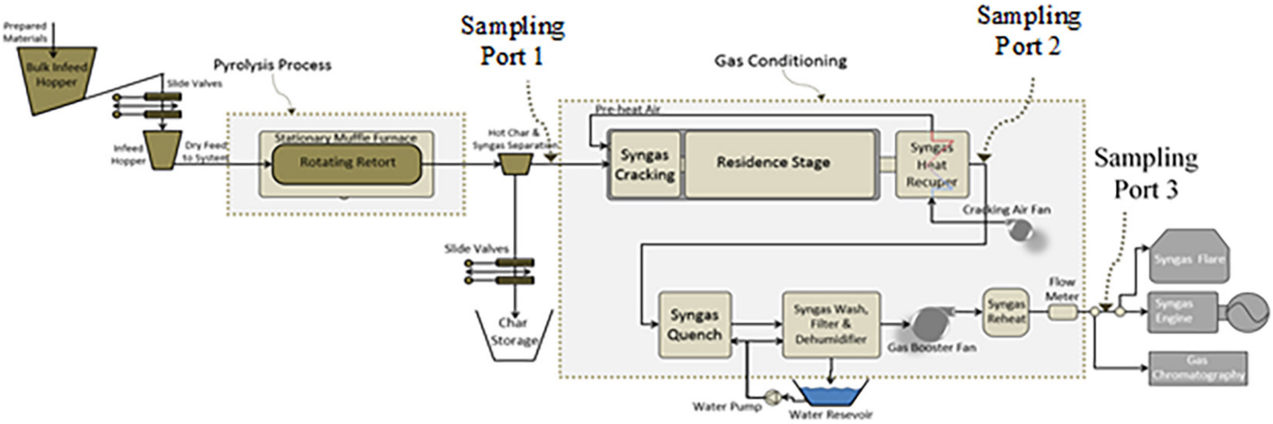

Figure 4.2. Schematic diagram of the pilot-scale facility.

The volumetric concentration of the gas components over the run time of the experiment, measured in-line at gas sampling point 3 (before the engine), is shown in Figures 4.4 and 4.5. The gas composition profiles for the major and minor gas components had effectively stabilised after 10 minutes. In order to ensure that a steady state had been reached, an additional 10 minutes were allowed before sampling the product gas for tars and NH_3.

Gas sampling at the first sampling port was impaired and, consequently, the composition of the pyrolysis gas without conditioning was not recorded. However, we assumed that the calorific value of the pyrolysis gas prior to conditioning was twice that after conditioning (14.2 MJ/m^3), as similar pilot-scale tests were carried out for wastewater sludge from milk processing mixed with FR and a similar relationship was always observed (Kwapinska *et al.*, 2019).

During the pilot-scale test, the conditioned pyrolysis gas was sampled in-line every 10–15 minutes and analysed by gas chromatography (Micro GC). The average gas composition for steady state operation is presented in Table 4.2. The calorific value of the conditioned pyrolysis gas was 7.1 MJ/m^3; as air was injected into the cracking reactor the final gas was diluted with N_2, which accounted for 53.5 vol.%. The total tar content was $7.0 \pm 0.3\,g/Nm^3_{dry\ gas}$. A yield of conditioned pyrolysis gas of 1.12 m^3/kg of dry feedstock was observed.

The tar content and composition were measured in duplicate at the three sampling ports along the pilot-scale facility. The average yield of total gas chromatography-detectable tars was reduced between sampling ports 1 and 2, from $14.6\,g/Nm^3_{dry\ gas}$ at port 1 to $8.3\,g/Nm^3_{dry\ gas}$ at port 2, located after the thermal cracking reactor. Further conditioning of the pyrolysis

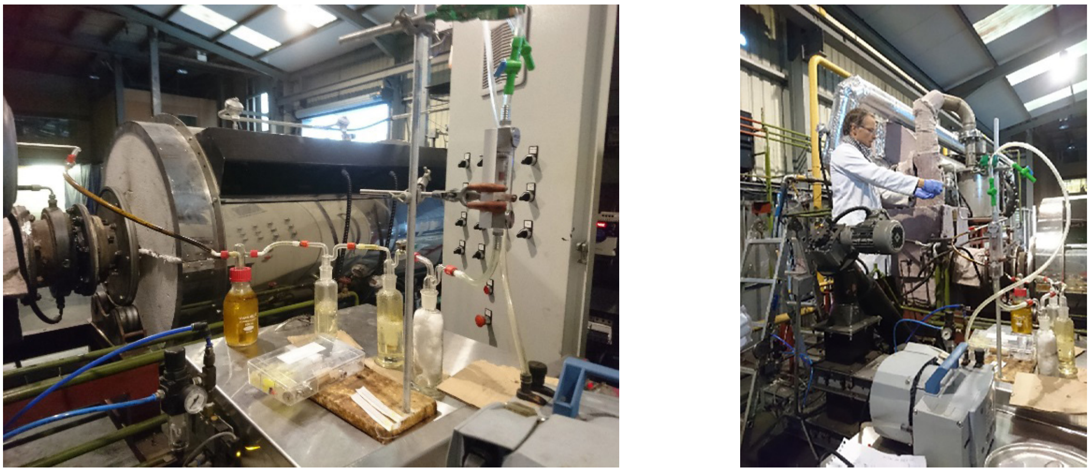

Figure 4.3. Set-up for NH_3 sampling and SPA tar sampling at the second sampling port.

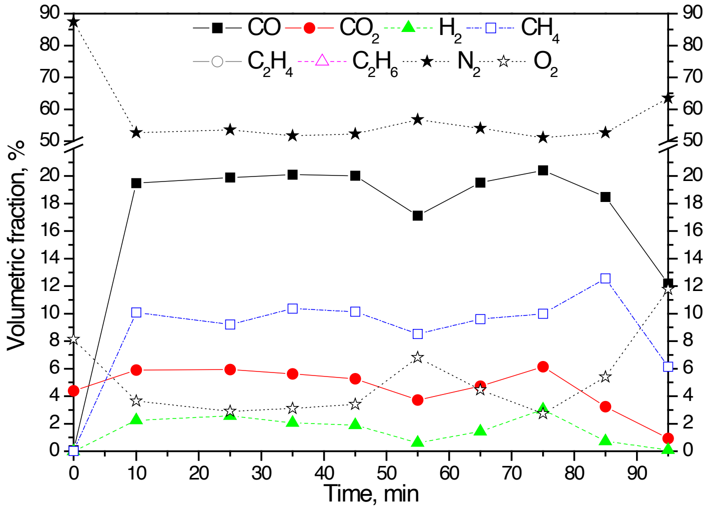

Figure 4.4. Content of major gas components in the pyrolysis gas after conditioning.

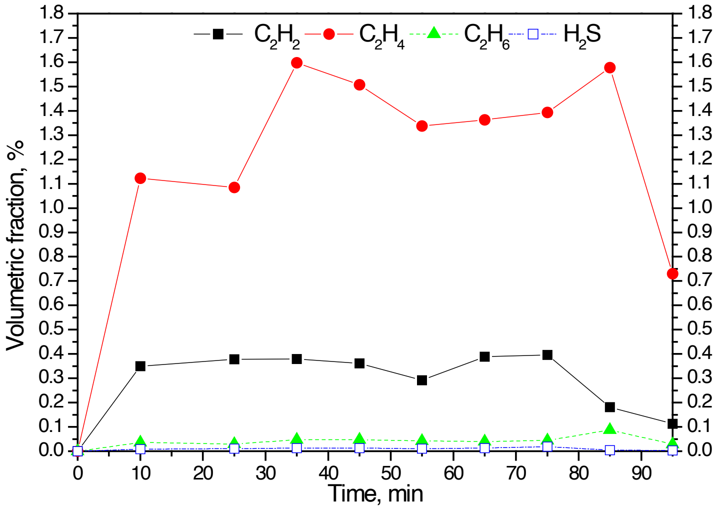

Figure 4.5. Content of minor gas components in the pyrolysis gas after conditioning.

Table 4.2. Test results. Average composition of the pyrolysis gas at steady state operation after conditioning (gas sampling port 3)

Pyrolysis gas	Composition
Gases, vol.%	
H_2	1.8±0.9
CO	19.0±1.6
CO_2	5.0±1.1
CH_4	9.8±1.3
C_2H_2	0.3±0.1
C_2H_4	1.3±0.2
C_2H_6	0.05±0.1
N_2	53.5±2.6
O_2	4.4±1.9
H_2S, ppm	119±45
NH_3, g/m^3	0.324
LHV, MJ/m^3	7.1±0.7
Total tar, g/Nm$^3_{\text{dry gas}}$	7.0±0.3
Water content, g/Nm$^3_{\text{dry gas}}$	6.5±7.8
Gas yield, m^3/hour	63.1±1.6
Gas yield, m^3/kg$_{\text{dry feed}}$	1.12±0.03

gas did not have much influence on the tar content measured at port 3, where a value of 7.0 g/Nm$^3_{\text{dry gas}}$ was recorded. Table A1.15 in Appendix 1 shows the yields of all identified tar compounds measured, recorded according to the IUPAC (International Union of Pure and Applied Chemistry) nomenclature and listed in the order in which they eluted.

Tar content can be viewed from two different perspectives, depending on the final use of the pyrolysis gas. When the hot raw gas is combusted directly, such as in boilers and industrial kilns, tars are a source of energy not accounted for in the calorific value of the dry pyrolysis gas. There is very little chance of tar condensation and thus there is no need for tar removal; usually, no tar limits are specified by boiler manufacturers. The N-containing tars, however, will release HCN and NH_3, mainly through secondary thermal cracking, and during combustion nitrogen oxides (NO_x) and N_2O will be released. Therefore, de-NOx technology would be required post combustion.

However, for use in an internal combustion gas engine, the tar has to be removed to levels specified by manufacturers. Internal combustion engines require cooled gas as there is a probability of tar condensation inside the engine or in the fuel-injection systems. In general, tar concentrations in the gas should be well below 100 mg/Nm^3 (Milne and Evans, 1998) but each manufacturer provides its own specifications. For the Dresser-Rand Group (Dresser-Rand, 2016) gas engine used in this study, gasification or pyrolysis tar limits are specified for a series of tar groups differentiated according to the number of aromatic rings in the tar molecules. The limit is < 1.5 g/MJ for tar molecules with a single aromatic ring, < 0.2 g/MJ for tar molecules with two aromatic rings and < 0.003 g/MJ for tar molecules with three aromatic rings; tar compounds with four or more aromatic rings are not allowed to enter the gas engine. The manufacturer also proposes the CEN/BT/TF 143 standard technical specification, also known as the tar protocol, as the methodology for determination of the tar content in the gas, rather than the alternative and more commonly used SPA method.

