epaResearch

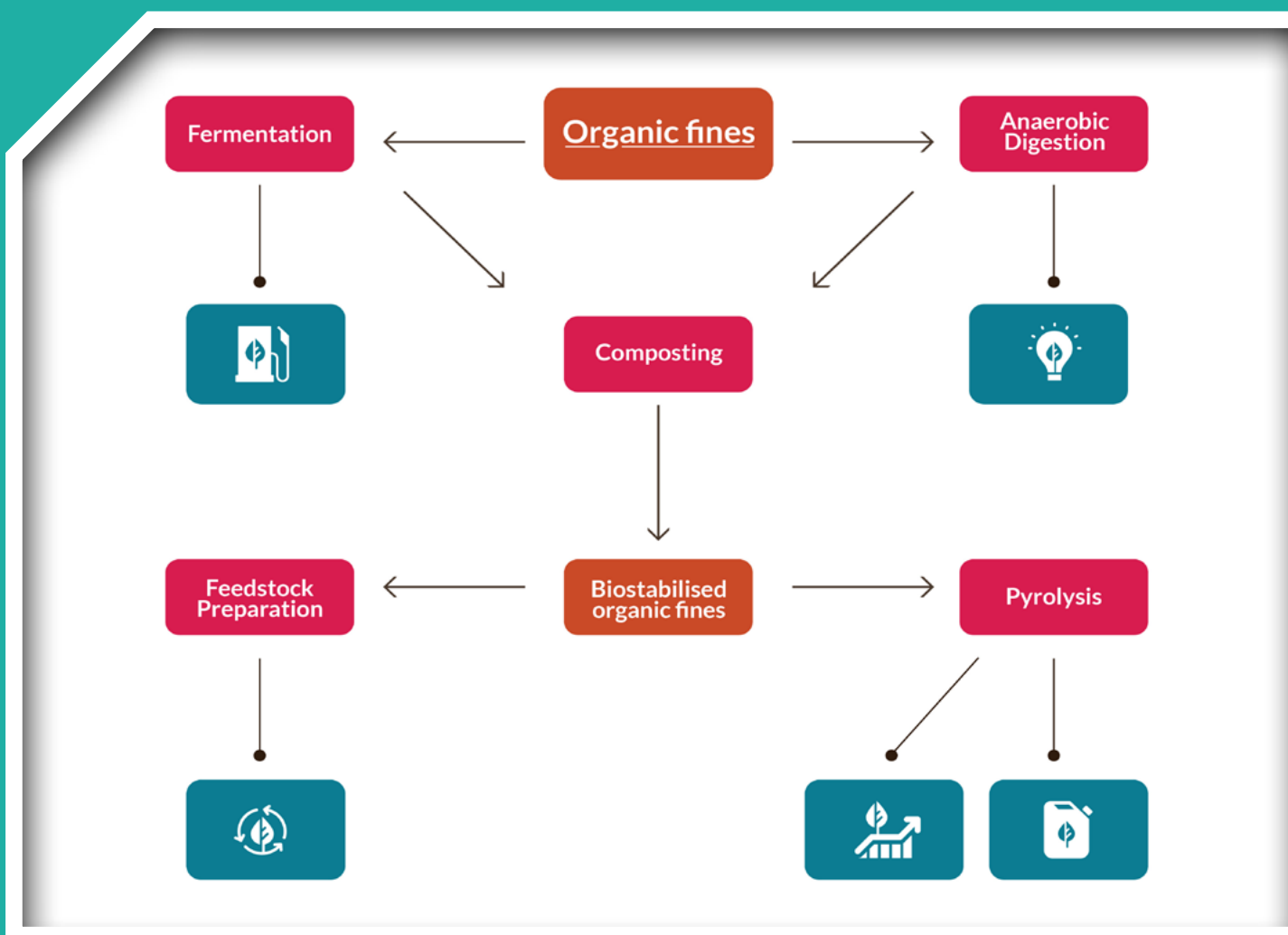# Valorisation Alternatives to Landfill for Organic Residues

Authors: Jessica Graça, Brian Murphy and Brian Kelleher

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Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The 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.

The work of the EPA can be divided into three main areas:

Regulation: Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

Knowledge: Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

Advocacy: Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.

Our Responsibilities Include:

Licensing
> Large-scale industrial, waste and petrol storage activities;
> Urban waste water discharges;
> The contained use and controlled release of Genetically Modified Organisms;
> Sources of ionising radiation;
> Greenhouse gas emissions from industry and aviation through the EU Emissions Trading Scheme.

National Environmental Enforcement
> Audit and inspection of EPA licensed facilities;
> Drive the implementation of best practice in regulated activities and facilities;
> Oversee local authority responsibilities for environmental protection;
> Regulate the quality of public drinking water and enforce urban waste water discharge authorisations;
> Assess and report on public and private drinking water quality;
> Coordinate a network of public service organisations to support action against environmental crime;
> Prosecute those who flout environmental law and damage the environment.

Waste Management and Chemicals in the Environment
> Implement and enforce waste regulations including national enforcement issues;
> Prepare and publish national waste statistics and the National Hazardous Waste Management Plan;
> Develop and implement the National Waste Prevention Programme;
> Implement and report on legislation on the control of chemicals in the environment.

Water Management
> Engage with national and regional governance and operational structures to implement the Water Framework Directive;
> Monitor, assess and report on the quality of rivers, lakes, transitional and coastal waters, bathing waters and groundwaters, and measurement of water levels and river flows.

Climate Science & Climate Change
> Publish Ireland's greenhouse gas emission inventories and projections;

> Provide the Secretariat to the Climate Change Advisory Council and support to the National Dialogue on Climate Action;
> Support National, EU and UN Climate Science and Policy development activities.

Environmental Monitoring & Assessment
> Design and implement national environmental monitoring systems: technology, data management, analysis and forecasting;
> Produce the State of Ireland's Environment and Indicator Reports;
> Monitor air quality and implement the EU Clean Air for Europe Directive, the Convention on Long Range Transboundary Air Pollution, and the National Emissions Ceiling Directive;
> Oversee the implementation of the Environmental Noise Directive;
> Assess the impact of proposed plans and programmes on the Irish environment.

Environmental Research and Development
> Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
> Collaborate with national and EU environmental research activity.

Radiological Protection
> Monitoring radiation levels and assess public exposure to ionising radiation and electromagnetic fields;
> Assist in developing national plans for emergencies arising from nuclear accidents;
> Monitor developments abroad relating to nuclear installations and radiological safety;
> Provide, or oversee the provision of, specialist radiation protection services.

Guidance, Awareness Raising, and Accessible Information
> Provide independent evidence-based reporting, advice and guidance to Government, industry and the public on environmental and radiological protection topics;
> Promote the link between health and wellbeing, the economy and a clean environment;
> Promote environmental awareness including supporting behaviours for resource efficiency and climate transition;
> Promote radon testing in homes and workplaces and encourage remediation where necessary.

Partnership and Networking
> Work with international and national agencies, regional and local authorities, non-governmental organisations, representative bodies and government departments to deliver environmental and radiological protection, research coordination and science-based decision making.

Management and Structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

Valorisation Alternatives to Landfill for Organic Residues

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Identifying pressures

The EPA's latest data (November 2022) show that municipal waste generation increased by over 440,000 tonnes in the last 5 years, and now amounts to 3.2 million tonnes. Currently, 16% of municipal waste in Ireland is landfilled, compared with the EU target of a maximum of 10% by 2030. In 2020, Ireland exported an estimated 39% (1.3 million tonnes) of all municipal waste generated.

The VALOR study looked at how the resource value of the mechanically separated organic fraction of municipal solid waste (MS-OFMSW) can be maximised. The study also characterised the organic fractions of municipal solid waste (MSW).

The VALOR study addresses the critical need to minimise landfilling and develop the beneficial use of the organic fraction of MSW, to formulate strategies to retain materials within a circular economy and to reduce demand for virgin raw materials.

Informing policy

The key policy and regulatory recommendations from the VALOR study are:

1. Promote and use the 0–10 mm subfraction of bio-stabilised residual waste (BSRW), commonly referred to as compost-like output (CLO), subject to additional screening for impurities, as a soil improver for remediation, non-agriculture production and soil restoration.