The average LHV of dry pyrolysis gas (excluding the tar fraction) derived from the blended AD-SS + FR chips feedstock at sampling port 3 was 7.1 MJ/Nm^3. The upper tar limit for the Dresser-Rand gas engine is 10.6, 1.4 and 0.02 g/Nm^3 for compounds with one, two and three aromatic rings, respectively.

The raw pyrolysis gas was conditioned in order to remove the problematic tar compounds that could cause fouling of the process installation. Table 4.3 shows the tar compounds measured from sampling ports 1, 2 and 3, grouped and classified on the basis of the number of aromatic rings. The concentrations of one, two and three aromatic ring tars were below the maximum tar limits specified by Dresser-Rand. However, despite the thermal cracking and subsequent water scrubbing, together with activated carbon filtration, molecules comprising the four aromatic ring tar group (anthracene, 4H-cyclopenta[def] phenanthrene, fluoranthene, pyrene, cyclopenta[cd] pyrene, tetraphene, benzo[e]acephenanthrylene, indeno[1,2,3-cd]pyrene) were observed in the pyrolysis gas at concentrations exceeding the engine specification. It should be noted that the tar group listed as “unknown” represent the quantities of identified species as the database on the gas chromatography mass spectrometry (GC-MS) was unable to identify all peaks. An efficient tar mitigation system is required if pyrolysis gas is to be used in internal combustion gas engines.

Quantifying the content of NH_3 in the pyrolysis gas proved difficult. The NH_3 content before gas conditioning was 36.9 g/Nm^3, which accounts for 43 wt% of the total N input into the system for the AD-SS + FR mixture. This value is higher than that reported in the literature, e.g. Wei *et al*. (2015) observed that 16 wt% of fuel-N was present as NH_3 during pyrolysis of SS whereas Aznar *et al*. (2009) reported that over 20 wt% of fuel-N was present as NH_3 during gasification of SS. The mass balance calculations revealed that 24 wt% of the initial N content was retained in the char, which is similar to results reported elsewhere (Aznar *et al*., 2009). As 33 wt% of the initial N content was not accounted for in the measurements, it could be an indication that the NH_3 was condensing in the lines used during gas sampling because of insufficient insulation or present in a form of HCN. On the other hand, it has been reported that, during gasification of N-containing SS, up to 44 wt% of the N was released as N_2 (Aznar *et al*., 2009) as a result of the catalytic effect of the mineral matter. In the present study it was difficult to distinguish between the N_2 entering the system with air in the interstices between the feedstock particles and N_2 potentially released from thermal conversion of the AD-SS + FR mixture. When we consider all of the limitations of the current system set-up, a significant amount of the N input with the feedstock was not accounted for.

Although NH_3 was removed from the gas in the water scrubber, the content of NH_3 remaining, 46.9 mg/MJ, exceeds the recommended limit of 1.5 mg/MJ for the Dresser-Rand internal combustion engine. By mixing AD-SS with FR it was possible to dilute/reduce the NH_3 content in the pyrolysis gas; nevertheless, the requirements for this specific engine were not met. The pilot-scale pyrolysis facility used in this case is typically used for testing materials that do not contain high amounts of N; therefore, it may be possible to improve and optimise the scrubber cleaning section. Alternatively, the fraction of FR mixed with the AD-SS could be increased to further dilute the concentration of NH_3.

The yield of pyrolysis char was 234 kg/tonne of AD-SS + FR mixture fed into the pyrolyser. Lepez *et al*. (2015) reported a similar yield of char of 29 wt% from SS after pilot-scale pyrolysis at 800°C in an integrated system of a contact drier and Spirajoule pyrolyser. The proximate and ultimate properties of chars from the pilot-scale tests are presented in Table 4.4. The pyrolysis char consisted mainly of a fixed carbon

Table 4.3. The yields of tar groups classified according to the number of aromatic rings in the compound

	Sum (gtar/Nm^{3}dry gas)				
Port	**Σ1 ring**	**Σ2 rings**	**Σ3 rings**	**Σ4+ rings**	**Unknown**
1	8.35	2.98	0.53	0.13	2.63
2	5.32	1.55	0.63	0.51	0.71
3	6.49	0.03	0.004	0.003	0.51

Table 4.4. Proximate and ultimate properties of char from pilot-scale pyrolysis of AD-SS + FR

Properties, wt%	Char
Moisture, a.r.	0.57
Ash content, d.b.	43.95
Volatile matter, d.b.	11.53
Fixed carbon, d.b.	45.15
HHV, MJ/kg, d.b.	17.85
C, d.b.	48.49
H, d.b.	1.50
N, d.b.	3.88
S, d.b.	0.47
O, d.b. (by difference)	1.71

a.r., as received basis; d.b., dry basis.

content of 45.2 wt% and an ash content of 44.0 wt% on a dry basis. The volatile matter content of 11.5 wt% indicated that the majority of the organic matter had decomposed.

The mass balance calculations revealed that 15 wt% of the S content was retained in the char, which is lower than data reported by Zhang *et al.* (2017), who found a 50% retention rate of S in the char for SS pyrolysis.

The composition of the mineral matter of char from pilot-scale pyrolysis of AD-SS + FR is presented in Table A1.17 in Appendix 1. All of the major elements and most minor elements were concentrated in the char, except for S and Cd. The pyrolysis char cannot be qualified as biochar for agricultural use as it did not meet the certification criteria. The concentrations of Pb, Cd, Cu, Ni, Zn and Cr in the char exceed the maximum allowable values specified in the EBC (EBC, 2012). However, the char is suitable for combustion, with an HHV of 17.85 MJ/kg and an activation energy for char combustion in the region of 89 kJ/mol.

4.1 Conclusions

The amount of raw pyrolysis gas generated was 570 m^3/tonne of dry feedstock, with a calorific value of 14 MJ/m^3. The content of impurities observed in the raw gas was high, at 36.90 mg/Nm^3 of NH_3, and 14.6 $g_{total\ tar}$/$Nm^3_{dry\ gas}$ was recorded. The pyrolysis gas is suitable for direct combustion in a gas boiler fitted with de-NO_x and de-SO_x (sulfur oxides) technology.

The raw pyrolysis gas was conditioned to reduce the tar content and remove NH_3 and H_2S. As air was used as the reagent gas in the high-temperature cracking reactor, a higher volume of the final pyrolysis gas was obtained as it had been diluted with N_2 from the air. The yield of conditioned pyrolysis gas was 1120 m^3/tonne of dry feedstock, with a calorific value of 7.1 MJ/m^3. The content of impurities in this gas was significantly reduced to 324 mg/Nm^3 for NH_3 and 7.0 $g_{total\ tar}$/$Nm^3_{dry\ gas}$. However, for NH_3, this exceeded the maximum permissible concentration for the engine. Moreover, tar compounds with four aromatic rings were observed in the gas, which are not permitted by the engine manufacturer. Dedicated tar cleaning is required and the water scrubbing section needs to be optimised if the gas is to be used in gas engines. In total, 320 kg of char was recovered per tonne of AD-SS + FR mixture. The pyrolysis char is suitable as a solid fuel.

5 Combustion Kinetics of OF-MSW and SS Chars

The kinetics of combustion of OF-MSW and SS chars from the laboratory-scale pyrolysis process were investigated thermogravimetrically at laboratory scale. The activation energy, a key kinetic parameter, for char combustion in air was determined according to the Standard Test Method for Decomposition Kinetics by Thermogravimetry (ASTM standard E1641-99) and the results are presented in Table 5.1.

The activation energy of a chemical reaction is closely related to the rate of reaction. Specifically, the higher the activation energy, the slower the chemical reaction rate as molecules can complete the reaction only once they have exceeded the activation energy barrier. Many reactions have such high activation energies that they do not proceed at all without an input of energy, for instance the oxidation (or combustion) of solid fuels.

Table 5.1. Activation energy for combustion of OF-MSW and SS pyrolysis chars in air

Char	Activation energy, kJ/mol
OF1	102.17
OF2-1	90.10
OF2-2	86.78
OF2-3	92.92
SS1	94.70
SS2	90.00
SS2 + FR	89.35
SS4 (Dec 17)	93.19
SS4 (Feb 18)	93.57
SS4 (Apr 18)	76.56
SS4 (28 Jun 18)	80.51
SS4 (Sep 18)	85.36
SS4 (Dec 18)	93.18
Graphite powder	160.84

The activation energy of the OF chars ranged from 93 to 102 kJ/mol, with no identifiable trend observed that could be related to the type of processing. The highest activation energy of 102 kJ/mol was observed for the OF1 char. Samples of OF were very heterogeneous and, as 20 mg of sample was used for each experiment, the amount and composition of mineral matter in the char could significantly affect the activation energy (Li *et al*., 2007; Hu *et al*., 2018a). It was previously reported that pyrolysis chars from OF-MSW, if produced at low and medium temperatures, belong to the most reactive technical carbon materials (Henrich *et al*., 1999). The main reason for the high reactivity is a highly disordered carbon structure in combination with high porosity.

The activation energy of SS chars varied from 77 to 95 kJ/mol, with an average of 88.4 kJ/mol. Mixing SS2 with FR did not affect the activation energy for combustion of char. Some variation in the activation energy for SS4 char combustion was observed over the sampling period, with the lowest activation energy observed for the SS4 sample collected in April 2018, with slightly higher values recorded for the samples from June and September 2018. The highest activation energy was for SS4 samples collected in December 2017 and 2018 and February 2018. Overall, a 20% difference in the activation energy for SS4 char combustion was observed throughout the year.

The activation energy of most OF-MSW and SS chars was lower than that of low-rank coal char (Hu *et al*., 2018b), confirming their high reactivity, and much lower than that of graphite, as presented in Table 5.1 and also confirmed in the literature (Henrich *et al*., 1999).