2. Adopt the oxygen uptake rate limit of 25 mmol O_2/kg organic matter/hour in the EU Fertiliser Regulation (EU 2019/1009, Component Material Category 3 (Compost)) as the stability reference for 0–10 mm CLO destined for use as a soil improver.

3. Recognise the carbon benefit of using CLO as a soil improver.

4. Promote glass recycling at household/commercial level to reduce the impurity content of BSRW and MS-OFMSW.

5. Support the development of anaerobic digestion infrastructure for MS-OFMSW and fund studies to provide better information about pre-treatment options and fuel products.

6. Use the BSRW 10–40 mm fraction for pyrolysis treatment, energy generation and added-value products, such as biochar.

Clarity around policy and support for feasible waste treatment processes will enable sustainable industry, improve recycling rates and deliver circular economy benefits.

Developing solutions

The VALOR study investigated and assessed potential recovery processes for the mechanically separated fractions of MSW. The unique findings of this project included the following:

- Sampling and characterisation of MS-OFMSW and BSRW provided information on their physical and chemical compositions in Ireland.

- Bioethanol from MS-OFMSW has potential as a biofuel but faces a number of practical barriers; biodiesel from BRSW is constrained by a relatively low-fat content.

- Anaerobic digestion of MS-OFMSW to produce biomethane and biogas is possible, but the digestate is unlikely to be used as a fertiliser.

Feasible opportunities for adding value to the organic fraction of MSW include using it as a soil improver. Studies show that BSRW assists with land restoration, produces grass of similar quality to that of agricultural grasslands and assists carbon sequestration in degraded soils.

Trials of soil restoration of bauxite residue deposits show that controlled fractions of BSRW are beneficial as a soil amendment and have effects comparable to those of commercial compost.

Valorisation Alternatives to Landfill for Organic Residues

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EPA Research Report

Prepared for the Environmental Protection Agency

by

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DISCLAIMER

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Executive Summary

The overall aim of the VALOR – Valorisation Alternatives to Landfill for Organic Residues – project was to investigate and assess potential higher-value options for the residual organic waste streams of municipal solid waste (MSW) and formulate strategies to minimise the disposal of MSW to landfill.

Ireland produces in excess of 600 kg of MSW per person per year, at the top end of the EU's 2018 waste generation statistics. Of this, 15% is landfilled. The EU target for landfill disposal is a maximum of 10% of municipal waste by 2030. The need to address the minimisation and beneficial use of MSW is therefore critical.

The literature review considered a wide range of technical studies and publications. The knowledge and expertise of waste management companies, Dublin City University, the University of Limerick and University College Cork were key to characterising waste fractions and treatment processes and to the three case studies. The authors developed a website and presented aspects of the VALOR studies in journals and at industry conferences.

The study characterised the organic fractions of MSW, and the treatment processes considered are depicted in Figure ES.1.

The specific focus of the VALOR study is bio-stabilised residual waste (BSRW), which is generated after the mechanically separated organic fraction of municipal solid waste (MS-OFMSW) is treated to achieve biodegradability stability.

This project investigated and assessed potential recovery processes for fractions of MSW. Biological treatments, soil improvers, biofuels and thermal treatments were identified as opportunities to add value to residual organic waste and provide alternatives to landfill.

Specific outcomes include the following:

- The sampling and characterisation undertaken provide information on the physical and chemical composition of MS-OFMSW and BSRW in Ireland.
- Both MS-OFMSW and BSRW are heterogenous, containing organic material, plastic, glass, stones and paper. No single treatment option was identified as a stand-alone added-value proposition.
- In terms of its value as a soil improver, the studies show that BSRW assists land restoration, produces grass of similar quality to agricultural grasslands and promotes carbon sequestration in degraded soils, with an appropriate monitoring and regulatory framework.
- The trials show that specific fractions of BSRW are beneficial as soil amendments in the restoration of soil with bauxite residue deposits and comparable to commercial compost.
- Although there is potential to produce bioethanol from MS-OFMSW, this process currently has a
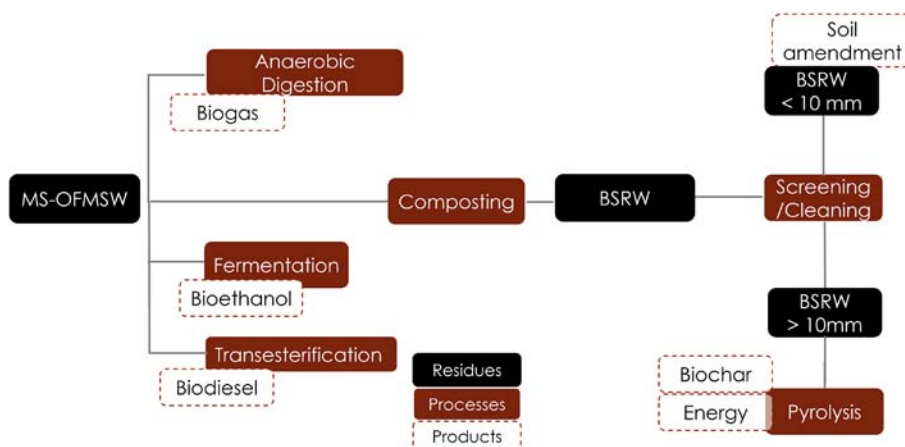
Figure ES.1. Processes considered for treating organic fractions of MSW.

number of practical barriers; BRSW's fat content is lower than is currently needed to produce biodiesel.

● Biomethane and biogas production from MS-OFMSW is considered possible; however, the digestate produced from anaerobic digestion is unlikely to have use as a fertiliser.

● The pyrolysis of the BSRW 10–40 mm fraction has the most potential for energy production; the biochar produced was found to be in line with European guidelines and suitable for land and non-land applications.

The key recommendations from the VALOR study are as follows:

1. To fully utilise BSRW and MS-OFMSW, the amounts of glass and other unwanted materials need to be reduced at the household and commercial levels. The proposed deposit-and-return scheme should be extended to include glass to reduce the impurity content of BSRW.

2. Active soil organic matter and microbial activity are essential elements of a healthy soil system. The BSRW 0–10 mm fraction can be used as a soil improver for soil remediation, restoration and non-agricultural production, and soil restoration of bauxite residue deposits. The BSRW 10–40 mm

fraction has significant potential for pyrolysis treatment, energy generation and added-value products, such as biochar and bio-oil.

3. Financial incentives are needed to support the development of infrastructure for the anaerobic digestion of MS-OFMSW and for studies to better inform pre-treatment options and fuel products.

4. Regulations requiring modifications and policy considerations include the need to:

● differentiate between BSRW that is stabilised and disposed of to landfill and the 0–10 mm fraction of BSRW commonly referred to as compost-like output (CLO), which is subject to additional screening to remove impurities and ensure its suitability for use as a soil improver;

● adopt the 25 mmol O_2/kg organic matter/ hour oxygen uptake rate limit given in the fertiliser regulation as the stability reference for 0–10 mm fraction of BSRW destined for use as a soil improver, applied in a controlled, verifiable manner similar to the nutrient management regime for sewage sludge land application;

● investigate the carbon benefit from the use of BSRW as a soil improver when devising new national policy (Table A1.2).

1   Introduction

Waste management is one of the major challenges we currently face, with the rapid growth of the human population and industrialisation increasing waste generation globally (Das *et al*., 2019). Municipal solid waste (MSW) is defined as "waste from households as well as other waste which, because of its nature or composition, is similar to waste from households" (Council Directive 1999/31/EC) (EU, 1999). The amount of MSW produced worldwide is estimated to be 2 billion tonnes per year, and this is projected to increase fivefold by 2050 (Pham *et al*., 2015). According to Eurostat, a total of 220 million tonnes of MSW was generated in 2018 across Europe, with nine countries, including Ireland, producing 600 kg or more per capita per year (Figure 1.1).