6 Sintering and Leaching Behaviour of OF-MSW and SS Ash

Combustion of OF-MSW and chars was carried out in a muffle furnace in order to investigate their sintering behaviour. Some level of sintering of the ash will typically take place in an oxidation/incineration furnace (Sabbas *et al.*, 2003). Solid phase reactions, transformation and recrystallisation during sintering generally lead to a product with lower porosity. The decrease in porosity tends to reduce the leachability of harmful components from the ash (Lindberg *et al.*, 2015; Luo *et al.*, 2019). The aim of this part of the study was to determine a suitable sintering temperature. Samples of feedstock were first ashed at 550°C, which is the standard temperature for determining ash content (Solid biofuels – Determination of ash content BS EN 14775:2009). Subsequently, the ash was divided into three equal samples (11 g) for further heating at 900°C, 1000°C and 1100°C for 5 minutes. The mass of each sample was recorded before and after heating/sintering and the calculated mass loss for each sample is presented in Table A1.16 (see Appendix 1). The average mass loss for OF-MSW derived ash samples as a result of volatilisation of metals increased with temperature, at 2.2 ± 0.5%, 2.3 ± 0.7% and 2.5 ± 0.7% for 900°C, 1000°C and 1100°C, respectively. The highest loss of mass was observed for OF3 ash, ranging from 3.2% to 3.6%, whereas the lowest was observed for OF1, at 1.7%. This observation again reflects the impact of the specific composition of the waste and its heterogeneity.

The leachability of heavy metals from ash generated at different temperatures was tested according to DIN 38414-S4, as required under the waste acceptance criteria (WAC 2003/33/EC), to determine if heavy metals can be leached by water and transferred to soil, becoming a hazardous material. The results presented in Table 6.1 show that most of the OF-MSW ashes heated at 900°C had metal concentrations well within the limits for non-hazardous landfill waste according to the European Landfill Directive (1999/31/CE63); the exceptions were OF2-3 and OF3. When the OF-MSW ashes were heated at 1000°C and 1100°C, the leachability of Cr for three of the OF-MSW samples and one OF-MSW char exceeded the limit. The leachability of sulfate was within the limit for hazardous materials. The pH values of leachates were in the range of 12.30–13.96 (see Table 6.1).

OF-MSW is very heterogeneous waste, comprising glass, metal pieces and sometimes stones, limiting the use of pyrolysis char for combustion; it should not be used as a soil amendment. Figure 6.1 shows photographs of the OF ash samples, which demonstrate its heterogeneity. The leaching tests showed similar leaching behaviour for OF-MSW ash and char ash. The concentration of Cr in OF-MSW and in the OF-MSW ash depends on the original composition of the samples. Because of the concentration of harmful metals in OF-MSW, an oxidation/sintering temperature of 1100°C is insufficient to generate non-hazardous ash.

For comparison, the leaching behaviour of ash generated from SS1, SS4 (September 2018) and SS2 + FR was tested. Samples of all SS ash heated at 900°C, 1000°C and 1100 fall into the category of either inert or non-hazardous material, as the leachability of all metals for these ash samples was very low. Results reported by other researches, however, show that some SS ashes have concentrations of Se, Hg, Sb and Mo that exceed hazardous limits (Lynn *et al.*, 2018; Cyr *et al.*, 2012). The pH values of leachates were in the range of 5.68–6.62 (Table 6.2).

Table 6.1. Leachability results according to DIN 38414-S4 (mg/kg$_{db}$)

	Ba	Cd	Cr	Cu	Hg	Ni	SO$_4$	Se	Zn
Inert[a]	20	0.4	0.5	2	0.0	0.4	1000	0.1	4
Non-hazardous[a]	100	1.0	10.0	50	0.2	10	20,000	0.5	50
Hazardous[a]	300	5.0	70.0	100	2.0	40,000	50,000	7.0	200
900°C									
OF1	1.4	0.0	29.0	0.0	1.1	0.0	2071	1.1	0.0
OF2-1	0.9	0.0	27.1	0.0	0.0	0.0	6826	1.7	0.0
OF2-2	2.4	0.0	29.3	0.0	0.3	0.0	985	1.7	0.0
OF2-3	1.3	0.0	105.3	0.0	0.0	0.0	383	1.9	0.0
OF3	2.4	0.0	304.8	0.0	0.0	0.0	6788	1.8	1.2
OF4	0.8	0.0	54.8	7.1	0.0	0.1	1407	2.1	0.0
OF2-2 char	1.9	0.0	22.0	0.0	0.0	0.0	14,419	1.4	0.0
OF2-3 char	3.7	0.0	33.2	0.0	0.0	0.0	8	1.1	0.0
SS1 char	0.4	0.0	0.3	0.0	0.0	0.0	8557	0.2	0.0
SS2 + FR char	0.8	0.0	0.8	0.0	0.0	0.0	10,086	0.2	0.0
SS4 (Sep 18)	–	–	–	9.08	–	–	–	–	18.5
1000°C									
OF1	1.40	0.00	30.10	0.00	0.00	0.00	29,220.52	1.40	0.00
OF2-1	1.30	0.00	459.75	0.00	0.00	0.00	26,097.21	1.00	0.00
OF2-2	1.00	0.00	35.50	0.00	0.30	0.00	41,784.58	1.40	0.00
OF2-3	1.10	0.00	136.81	0.00	0.00	0.00	35,135.31	1.60	0.00
OF3	1.70	0.00	441.14	0.00	0.00	0.00	22,115.21	1.00	20.30
OF4	1.10	0.00	39.80	0.00	0.00	0.00	40,248.42	2.20	0.00
OF2-2 char	1.20	0.00	27.90	0.00	0.00	0.00	24,544.25	1.80	0.00
OF2-3 char	0.80	0.00	124.31	0.00	0.00	0.00	12,483.65	1.80	0.00
SS1 char	0.20	0.00	0.20	0.00	0.00	0.00	41,28.41	0.00	0.00
SS2 + FR char	0.40	0.00	0.30	0.00	0.00	0.00	64,85.45	0.20	0.00
SS4 (Sep 18)	–	–	–	3.03	–	–	–	–	3.03
1100°C									
OF1	1.10	0.00	37.40	0.00	0.00	0.00	45,387.34	1.00	0.00
OF2-1	8.00	0.00	359.34	0.00	0.00	0.00	22,090.01	1.00	0.00
OF2-2	1.40	0.00	33.30	0.00	0.00	0.00	28,585.66	1.30	0.00
OF2-3	1.40	0.00	110.91	0.00	0.00	0.00	28,294.03	0.70	0.00
OF3	0.90	0.00	482.25	0.00	0.00	0.00	25,245.12	0.60	0.00
OF4	1.00	0.00	23.20	0.00	0.00	0.00	47,561.36	0.60	0.00
OF2-2 char	0.80	0.00	31.70	0.00	0.00	0.00	42,915.69	0.90	0.00
OF2-3 char	0.90	0.00	90.81	0.00	0.00	0.00	32,610.26	0.80	0.00
SS1 char	0.00	0.00	0.00	0.00	0.00	0.00	210.62	0.20	0.00
SS2 + FR char	0.10	0.00	0.20	0.00	0.00	0.00	6485.45	0.40	0.00
SS4 (Sep 18)	–	–	–	0.00	–	–	–	–	0.00

[a]Limits according to the European Landfill Directive (1999/31/CE63).

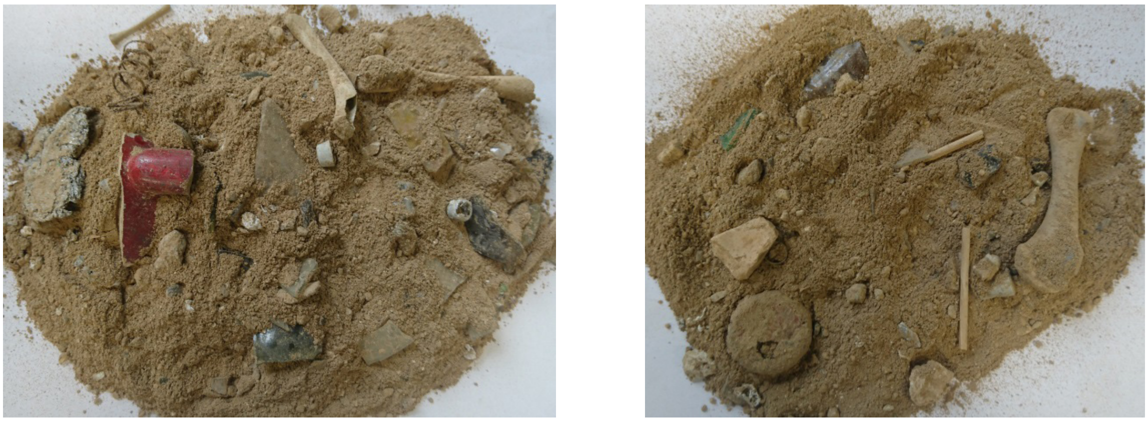

Figure 6.1. Ash of OF-MSW.

Table 6.2. pH of leachates prepared according to DIN 38414-S4

pH	900°C	1000°C	1100°C
OF1	13.83	13.76	12.62
OF2-1	13.75	13.95	13.56
OF2-2	13.92	13.60	13.95
OF2-3	13.91	13.49	13.95
OF3	13.96	13.93	13.50
OF4	13.37	13.34	12.30
OF2-2 char	13.97	13.88	12.79
OF2-3 char	13.70	13.42	12.63
SS1 char	6.60	6.62	6.60
SS2 + FR char	5.68	5.40	6.21

7 Techno-economic Evaluation

Across the EU, Member States have agreed to a range of sustainability initiatives that promote energy decarbonisation to reduce greenhouse gas (GHG) emissions, as well as frameworks to improve waste management and develop a more resource-efficient circular economy. These initiatives impose binding renewable energy and waste management obligations on the State, as well as potentially creating economic opportunities for stakeholders.

The EU waste management framework[1] lays down some basic waste management principles: requiring that waste be managed without endangering human health and harming the environment, and in particular without risk to water, air, soil, plants or animals, without causing a nuisance through noise or odours, and without adversely affecting the countryside or places of special interest. It obligates EU Member States to introduce waste management policies to increasingly and effectively recycle and reuse materials to create a circular economic pattern, consistent with the accepted waste management hierarchy (Figure 7.1). Pursuant to this framework Ireland has agreed measures to pre-treat and reduce biodegradable wastes routed to landfill by 65% over baseline levels. This obligation requires a reduction in biodegradable municipal waste routed to landfill to 427,000 tonnes by 2020 (equivalent to 35% of the total quantity produced by weight in 1995).

In respect of energy decarbonisation and climate change, EU directives establish a legal framework that obliges the State to meet agreed targets for reducing GHG emissions and increasing renewable energy substitution in the short term (2020) (Table 7.1), medium term (2030) and long term (2050). The 2020 objectives have been established in national legislation, with an objective of a 20% reduction in GHGs over 1990 baseline levels. The targets for 2030 under the 2030 climate and energy framework[2] are (1) at least a 40% cut in GHG emissions (from 1990 levels), (2) at least a 32% share for renewable energy and (3) at least a 32.5% improvement in energy efficiency.