MSW composition is monitored as part of the waste management systems in many countries and is most associated with the production and consumption of goods. Geographical location, climate, socio-economic factors, current waste management practices and season all affect the composition. Nearly 50% of MSW globally is composed of biowaste (e.g. kitchen and garden material). The biowaste fraction of MSW tends to be higher in low-income countries, and the proportion of paper, plastics and other inorganic materials (e.g. metals) tends to be higher in higher-income countries (Pharino, 2017). Across Europe, it is estimated that 30–40% of total MSW consists of biowaste (Edjabou *et al*., 2015), in line with the latest characterisation of MSW composition in Ireland (EPA, 2018).

Currently, residual organic waste that is part of MSW (e.g. black bin waste) is subject to various treatments before being disposed of and/or recovered. In Ireland, MSW has two main disposal pathways: incineration and landfill. The EU's Circular Economy Action Plan aims to increase the recycling and material recovery of municipal waste and drastically reduce its disposal to landfill. The aim of the VALOR – Valorisation Alternatives to Landfill for Organic Residues – project

was to investigate and assess potential higher-value options for the residual organic waste streams of MSW and formulate strategies to minimise disposal to landfill.

Although bio-stabilised waste is defined in the Waste Management (Landfill Levy) Regulations 2015 (S.I. No. 185/2015), there is a lack of clarity about other potential uses of the outputs of mechanical–biological treatment. Therefore, for this project, the wastes to be studied are defined as follows:

- **Mechanically separated organic fraction of municipal solid waste (MS-OFMSW)** refers to the fine fraction of < 60 mm produced during the mechanical treatment of the residual waste (e.g. mixed waste, black bin waste) and constitutes the feedstock for in-vessel composting processes.
- **Bio-stabilised residual waste (BSRW)** refers to the waste that is generated after the MS-OFMSW has been subject to a composting process. Currently, in Ireland, BSRW is treated to achieve an EPA-approved biodegradability stability standard prior to landfilling (EPA, 2011).
- **Compost-like output** (CLO) is a subfraction of BSRW that is typically screened to include BSRW of < 10 mm and is subject to additional processing to remove glass and plastic. This subfraction is also defined throughout Europe, in research and/or policy documents, as a stabilised fraction, CLO or MSW compost (Amlinger *et al*., 2004).

In this project, we also evaluated compost, which refers to the material produced from source-segregated organic waste (e.g. food waste, green waste) after it has gone through a composting process. Compost quality is assessed using quality standards, and it is used in land or land-related applications. Compost quality is evaluated in Chapter 9 of this report.
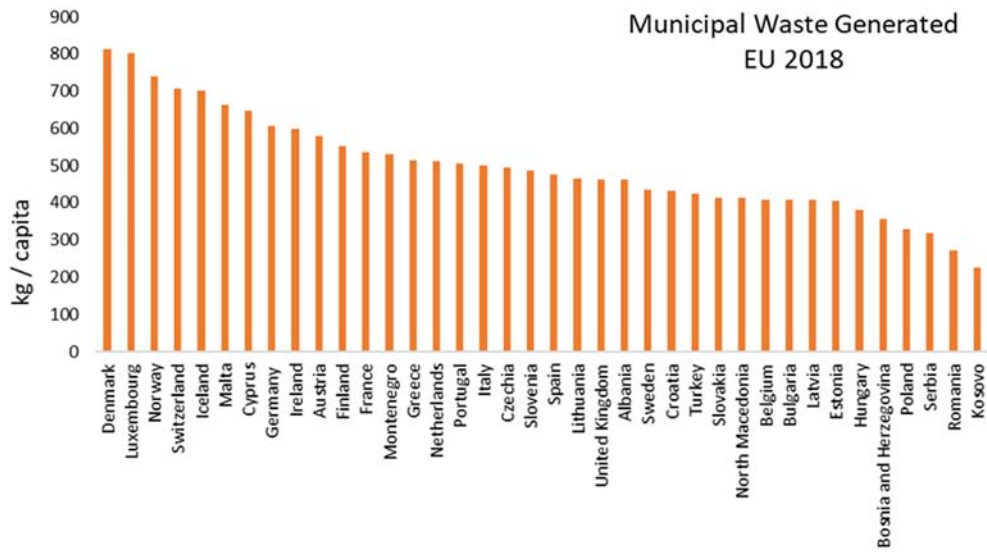
Figure 1.1. Municipal waste generated in European countries in 2018 (source: Eurostat).