Non-compliance with these obligations may attract the imposition of penalties, which a recent Oireachtas committee report (Houses of the Oireachtas, 2017) estimated may reach as high as €610 million by 2020, rising to €3.7–5.5 billion by 2030.

The 2016 EPA greenhouse emissions projections to 2020 (EPA, 2016) report on progress against emissions targets indicates that 2020 target levels are unlikely to be achieved, in part because of the difficulties in managing agricultural emissions, as well as continued reliance on fossil fuel energy. Thermal demands are particularly problematic, as the diffuse nature of these requirements makes it difficult to adopt a "one-size-fits-all" solution. Ireland's current approach to the transition requires changes to the energy technology deployed at the consumer level, as well as changes to the sources of energy utilised.

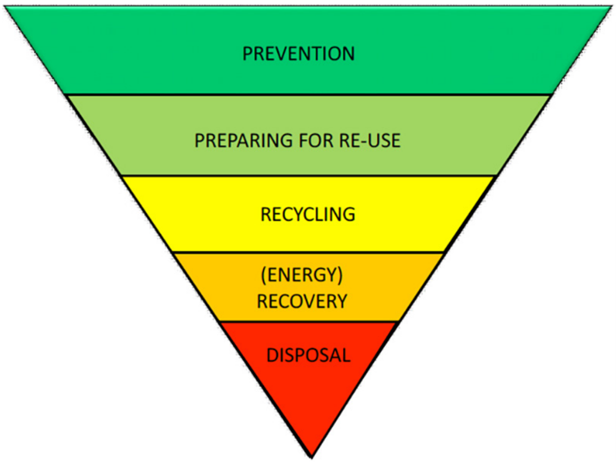

Figure 7.1. EU waste hierarchy. Source: European Commission (https://epthinktank.eu/2017/05/29/circular-economy-package-four-legislative-proposals-on-waste-eu-legislation-in-progress/waste_hierarchy/; accessed March 2020).

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[1] Directive 2008/98/EC on waste (Waste Framework Directive).

[2] See https://ec.europa.eu/clima/policies/strategies/2030_en#tab-0-0 (accessed September 2019).

Table 7.1. Ireland's 2020 renewable energy targets

Energy vector	Final energy consumption, %	2020 renewable energy target, %	2015 (actual), %	2030 target, %
Electricity	19	40	25.3	TBD[a]
Thermal energy	41	12	6.5	TBD[a]
Transport energy	40	10	5.7	TBD[a]
Total (Ireland)	100	16	9.1	TBD[a]
Rest of EU	–	20	16.7	27

[a]To be finalised pursuant to current negotiations.
Source: SEAI (2017).

The OF-PYR project evaluated the technical and economic considerations that impact prospects for the commercial deployment of pyrolysis for renewable energy and nutrient recovery from OF-MSW and SS. The objectives of the review were to determine whether waste-to-energy via pyrolysis (pyroenergy) can offer economic and/or environmental benefits relative to current disposal options, as well as making a significant contribution toward the State's sustainability objectives. The evaluation reviewed:

- factors that impact feedstock availability and the supply chain, including feedstock characteristics referenced above (Table 7.1), as well as requirements for aggregation and conditioning in the context of current stakeholder operating protocols, development plans and contractual commitments;
- practical observations in respect of the technology performance and a review of commercial and regulatory factors that impact the economic viability of pyroenergy deployment, including:
  - a review of alternative technology configurations for different types of energy recovery;
  - siting and scale requirements;
  - planning, licensing and regulatory factors that impact technology deployment;
- factors that impact routes to market and valorisation of the energy and nutrient outputs.

In 2016, Ireland's municipal waste operators processed *c.*2.7 million metric tonnes of mixed municipal waste, of which *c.*2.0 million metric tonnes was routed for recycling and/or energy recovery and 0.7 million metric tonnes was routed for disposal at landfill sites.[3] Currently, the OF fraction derived from waste is usually stabilised by composting prior to disposal as landfill cover. A market structure has evolved whereby facilities have been established that receive and stabilise OF sourced from multiple operators. This facilitates material aggregation and a standardised approach to treatment, but facilities are usually located at sites that offer limited prospects for energy valorisation. Accordingly, treatment is oriented toward disposal and incurs a corresponding disposal cost.

Management of SS is being standardised under a National Wastewater Sludge Management Plan (NWSMP) published by Irish Water (2014), pursuant to which satellite de-watering sites will collect and de-water SS to *c.*20% dry matter, which will then be transported to hubs for processing. Processing hubs are currently operated by design, build and operate contractors that charge a fee for SS processing and disposal. The NWSMP expresses a preference for processing SS in compliance with current biosolids regulations, which allow disposal via land spread to agricultural lands under certain conditions. Access to agricultural land banks that are willing to accept SS, however, is diminishing because of pressures from food quality assurance schemes and new organic fertiliser specifications that discourage exposure of the food chain to SS (and derivatives).

Pyroenergy may offer an alternative for reuse that can progressively displace current disposal routes. The economic value to be derived from pyrolysis of these feedstocks comprises a combination of:

- potential cost savings over current disposal methods;

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[3] Environmental Protection Agency 2016 statistics: http://www.epa.ie/nationalwastestatistics/municipal/ (accessed April 2020).

- the value of the net energy that can be recovered from the process if it can be valorised; and
- the value associated with the reduced environmental impact with regard to air/water/soil quality and mitigation of GHG emissions from energy decarbonisation.

Pyroenergy can be deployed at moderate scale, which may be well suited to serve Ireland's large number of rural wastewater treatment plants. By monitoring and regulating operating parameters, thermal technology can react more quickly to modest variations in feedstock character, maintaining efficient energy recovery and avoiding the catastrophic process inhibition that is sometimes suffered by biological processes. High process temperatures also address concerns regarding biohazards that may otherwise arise when waste materials are processed for disposal. Thermal technologies, however, require moisture removal prior to processing, and valorisation of the calorific value requires market outlets for heat, which in Ireland are less well developed than market outlets for gaseous energy.

Although pyrolysis in waste-to-energy processes is at an early stage, there have been some notable successes that have the potential to be developed to expand the application. A range of factors impact techno-economic viability. Considerations in respect of pyroenergy include:

- *OF-MSW feedstock supply and conditioning*. The character of the OF-MSW fraction is dependent on the processes utilised to separate mixed MSW. If screening processes are used, large screen apertures generate OF-MSW fractions with a slightly higher organic/plastic content, whereas small screen apertures generate OF-MSW fractions consisting of high levels of inert material. The OF-MSW CV is related to the relative concentrations of organics/plastics and inert metals/glass/rubble.
  - Pyrolysis is optimised when the feedstock is dried and densified into particle sizes that allow free movement of material and good heat transfer. OF-MSW is highly heterogeneous and very moist. The presence of contaminants that vary in size and chemistry preclude the material flow required for the smooth operation of feed systems. The high moisture content can inhibit the separation of the inert contaminants unless they are dried or composted. The high moisture content increases the energy required for drying whereas composting significantly reduces the organic fraction and the corresponding CV.
  - The highly heterogeneous nature of OF-MSW makes feedstock conditioning difficult and increases the energetic input and cost throughout the pyrolysis process. There is also unlikely to be an incremental energy efficiency improvement to warrant investment in the processing technology.
- *SS feedstock supply and conditioning*:
  - Ireland's 1100 municipal wastewater treatment plants, together with private septic tank sources, annually generate *c*.70,000 dry metric tonnes of SS. Volumes are expected to grow to *c*.96,000 dry metric tonnes as wastewater treatment infrastructure continues to be upgraded.
  - The SS supply is highly dispersed across numerous rural plants and domestic septic tanks. Irish Water's NWSMP outlines a programme to aggregate, de-water and treat SS, linking a series of satellite de-watering sites with sludge-processing hubs that will facilitate efficient access to an aggregated resource and provide sites to efficiently condition feedstocks for renewable energy valorisation.
  - Pyrolysis is optimised when the feedstock is dried and densified. Adaptations to existing feedstock drying/densification protocols and technology will be required to condition SS to a suitable standard at a reasonable cost.
  - The intensive energetic cost of conditioning can be met by optimising the drying/densification technology and combusting a proportion of feedstock to meet the thermal requirements.
  - Deployment of conditioning technology as far up the NWSMP chain as is economically viable can leverage wastewater treatment plant infrastructure to reduce the associated transport requirements.
  - The NWSMP expresses a preference to treat sludge by anaerobic digestion to facilitate continued disposal via agricultural land spread. Irish regulations allow agricultural land spread under controlled conditions although, historically, compliance monitoring has been problematic.

  - The number of agricultural land banks that accept SS is rapidly dwindling. Public opinion is evolving against agricultural land spread in response to concerns over food safety. Food quality assurance programmes increasingly preclude acceptance of SS onto quality-certified farmland, whereas new EU organic fertiliser specifications preclude the incorporation of SS (and digestate/compost derivatives) if organic fertilisers are to bear CE certification.
  - Pyrolysis of SS will complement Irish Water's NWSMP by offering a viable alternative processing option that avoids land spread complications. The CV of dry SS is similar to that of digestates that have undergone anaerobic digestion and so pyroenergy can be applied as a supplemental method of treating digestates that have undergone anaerobic digestion.
  - The costs of conditioning/transporting dried SS for pyroenergy could be comparable to the costs of pasteurising/transporting de-watered sludge for disposal via land spread if conditioning technologies and protocols can be suitably adapted. The integration of adapted sludge-drying/densification technology into the NWSMP chain, together with introduction of a framework that promotes viable routes to market for pyroenergy, may provide a sustainable means for sludge management at costs that are comparable to current land spread costs.
- *Technical, operational and deployment considerations*:
  - Pyrolysis can be deployed in a continuous process to convert conditioned feedstock to a combustible syngas and biochar solid fuel. Each of these energy carriers can be utilised directly or blended with other fuels to supply renewable energy.
  - Pyrolysis is endothermic, requiring an external source of heat to operate continuously. Process energy requirements can be met by combustion of a proportion of the biochar and/or syngas. Energetic efficiency and GHG mitigation are optimised when the technology for heat recovery is integrated with routes to market suited to valorisation of low-grade recovered heat.
  - Pyroenergy requires a moderate minimum scale to remunerate skills/technology costs. The scale is estimated at *c.*1–1.5 MT of feedstock/hour, equating to 40,000–60,000 $\mathrm{MWh_{th}}$ annual input. It is most efficient when operated continuously and, accordingly, requires market outlets offering a reasonable scale and a constant energy demand.
  - Pyroenergy installations can be configured to supply either co-generated heat and power (CHP) or steam/hot water. Boiler configurations have a lower cost and are less complex than CHP configurations. Gas boilers are widely available at modest cost and are adaptable to handle variations in syngas quality. Gas is readily stored and integration of new heat sources with existing heat distribution infrastructure is less complex than interconnecting with electricity distribution infrastructure.
  - Siting pyroenergy installations has a significant bearing on techno-economic viability. Wastewater treatment plants located in/adjacent to population centres may offer sites with available infrastructure that can be leveraged to minimise energy costs. Site layouts are designed to minimise the impact on the surrounding residential environment, yet sites are close enough to population centres to enable cost-effective access to energy market outlets. Amendments to current planning and licensing authorisations would be required to utilise these sites.
  - Pyroenergy applications will require planning and licensing authorisations. Public sentiment can weigh against waste-to-energy projects, which may delay deployment unless an acceptable planning framework can be developed.
  - Pyroenergy will be subject to waste management regulations, including waste incineration regulations, that may impose continuous emissions monitoring and reporting requirements even if the syngas is conditioned to achieve an "end-of-waste" standard such that combustion emissions are no worse than those from combustion of natural gas. Conditioning technologies are available to achieve syngas "end-of-waste".

  - If the biochar remains classified as a waste, combustion may be subject to continuous emissions monitoring, reporting and management requirements required under waste incineration regulations. Market circumstances are evolving that may create demands for char solid fuels, which may enable an “end-of-waste” re-designation. Emissions from the combustion of non-wastes are regulated under the medium combustion plant (MCP) regulations, which require less onerous periodic monitoring and reporting.
  - Pyroenergy installations are new to the market and, accordingly, access to market finance is not readily available to fund infrastructure deployment. A State-supported programme comprising low-cost finance structured to facilitate access to existing grant-aid assistance for renewable energy projects will assist with early market deployment.
- *Valorisation of biochar*:
  - The EBC scheme has published specifications that have become the de facto standards for marketing of biochar as a soil conditioner in the EU. Biochar qualifies as a biosolid under Irish regulations governing SS application to agricultural soils. These biosolids regulations establish limits for the levels of heavy metals that can be applied to agricultural soils in any one year.
  - Pyrolysis concentrates heavy metals and inert contaminants in the biochar. The char from OF-MSW and SS is not suitable to be marketed as a soil conditioner nor is it suitable for disposal via land spread to agricultural lands. The best option is valorisation as a solid fuel either to provide process energy for feedstock conditioning and pyrolysis or to be packaged and sold as a biomass-derived replacement for coal or peat. The char has a high ash content. Concerns regarding fly-ash and aerosols can be addressed by designs that minimise fly-ash discharge in the flue gas.
  - Market outlets may be developing for biochar-based solid fuels as renewable components of smokeless coal fuels, fuels for cement kilns and components of coke used in iron smelting. Development of significant external market outlets may facilitate “end-of-waste” re-designation, which would have positive implications in terms of valorisation opportunities.
- *Valorisation of energy outputs*:
  - SS and OF-MSW are considered to be biomass and, accordingly, pyroenergy outputs will be considered to be renewable subject to meeting lifecycle GHG savings and other sustainability criteria adopted in the future.
  - Pyroenergy installations can be configured to supply either CHP or steam/hot water. Renewable energy outputs cost more than conventional fossil fuel energy and transitional market supports are required to equalise renewable energy costs with fossil fuel costs. In the context of available energy distribution infrastructure, current market subventions are not suitably structured to support pyroenergy applications.
  - Valorisation of renewable energy outputs requires timely and cost-effective access to energy distribution infrastructure. Efficiencies of scale and continuous plant operation can be optimised if renewable energy share in electricity (RES-E) and/or renewable energy share in heat (RES-H) distribution infrastructure enables access to large industrial “anchor tenants” backed up by aggregated community/national demands. Access to aggregated demands increases scale, offers a means to valorise low-grade heat and mitigates variability in the individual customer’s load profile.
  - In Ireland, access to sizeable continuous industrial heat demands is limited. District heat networks can potentially provide timely and cost-effective means to access community demands; however, district heating infrastructure is not widely available. Pyroenergy projects may have to be considered in the context of co-developing heat distribution infrastructure in order to create viable market outlets that can optimise energy efficiency.
  - A Renewable Heat Support Scheme (RHSS) offers suitable supports for the first 1300 MWh_{th} per annum of qualifying RES-H used by small and medium-sized businesses. The RHSS is designed to support individual RES-H plant deployments rather than distribution infrastructure serving aggregated community

demands. Development of a feed-in support tariff to support RES-H placed on the market may overcome this constraint

- The national power grid potentially provides access to a national electricity pool; however, a backlog of applications to supply RES-E via the grid currently exceeds foreseeable capacity requirements. This excess capacity may constrain demands for new RES-E supplies in the near term.
- RES-E outputs supplied to the national pool may qualify for subvention under a recently announced Renewable Electricity Support Scheme (RESS). CHP, however, is subject to high efficiency criteria, requiring residual heat to be used efficiently if the RES-E outputs are to qualify for market subventions. This effectively means that the availability of a thermal demand determines the economic viability of CHP applications. Constant (sizeable) thermal demands are not widely available in Ireland and development of infrastructure to aggregate community demands takes time. This constraint effectively means that PROENERGY CHP is precluded from accessing RES-E subventions, unless frameworks are adapted to enable moderate RES-E subventions to co-exist with moderate RES-H subventions within a specified market development period. Such an adaptation will allow a progressive build-up to compliance with the high efficiency criteria.
- Connecting to the grid and marketing RES-E to the national pool is governed under complex integrated single energy market protocols. Access to grid capacity is subject to a new competitive bidding process, which can inadvertently preclude CHP applications as they are subject to high efficiency criteria, which can be difficult to achieve within the short time frames applicable to a competitive bidding process.

A detailed discussion of these considerations is available in the tcbb RESOURCE report, *A Technical and Economic Review of Energy and Nutrient Recovery from Advanced Pyrolysis of Wastewater Treatment Sludge and Organic Fines*, which is available on the tcbb RESOURCE website (http://www.tcbbresource.ie/of-pyr-project; accessed 21 June 2019).

8 Conclusions and Recommendations

8.1 Overview

European Union and State strategies incorporate statutory and aspirational drivers towards a more circular, sustainable economy. Sustainability objectives include improved reuse of waste, mitigation of GHG emissions, decarbonisation of the energy mix and improved recovery and recycling of plant nutrients.

The economic value to be derived from pyrolysis of these feedstocks comprises a combination of:

- potential cost savings over current methods of disposal;
- the value of the net energy that can be recovered from the process if it can be valorised; and
- the value associated with the reduced environmental impact with regard to air/water/soil quality and mitigation of GHG emissions from energy decarbonisation.

In the OF-PYR project a range of tasks was performed, including pyrolysis at laboratory scale and characterisation of all pyrolysis products for OF-MSW and SS; pyrolysis at pilot scale for AD-SS and characterisation of products; investigation of the combustion properties of pyrolysis chars; and investigation of the sintering and leaching behaviour of ash. The relative character of the materials was analysed, the energetic relationships were determined and a mass and energy balance was established. The techno-economic viability of renewable energy recovery in the context of current waste management protocols, market structures, regulatory regimes, the availability of market outlets for renewable energy and other market factors was evaluated. The purpose of this study was to investigate the potential of pyrolysis as a conversion technology for the distributed treatment of OF-MSW and SS as an alternative to other disposal options.

8.2 Properties of OF-MSW

The properties of OF-MSW from four waste processors were tested. The moisture content was lower for composted OF-MSW, at around 20 wt%, and much higher for fresh, uncomposted OF-MSW, varying from 55 wt% to 63 wt%. All OF-MSW samples were very heterogeneous and contained organic and plastic fractions in addition to glass (12.9–21.4% of the original mass of the dried OF-MSW samples), metal (0.1–3.4%) and stones (only in composted samples, 2.5–4.7%). The proximate properties of OF-MSW were highly variable, in particular the content of ash, which was 27–44 wt% regardless of the type of processing applied. Volatile matter content varied from 41 wt% to 48 wt% for composted samples and from 54 wt% to 60 wt% for uncomposted, dried samples. The HHV after composting was lower, at 13.6–15.9 MJ/kg, than that for uncomposted OF-MSW, at 17.2 MJ/kg (dry basis). Significant differences in the composition of mineral matter between OF-MSW samples were observed. The heavy metal content was high, especially for Ti, Cr, Zn and Ni.

8.3 Pyrolysis of OF-MSW at Laboratory Scale

Heterogeneity of the OF-MSW samples played a central role in determining the distribution of the pyrolysis products. The yield of gas was good (32 ± 7 wt%); however, its quality was moderate and variable dependent on the specific composition of the OF-MSW sample (e.g. a higher plastic content leads to a higher gas yield). The CV of the gas varied from 15.5 to 18.9 MJ/m^3. The presence of metal and glass pieces means that the material is unsuitable for use as a soil amendment. Moreover, the concentrations of Pb, Cu, Ni, Zn and Cr in OF-MSW chars was higher than the maximum allowable limits set by the EBC. The OF-MSW char can therefore be used only as a fuel for combustion.

8.4 Properties of SS

The SS samples had a relatively low ash content (20–32 wt%) and a high volatile matter content (53–73 wt%), with an LHV of 16–19 MJ/kg, which makes them potentially attractive feedstocks for pyrolysis if recovery of energy in the form of a high

CV gas is the objective. There was seasonal variation in the ash content, volatile matter content and CV. Mineral matter composition varied between SS samples. The concentrations of heavy metals were below the EU regulatory limits for biosolids.

8.5 Pyrolysis of SS at Laboratory Scale

The distribution of pyrolysis products depends on the specific properties of SS, but it also reflects the type of SS treatment. A higher char yield was obtained for granulated and pelleted SS (43–45 wt%) than for belt press cake SS (37.7 wt%), whereas the opposite trend was observed for gas yield (26–29.5 wt% vs 34.2 wt%, respectively). Mixing SS with FR increased the yield and CV of the gas. Seasonal variation in SS properties was observed in the distribution of pyrolysis products. The lowest gas yield of 20 wt% (desirable) and the highest liquid yield of 45 wt% (undesirable) was obtained for the February 2018 sample. All of the major elements and most of the minor elements were concentrated in the char. Cu, Ni and Zn concentrations in SS chars were too high for their use as soil amendments according to the EBC.