2   Organic Fraction of Municipal Solid Waste

2.1   Generation of MS-OFMSW

Mechanical–biological treatment is a combination of the mechanical processing (e.g. shredding, size separation, material separation) and biological treatment (e.g. aerobic or anaerobic degradation) of residual MSW (Di Lonardo *et al*., 2012) prior to disposal or recovery. The main outputs from the composting/digestion of MS-OFMSW are refuse-derived fuel (RDF), recyclables and BSRW. MS-OFMSW is not suitable for disposal in landfill without biological treatment, since ongoing biological activity will generate the uncontrolled release of odours, greenhouse gases and harmful leachates, incurring greater economic and environmental costs.

Previous studies have demonstrated that the biodegradable matter in MS-OFMSW can range from 40% to 80% (López *et al*., 2010; Montejo *et al*., 2010; Di Lonardo *et al*., 2012); this is significantly influenced by the type of waste management treatment. As a result, when recyclables are collected separately at source, this is expected to have an impact on the amount of physical impurities in the MS-OFMSW (López *et al*., 2010). Throughout the year, the composition of MS-OFMSW is prone to change. A higher content of green waste in spring and summer has been reported and tends to reflect increases in organic matter and particle size (Ashkiki *et al*., 2019). In addition, the moisture content of MS-OFMSW is approximately 50%, and the materials display a pH indicating acidity (pH of 5–5.5) (Di Lonardo *et al*., 2015; Graça *et al*., 2021).

The presence of contaminants (e.g. heavy metals and organic pollutants) and impurities (non-degradable material such as plastic, metal, textiles, stone and glass) in MS-OFMSW may influence the treatment and disposal of this waste and the potential for valorisation, that is, adding value. Because MS-OFMSW is subject to further treatment before disposal, few studies have focused on inorganic (metals) and organic pollutants and impurities. The impurity content reported in the literature ranges between 36% and 51% (Montejo *et al*., 2010), with the majority of impurities being glass, plastic and paper. The impurities fraction is expected to depend on several factors, such as the use of

separate collection systems, levels of mechanical screening, socio-economic conditions and the geographical location of households. Impurities cause problems with the efficiency and operation of recycling and recovery operations (Beneroso *et al*., 2015) and may make the final outputs unsuitable as high-value products. Heavy metal contamination of MS-OFMSW has been linked to the presence of batteries, waste electrical and electronic equipment (WEEE) and other wastes (Smith, 2009). Heavy metals tend to be concentrated in MS-OFMSW because of the high affinity of metals to bind to putrescible materials and fine particulate fractions (Smith, 2009). With targets for material recycling increasing at the EU level, increasing the recycling efficiency of specific waste streams, such as for WEEE and batteries, is expected to reduce the amount of these materials in MSW and ultimately contribute to a reduction in the heavy metal content of MS-OFMSW and BSRW.

2.2   Biological Treatment of MS-OFMSW

Both composting and anaerobic digestion (AD) commercial plants are widespread in Europe, as biological treatments are seen as more economically feasible than thermal treatments (Langdon *et al*., 2019). There is little doubt that MS-OFMSW is suitable for both processes; however, feedstock characteristics and composition can limit the viability of the processes and the reuse of their outputs. Biological treatments are based on microbial-mediated reactions that transform organic molecules such as proteins, carbohydrates and fats into CLO or methane, the main products of composting and AD, respectively.

Commercial AD plants for MS-OFMSW serve as a methane/energy production system, adding value prior to a further treatment operation or disposal of the digestate. AD consists of a series of microbially mediated processes that transform organic material into methane, carbon dioxide and trace gases. Methane yields in commercial plants can vary as a result of the heterogeneity of MS-OFMSW, but it is largely accepted that the biogas yield is lower from MS-OFMSW than from source-segregated

organic waste because of the higher fraction of non-biodegradable solids (Campuzano and González-Martínez, 2016) and the content of poorly digestible lignocellulosic material in MS-OFMSW. Pre-treatment steps are often required before the AD of MS-OFMSW (Fantozzi and Buratti, 2011). These steps are related to the performance of the mechanical separation employed to optimise the process and produce marketable outputs (e.g. RDF, recycling materials, methane, compost) (Edo-Alcón *et al*., 2016). The final by-products, digestate and liquor will also require further treatment and/or disposal.