8.6 Pyrolysis of AD-SS Mixed with Forestry Residue at Pilot Scale

Pyrolysis of the AD-SS and FR mixture (70:30 by weight) resulted in 570 m^3 of gas/tonne of dry feedstock, with a CV of 14 MJ/m^3, and 320 kg of char, with a CV of 17.85 MJ/kg. Although the content of impurities in the raw gas was high, at 36.90 mg/Nm^3 of NH_3 and 14.6 $g_{total\ tar}/Nm^3_{dry\ gas}$, the gas is suitable for direct combustion in a gas boiler with de-NO_x and de-SO_x technology. The raw pyrolysis gas was conditioned and the yield of conditioned pyrolysis gas (diluted with N_2) increased to 1120 m^3/tonne, with a CV of 7.1 MJ/m^3. Impurities in this gas were significantly reduced, to 324 mg/Nm^3 for NH_3 and 7.0 $g_{total\ tar}/Nm^3_{dry\ gas}$. However, the maximum permissible content of NH_3 for the gas engine used was exceeded. A dedicated tar cleaning section is required and the water scrubbing section needs to be optimised if a gas engine is used. In total, 320 kg of char was obtained from a tonne of AD-SS and FR mixture. The pyrolysis char is suitable as a fuel for combustion; however, the heavy metal concentration prohibits European Biochar Certification as a soil amendment.

8.7 Combustion Properties of OF-MSW and SS Cars

The chars produced at 700°C from OF-MSW and SS belong to the group of very reactive technical carbon materials, with activation energies between 86–102 kJ/mol and 76–94 kJ/mol, respectively.

8.8 Leaching Behaviour of OF-MSW and SS Ash

Because of the very high concentration of harmful metals in OF-MSW, an oxidation/sintering temperature of 1100°C was insufficient to generate non-hazardous ash. The leachability of Cr from OF-MSW ash exceeded the allowed limit for hazardous material set by the European Landfill Directive (1999/31/CE63). The SS ash falls into a category of either inert or non-hazardous material, as the leachability of all metals for these ash samples was very low.

8.9 Techno-economic Evaluation

Generation of OF-MSW pyroenergy, although technically viable, is unlikely to offer an improvement over current processing methods (e.g. composting and spread as landfill cover) as the moisture content, as well as the content of metal, glass, rubble and other inert contaminants, makes feedstock conditioning difficult. Low levels of volatile fractions (relative to fixed carbon, ash and inert contaminants) impede energy recovery, resulting in low incremental energy outputs, the value of which is unlikely to remunerate the cost of technology deployment. Pyrolysis results in large proportions of contaminated char that are unsuitable for use other than disposal as landfill cover. Generation of SS pyroenergy is techno-economically viable and will contribute toward sustainable waste reuse, GHG mitigation and energy decarbonisation objectives provided that it is deployed in a market structure that aggregates supplies of de-watered SS at satellite sites and forwards these supplies to processing hubs; it adapts feedstock drying and/or conditioning technology to minimise the energy and capital cost of feedstock drying/densification; syngas conditioning technology is optimised to comply with engine manufacturers' standards or, if used in boiler applications, to achieve an "end-of-waste" standard; appropriate deployment sites are able to procure the relevant planning and licensing authorisations; viable market outlets can be identified that offer access to a continuous sizeable thermal energy demand and transitional market supports are available to subsidise the cost of supply chain development and customer transition; and energy distribution infrastructure is available at a reasonable cost, enabling access to an aggregated energy demand and viable market outlets. Techno-economic viability is dependent on introduction of a broader, coherent bioenergy framework that finances processing/energy distribution infrastructure and incentivises the transition to renewable energy, with market supports structured as feed-in tariffs that are payable to energy generators for renewable energy placed on the market. SS pyroenergy is unlikely to contribute towards improved nutrient recycling without development of additional nutrient recovery technology, as P is mineralised in biochar in forms that reduce plant availability and some heavy metal residues are concentrated at levels that exceed recommended thresholds, precluding sale as a soil conditioner and land spread back to agricultural lands.

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Abbreviations

AD-SS	Anaerobically digested sewage sludge
CHP	Co-generated heat and power
CV	Calorific value
EBC	European Biochar Certificate
EU	European Union
FR	Forest residue
GHG	Greenhouse gas
HHV	Higher heating value
LHV	Lower heating value
MCP	Medium combustion plant
MSW	Municipal solid waste
NO_x	Nitrogen oxides
NWSMP	National Wastewater Sludge Management Plan
OF	Organic fines
OF-MSW	Organic fine component from the mechanical sorting of municipal solid waste
RES-E	Renewable energy share in electricity
RES-H	Renewable energy share in heat
RHSS	Renewable Heat Support Scheme
SO_x	Sulfur oxides
SPA	Solid phase adsorption
SS	Sewage sludge derived from municipal wastewater treatment plants
SS+FR	Sewage sludge with forestry residue

Appendix 1 Properties of OF-MSW and SS: Results from Laboratory- and Pilot-scale Pyrolysis

Table A1.1. Proximate properties of OF-MSW (dry basis)

Properties	OF1: composted	OF2-1: unprocessed, unscreened	OF2-2: freshly composted, screened	OF2-3: old composted, screened	OF3: uncomposted	OF4: composted
As received basis						
Moisture, wt%	19.56	55.30	25.10	–	63.41	17.30
Dry basis						
Ash content, wt%,	41.47	26.88	42.90	40.05	44.44	39.61
Volatile matter, wt%	42.15	59.84	40.79	48.44	53.62	48.57
Fixed carbon, wt%	16.38	13.28	16.31	11.51	1.94	11.82
HHV, MJ/kg	15.57	17.16	15.88	13.62	–	15.57

The fixed carbon content was found by difference.

Table A1.2. Ultimate properties of OF-MSW (dry basis)

Element	OF1: composted	OF2–1: unprocessed, unscreened	OF2–2: freshly composted, screened	OF2–3: old composted, screened
C, wt%	37.48	45.03	35.88	34.36
H, wt%	4.13	5.37	2.94	3.73
N, wt%	2.48	2.35	1.69	2.06
S, wt%	1.44	0.56	1.15	1.12
O, wt%	16.12	19.81	15.44	18.69

Table A1.3. Average product distribution from pyrolysis of OF-MSW samples at 700°C for 10 minutes

Sample	Char yield, wt%	Liquid yield, wt%	Gas yield, wt%
OF1	52.0	14.0	33.0
OF2-1	38.6	31.7	29.6
OF2-2	57.0	19.6	23.3
OF2-3	52.4	18.6	29.0
OF3	47.8	7.4	44.9
OF4	52.2	13.6	34.2

Table A1.4. Proximate properties of chars from pyrolysis of OF-MSW at 700°C for 10 minutes (dry basis)

Properties	OF1: composted	OF2-1: unprocessed, unscreened	OF2-2: freshly composted, screened	OF2-3: old composted, screened	OF3: uncomposted	OF4: composted
Ash content, wt%,	64.20	66.70	58.44	71.72	74.44	81.65
Volatile matter, wt%	3.90	10.59	10.80	13.18	5.25	3.51
Fixed carbon, wt%	31.90	22.73	30.76	15.10	20.31	14.85
HHV, MJ/kg	12.20	10.70	12.53	8.84	13.22	12.60

Table A1.5. Ultimate properties of chars from pyrolysis of OF-MSW at 700°C for 10 minutes (dry basis)

Element	OF1: composted	OF2-1: unprocessed, unscreened	OF2-2: freshly composted, screened	OF2-3: old composted, screened
C, wt%	34.96	31.17	37.96	29.14
H, wt%	0.42	0.45	0.47	0.36
N, wt%	1.13	1.15	1.05	0.87
S, wt%	2.41	0.76	1.27	2.21
O, wt%	–3.14	–0.21	0.80	–4.29

Table A1.6. Pyrolysis gas composition (N_2-free basis)

Gases, vol.%	OF1: composted	OF2-1: unprocessed, unscreened	OF2-2: freshly composted, screened	OF2-3: old composted, screened	OF3: uncomposted	OF4: composted
H_2	10.4±0.3	19.0±5.5	15.8±1.7	26.2±4.2	18.8	13.1
CO	28.0±3.0	20.6±1.2	15.0±2.2	21.7±5.7	33.0	26.9
CO_2	9.5±2.8	22.6±3.0	28.3±1.9	24.4±2.4	15.8	21.5
CH_4	25.4±1.2	18.0±1.7	15.1±1.9	13.5±1.5	22.1	21.8
C_2H_4	14.1±2.3	9.7±0.4	9.4±0.1	7.4±2.4	9.2	12.1
C_2H_6	2.1±0.5	2.9±0.1	3.1±0.3	0.9±0.3	0.5	1.7
C_2H_2	–	0.1±0.03	0.1±0.03	0.3±0.1	0.6	0.4
H_2S, ppm	–	162±182	865±138	1572±539	–	–
LHV, MJ/m^3 N_2 free	23.5±0.9	18.9±0.8	17.1±0.9	15.5±1.1	20.3	21.1

ppm, parts per million.

Table A1.7. List of the most abundant compounds detected in the aqueous fraction of pyrolysis liquids

Residence time, minutes	Compounds	OF2-1	OF2-2	OF2-3	SS4 (Feb 18)	SS4 (Apr 18)	SS4 (8 Jun 18)	SS4 (28 Jun 18)
1.513	Propanoic acid				+			
1.557	2-Propenoic acid	+				+	+	+
1.782	Pyrazine	+	+					
1.797	Oxalic acid, dicyclobutyl ester				+		+	+
1.887	Pyridine	+	+	+		+	+	+
1.896	2-Propanol, 1-ethoxy-				+			
1.948	Pyrrole				+		+	
2.060	Toluene	+	+	+	+		+	
2.105	Acetamide	+				+	+	+
2.174	Ethanimidic acid, ethyl ester				+			+
2.196	Propanoic acid, 2-(amino-oxy)-		+					
2.504	Acetic acid	+				+		
2.586	Pyridine, 2-methyl-		+	+	+	+	+	+
7.606	Pentanoic acid	+	+					
23.710	2,4-Imidazolidinedione, 5,5-dimethyl-	+	+	+	+	+	+	+
25.641	2,4-Imidazolidinedione, 5-methyl-	+				+	+	+
25.911	2,4,5-Trioxoimidazolidine		+	+	+			
27.340	dl-5-Ethyl-5-methyl-2,4-imidazolidinedione	+	+	+	+	+	+	+
28.850	1H-tetrazole-1,5-diamine							+
30.230	4-Amino-4,5(1H)dihydro-1,2,4-triazole-5-one	+	+	+			+	+

Table A1.8. List of the most abundant compounds detected in the oil fraction of pyrolysis liquids

Residence time, minutes	Compound name	OF2-1	OF2-2	OF2-3	SS4 (Feb 18)	SS4 (Apr 18)	SS4 (8 Jun 18)	SS4 (28 Jun 18)
1.415	Benzene				+ (3)			
1.887	Pyridine	+	+	+		+	+	+
1.956	Pyrrole				+	+	+	+
2.060	Toluene	+ (3)	+ (2)	+	+ (1)	+ (1)	+ (1)	+ (1)
2.594	Pyridine, 2-methyl-	+	+	+		+	+	+
3.338	Ethylbenzene	+ (2)	+ (3)	+ (2)	+	+	+	+
3.480	p-Xylene	+	+	+	+	+		+
3.969	Styrene	+ (1)	+ (1)	+ (1)	+ (2)	+ (2)	+ (2)	+ (2)
7.178	α-Methylstyrene	+ (4)	+	+				
7.283	Benzonitrile				+	+	+	+
7.501	Phenol	+	+	+		+	+	+
10.176	Indene	+	+	+	+		+	+
11.228	Phenol, 2-methyl-	+	+	+		+		
12.385	Phenol, 3-methyl-	+	+	+	+	+	+	+ (4)
17.172	Naphthalene	+ (5)	+ (4)	+ (3)	+	+	+ (4)	+
22.876	Indole	+	+	+	+	+ (3)	+ (3)	+ (3)
23.184	Naphthalene, 1-methyl-	+	+	+		+	+	+
26.363	Biphenyl	+	+	+				
29.120	Acenaphtalene	+		+				
34.448	Fluorene	+	+	+				
41.520	Phenanthrene	+	+	+		+		+
48.020	2-Phenylnaphthalene	+	+					
48.358	Hexadecanoic acid	+	+			+		
51.717	Pyrene	+	+	+				

(1), (2), (3), (4), (5) – the order of the most abundant compounds

Table A1.9. Proximate properties of SS samples

Properties	SS1	SS2	SS2 + FR	SS3 after AD	SS4 (Oct 17)	SS4 (Dec 17)	SS4 (Feb 18)	SS4 (Apr 18)	SS4 (8 Jun 18)	SS4 (28 Jun 18)	SS4 (Sep 18)	SS4 (Oct 18)	SS4 (Dec 18)
As received													
Moisture, wt%	9.78	6.06	14.05	6.68	85.24	84.90	–	89.68	89.41	86.68	85.37	84.92	88.90
Dry basis													
Ash content, wt%	32.13	28.70	20.86	15.72	26.13	28.84	21.44	20.26	24.31	23.25	30.30	25.57	24.52
Volatile matter, wt%	52.78	58.97	66.11	73.03	62.00	61.23	72.20	72.70	69.45	70.10	63.44	65.11	67.95
Fixed carbon, wt%	15.09	12.33	13.03	11.26	11.87	9.93	6.36	7.03	6.24	6.64	6.26	9.32	7.53
HHV, MJ/kg	16.85	16.65	16.60	21.34	16.30	16.20	19.96	18.80	17.60	17.80	16.73	16.65	17.73

AD, anaerobic digestion.

Table A1.10. Ultimate properties of SS samples

Elements	SS1	SS2	SS2+FR	SS3 after AD	SS4 (Oct 17)	SS4 (Dec 17)	SS4 (Feb 18)
C, wt%	37.28	39.47	40.76	46.85	38.83	39.03	42.90
H, wt%	5.50	5.17	6.06	6.16	5.38	5.42	5.42
N, wt%	5.67	5.44	3.81	4.59	6.72	6.79	8.18
S, wt%	1.01	0.82	0.19	0.87	0.80	0.72	0.77
O, wt%	17.94	20.68	28.29	25.94	22.14	19.20	25.94

Oxygen calculated by difference.

AD, anaerobic digestion.

Table A1.11. Average product distribution from pyrolysis of SS samples at 700°C for 10 minutes

Sample	Char yield, wt%	Liquid yield, wt%	Gas yield, wt%
SS1	44.8	25.7	29.5
SS2	42.6	31.4	26.0
SS2+FR	37.8	26.0	36.2
SS4 (Dec 17)	38.7	29.0	32.4
SS4 (Feb 18)	35.3	44.8	19.9
SS4 (Apr 18)	30.6	27.4	42.0
SS4 (8 Jun 18)	34.1	28.6	37.3
SS4 (28 Jun 18)	34.2	32.0	33.8
SS4 (Sep 18)	48.0	14.8	37.2
SS4 (Oct 18)	40.1	25.6	34.3
SS4 (Dec 18)	40.4	23.0	36.6

Table A1.12. Ultimate properties of chars from pyrolysis of SS at 700°C for 10 minutes (dry basis)

Element	SS1	SS2+FR	SS4 (Dec 17)
C, wt%	28.68	42.22	28.11
H, wt%	0.09	0.89	0.54
N, wt%	1.94	2.20	2.67
S, wt%	0.41	0.16	0.57
O, wt%	–0.41	0.67	–3.04

Table A1.13. Proximate properties of chars from pyrolysis of SS at 700°C for 10 minutes (dry basis)

Properties	SS1	SS2 +FR	SS4 (Dec 17)	SS4 (Feb 18)	SS4 (Apr 18)	SS4 (8 Jun 18)	SS4 (28 Jun 18)	SS4 (Sep 18)	SS4 (Oct 18)	SS4 (Dec 18)
Ash content, wt%	69.40	53.79	71.21	63.80	64.93	68.56	62.36	70.89	62.66	65.18
Volatile matter, wt%	3.18	24.81	16.02	10.63	7.60	11.77	11.82	4.94	6.61	5.81
Fixed carbon, wt%	27.42	21.40	12.77	25.60	27.47	19.67	25.82	24.18	30.86	29.00
HHV, MJ/kg	11.71	13.09	8.56	13.78	15.85	13.68	12.82	11.59	12.96	12.94

Table A1.14. Pyrolysis gas composition (N_2-free basis) (pyrolysis at 700°C for 10 minutes)

Gases, vol.%	SS2	SS2+FR	SS4 (Oct 17)	SS4 (Dec 17)	SS4 (Feb 18)	SS4 (Apr 18)	SS4 (8 Jun 18)	SS4 (28 Jun 18)	SS4 (Sep 18)	SS4 (Oct 18)	SS4 (Dec 18)
H_2	10.0±2.8	0.2±0.2	17.9±3.5	18.1±4.7	11.5±0.1	10.7±1.0	13.5±0.1	12.4±0.9	15.6	9.3	10.7±2.3
CO	18.4±1.9	40.9±5.6	19.5±0.4	23.6±0.6	22.3±4.5	28.3±1.8	22.8±4.1	23.1±3.4	15.9	21.1	20.6±1.9
CO_2	23.2±1.6	0.7±0.6	15.5±4.1	15.1±1.3	20.6±0.3	18.2±0.5	19.8±0.5	19.8±1.4	24.5	24.5	23.2±1.6
CH_4	16.7±2.4	30.7±5.5	22.0±2.1	20.9±0.5	24.1±2.0	20.9±0.9	20.7±0.7	22.3±0.3	17.8	17.8	16.1±1.4
C_2H_4	7.9±0.7	13.1±1.6	8.7±4.9	13.1±1.8	11.3±1.1	11.0±0.04	10.2±0.8	10.0±0.2	10.4	10.4	9.1±0.6
C_2H_6	2.8±0.4	4.1±1.1	1.3±0.7	1.8±0.2	3.5±0.3	3.1±0.05	2.4±0.2	2.6±0.4	2.1	2.1	2.3±0.4
C_2H_2	1.0±0.2	0.1±0.1	0.4±0.3	0.5±0.1	0.2±0.04	0.3±0.01	0.3±0.07	0.3±0.05	0.4	0.4	0.7±0.1
H_2S, ppm	9500±1500	2.0±2.3	187±251	1343±1245	–	–	–	–	–	–	6752±784
LHV, MJ/m^3 N_2 free	16.4±0.7	26.6±0.1	18.5±2.5	21.7±0.6	21.8±1.0	20.9±0.5	19.6±0.1	20.1±0.3	16.95	17.8	16.7±0.3

ppm, parts per million.

Table A1.15. Tar compounds identified at three sampling ports[a]

		Port 1 (gtar/Nm^3 a.r.)		Port 2 (gtar/Nm^3 a.r.)			Port 3 (gtar/Nm^3 a.r.)			
	Tar compounds	a	b	a	b	c	a	b	c	d
1	Propenenitrile, 2-methyl-	0.330	0.291	–	–	–	–	–	–	–
2	Isobutyronitrile	0.127	0.132	–	–	–	–	–	–	–
3	Cyclohexadiene	0.045	0.041	–	–	–	–	–	–	–
4	1,3-Cyclopentadiene, 5-methyl-	0.018	0.019	–	–	–	–	–	–	–
5	2-Butenenitrile	0.070	0.066	–	–	–	–	–	–	–
6	Benzene	1.014	1.061	5.416	4.282	5.125	6.122	5.722	6.301	6.975
7	Thiophene	0.047	0.048	0.099	0.060	0.065	0.069	0.058	0.054	0.045
8	3-Butenenitrile	0.033	0.032	–	–	–	–	–	–	–
9	Butanenitrile, 2-methylene-	0.020	0.019	–	–	–	–	–	–	–
10	Pyrazine	0.040	0.039	–	–	–	–	–	–	–
11	Pyridine	0.416	0.369	0.020	–	–	–	–	–	–
12	Toluene	2.609	3.222	0.095	0.069	0.093	0.082	0.069	0.070	0.086
13	Thiophene, 2-methyl-	0.005	0.006	–	–	–	–	–	–	–
14	Thiophene, 3-methyl-	0.028	0.032	–	–	–	–	–	–	–
15	Pyridine, 2-methyl-	0.131	0.108	–	–	–	–	–	–	–
16	1H-pyrrole, 2-methyl-	0.020	0.016	–	–	–	–	–	–	–
17	Ethylbenzene	0.301	0.285	–	–	–	–	–	–	–
18	*o*/*m*/*p*-Xylene	0.582	0.536	–	–	–	–	–	–	–
19	Phenylethyl	0.012	0.012	0.019	0.010	0.024	0.010	0.008	0.008	0.008
20	Styrene	1.597	1.432	0.138	0.088	0.131	0.080	0.067	0.072	0.056
21	Pyridine, 3,5-dimethyl-	0.061	0.058	–	–	–	–	–	–	–
22	Benzene, propyl-	0.027	0.025	–	–	–	–	–	–	–
23	Benzene, 1-ethyl 3-methyl-	0.066	0.058	–	–	–	–	–	–	–
24	Benzene, 1,2,4-trimethyl-	0.017	0.015	–	–	–	–	–	–	–
25	Benzonitrile	0.167	0.176	0.079	0.036	0.099	–	–	–	–
26	Benzene, 1-ethyl-2,3,4-methyl-	0.508	0.456	–	–	–	–	–	–	–

Table A1.15. Continued

		Port 1 (gtar/Nm^3 a.r.)		Port 2 (gtar/Nm^3 a.r.)			Port 3 (gtar/Nm^3 a.r.)			
	Tar compounds	a	b	a	b	c	a	b	c	d
27	Butanoic acid, butyl ester	–	–	0.042	0.041	0.052	0.040	0.035	0.034	0.030
28	Benzene, 1-propenyl-	0.049	0.043	–	–	–	–	–	–	–
29	Indene	0.522	0.479	0.081	0.060	0.078	0.006	0.006	0.005	0.005
30	*o*/*m*/*p*-Cresol	0.517	0.485	–	–	–	–	–	–	–
31	Benzofuran, 7-methyl-	0.151	0.153	–	–	–	–	–	–	–
32	Naphthalene, 1,2-diydro-	0.185	0.186	–	–	–	–	–	–	–
33	Naphthalene	1.058	1.038	1.371	1.135	1.521	0.026	0.030	0.029	0.018
34	Benzo(b)thiophene	0.054	0.062	0.027	0.042	0.045	–	–	–	–
35	Quinoline	0.110	0.101	–	–	–	–	–	–	–
36	Naphthalene, 2-methyl-	0.262	0.283	0.009	0.007	0.011	–	–	–	–
37	Indole	0.149	0.214	–	–	–	–	–	–	–
38	Naphthalene, 1-methyl-	0.208	0.231	0.010	0.006	0.012	–	–	–	–
39	Dodecane, 2,6,11-trimethyl-	–	–	0.004	0.005	0.004	0.004	0.003	0.003	0.003
40	Naphthalene, 2-ethenyl-	0.103	0.101	0.036	0.023	0.042	–	–	–	–
41	Biphenyl	0.051	0.062	0.012	0.006	0.015	–	–	–	–
42	Acenaphthylene	0.113	0.139	0.365	0.230	0.397	0.003	0.003	0.003	0.002
43	Naphthalene 2-carbonitrile	0.060	0.074	0.028	0.013	0.029	–	–	–	–
44	Benzofuran	–	–	0.008	0.002	0.009	–	–	–	–
45	Naphthalene 1-carbonitrile	0.015	0.023	0.012	0.005	0.011	0.004	0.003	0.003	0.003
46	Fluorene	0.072	0.091	0.030	0.018	0.033	–	–	–	–
47	Benzene, 1,1′-(diazomethylene)bis-	0.015	0.016	–	–	–	–	–	–	–
48	Dibenzothiophene	–	–	0.009	0.005	0.011	–	–	–	–
49	Phenanthrene/anthracene	0.152	0.227	0.296	0.153	0.330	–	–	–	–
50	Acridine	0.003	–	–	–	–	–	–	–	–
51	1/2-Methylanthracene	0.036	0.051	–	–	–	–	–	–	–
52	4H-Cyclopenta(def)phenathrene	–	–	0.023	0.009	0.026	–	–	–	–
53	Naphthalene, 2-phenyl-	0.079	0.102	0.009	0.004	0.013	–	–	–	–
54	Fluoranthene	0.021	0.030	0.137	0.073	0.161	0.002	0.001	0.001	0.000
55	Pyrene	0.021	0.030	0.172	0.092	0.212	0.002	0.002	0.002	0.001
56	Pyrene, 1-methyl-	0.016	0.022	–	–	–	–	–	–	–
57	Benzo[ghi]fluoranthene	–	–	0.015	0.008	0.017	–	–	–	–
58	Cyclopenta(cd)pyrene	–	–	0.046	0.026	0.065	–	–	–	–
59	Benzo(c)phenanthrene	0.008	0.010	–	–	–	–	–	–	–
60	Benz(a)athracene	0.015	0.022	0.019	0.013	0.030	–	–	–	–
61	Benz(a)anthracene, 7-methyl-	0.004	0.006	–	–	–	–	–	–	–
62	Benzo(e)acephenanthrylene	–	–	–	–	–	–	–	–	–
63	Benzo(e)pyrene	–	–	0.013	0.007	0.019	–	–	–	–
64	Benzo(k)fluoranthene	0.005	0.007	0.022	0.013	0.039	–	–	–	–
65	Indeno(1,2,3-cd)pyrene	0.003	0.003	0.035	0.019	0.053	–	–	–	–

[a] Yields of individual tar compounds were measured by duplicate, triplicate or quadruplicate SPA sampling.

a.r., as received basis.

Table A1.16. Mass loss during heating of ash prepared at 550°C to 900°C, 1000°C and 1100°C

Material	Mass loss when heating from 550°C to 900°C, %	Mass loss when heating from 550°C to 1000°C, %	Mass loss when heating from 550°C to 1100°C, %
OF1	1.65	1.72	1.70
OF2-1	2.11	1.98	2.46
OF2-2	2.01	2.31	2.56
OF2-3	2.15	2.21	3.41
OF3	3.20	3.58	3.39
OF4	1.83	1.73	2.00
OF2-2 char	2.22	2.39	2.58
OF2-3 char	1.86	1.88	1.96
SS1 char	n/a	0.47	0.73
SRF char	n/a	1.38	n/a

Table A1.17. Content of major and minor ash-forming elements in the AD-SS + FR pellets and char from pilot-scale pyrolysis

Element	AD-SS + FR pellets, $mg/kg_{dry\ matter}$	AD-SS + FR char, $mg/kg_{dry\ matter}$	Maximum allowable concentration as set by the EBC, $mg/kg_{dry\ matter}$
Al	5558.67	18,067.4	
Ca	17,738.78	57,044.27	
Fe	6231.00	19,527.47	
K	1680.48	5403.55	
Mg	3706.90	11,756.57	
Na	1778.26	5696.83	
P	12,105.93	38,443.06	
S	2998.84	6701.16	
Si	21,656.76	69,163.75	
Ag	35.07	109.72	
As	0.34	0.00	13
Ba	444.40	1474.85	
Cd	1.35	2.11	1.5
Co	0.00	0.00	
Cr	26.97	97.06	90
Cu	415.40	1325.04	100
Hg	0.00	0.00	1
Mn	189.49	609.77	
Mo	7.42	23.21	
Ni	17.53	69.63	50
Pb	48.55	162.47	150
Sb	1.35	0.00	
Se	0.67	0.00	
Ti	1061.43	3428.65	
Sn	22.25	94.95	
V	8.09	27.43	
Zn	99.32	3135.37	400

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Valorisation of Composted Organic Fines and Sewage Sludge Using Pyrolysis (OF-PYR)

Authors: Marzena Kwapinska, David A. Agar,
Bart Bonsall and James J. Leahy

Identifying Pressures

Two common and widespread difficult waste streams are sewage sludge derived from municipal wastewater treatment plants (SS) and the organic fine component from the mechanical sorting of municipal solid waste (OF-MSW). OF-MSW cannot be recycled and is extremely heterogeneous (containing food waste, plastics, metals, paper and glass) and after composting is used as a cover material at landfill sites. Although at present 80% of SS is reused in agriculture, the agricultural outlet for SS is under increasing scrutiny, mainly because of perceptions of contamination risk. There are emerging restrictions, mostly driven by private organisations and food quality agencies, leading to a reduction in the availability of agricultural outlets. This is because of a tendency to exclude SS from lands used for food production under quality assurance schemes (An Bord Bia and the Grain Assurance Scheme). Consequently, it is important to investigate alternative outlets for SS to reduce the risk associated with depending solely on land spreading as an outlet.

Informing Policy

Thermal treatment of SS is undertaken in many European Union jurisdictions; this process enables the destruction of organic pollutants at high temperatures through complete inertisation. Advantages of thermal treatment include sterilisation and volume reduction. Pyrolysis is a thermal conversion technology that applies high temperatures to depolymerise organic molecules, resulting in a combustible syngas and solid char, which can potentially be used as a soil conditioner or as a solid fuel energy carrier. Because pyrolysis is performed at a small scale, it is suitable for deployment in small cities and towns; this can avoid the long-distance transportation of waste.

Developing Solutions

The OF-PYR project investigated the potential of slow pyrolysis as a technology for the treatment of OF-MSW and SS as an alternative to other disposal options. Pyrolysis of OF-MSW enables the recovery of energy in the form of a high-energy gas. However, the composition of the feedstock and variable levels of volatile fractions (relative to fixed carbon, ash and inert contaminants) affect energy recovery and can result in low-energy outputs, the value of which is unlikely to remunerate the cost of technology deployment. Pyrolysis results in large proportions of contaminated char that is unsuitable for use other than disposal as landfill cover. It is recommended that the high-energy fraction of OF-MSW (e.g. higher plastic content leads to a higher gas yield) is separated from the high mineral matter fraction before energy recovery.

Pyrolysis of SS provides valorisation of energy in the form of a gas, which could be directly used in a boiler, or in a gas engine after dedicated conditioning, to produce heat and electricity. Syngas conditioning technology needs to be optimised to comply with engine manufacturers' standards or, if used in boiler applications, to achieve an "end-of-waste" standard. Pyrolysis of SS is unlikely to contribute towards improved nutrient recycling without development of additional nutrient recovery technology, as phosphorus is mineralised in biochar in forms that reduce plant availability and some heavy metal residues are concentrated at levels that exceed recommended thresholds, precluding sale as a soil conditioner or disposal via land spreading. SS char is a solid fuel whose combustion results in inert or non-hazardous ash, as per current regulations.

EPA Research: McCumiskey House,
Richiew, Clonskeagh, Dublin 14.

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