The composting of MS-OFMSW is well established as a waste management process, and the waste generated is defined as BSRW. The composting of MS-OFMSW is currently regarded in Ireland as a pre-treatment prior to landfill, the aim of which is to reduce the decomposition of the waste to minimise odours and methane and leachate generation (EPA, 2011). The amount of BSRW in Ireland increased from 50,000 tonnes in 2013 to 138,000 tonnes in 2018 (EPA, 2020), reflecting the fact that most residual organic waste is subject to stabilisation prior to landfill and highlighting the need for alternative valorisation routes for this residual organic waste.

Recovery and/or disposal operations for BSRW in European countries are not clear (Di Lonardo *et al*., 2015). In the UK, CLO from BSRW can be used for soil remediation under permit from the Environment Agency; however, it is mostly used as landfill cover material (Rigby *et al*., 2021). In some southern European countries, BSRW is currently used as low-grade compost, and land spreading is permitted (Langdon *et al*., 2019) if the material is compliant with quality standards in each country. This reflects the demand for organic matter to maintain soil fertility in these regions. However, the quantities of BSRW produced, used and disposed of across European countries are relatively unknown (Stretton-Maycock and Merrington, 2009).

2.3 Value of BSRW as a Soil Improver

In line with the EU's Circular Economy Action Plan, BSRW has the potential to be used as a soil improver, although the potential risks and benefits should be assessed and defined before this is done. Previous studies have looked at the effects of BSRW on soil

properties (e.g. chemical, physical and biological) and crop yields in different scenarios (Hargreaves *et al*., 2008). Overall, it has been found that BSRW benefits soil by improving its physical and chemical properties, in particular by increasing soil organic matter content, which is the main reason why southern European countries use BSRW on land. BSRW is increasingly used in agriculture as a soil conditioner but also as a fertiliser. It has been shown that BSRW can reduce artificial fertiliser usage (Ribas-Agusti *et al*., 2016) and improve the biological nutrient cycle (Sadet-Bourgeteau *et al*., 2018). One disadvantage of using BSRW in soil is the potentially high concentration of heavy metals and organic pollutants and their potential for adverse environmental and human effects. In countries where BSRW can be used as a soil improver, the legislation defines maximum limits for annual inputs (Decreto-Lei No. 103/2015). Smith (2009) reviewed the impact of heavy metals and showed that the bioavailability of potentially toxic elements from BSRW was comparable to that from sewage sludge and reported that metal content does not constitute a barrier to end-of-waste criteria. Thus, a set of practical limits, similar to those in sewage sludge land use legislation, could be introduced. The composition of BSRW in relation to its content of heavy metals and other potential pollutants and impurities is highly dependent on the efficiency of the mechanical treatment of the MS-OFMSW (Donovan *et al*., 2010). In this context, it is noted that contaminants and impurities are distinct materials. Contaminants are considered substances such as heavy metals or persistent organic pollutants, for example polycyclic aromatic hydrocarbons (PAHs), whereas impurities are physically undesirable materials such as glass, plastic and stones.

The lack of specific guidelines means that the heavy metal content of BSRW in most European countries is often measured against the threshold values for compost produced from source-segregated materials. These values vary between EU Member States and/or sewage sludge legislation. It is more challenging for BSRW to attain the criteria set for high-quality composts (Epelde *et al*., 2018); however, studies comparing sewage sludge compost and BSRW have reported that the latter complies with the allowable limits (Alvarenga *et al*., 2017). Furthermore, studies have shown that the biological treatment of organic waste can degrade a diverse range of

organic pollutants (Huang *et al*., 2019; Graça *et al*., 2021). BSRW could be used for land remediation or reclamation, as well as in other non-agricultural applications, and further research is needed to understand how it can be recovered for use as a soil improver without damaging the environment or human health.

2.4   Biofuels from MS-OFMSW

Fermentation is a biological process that produces ethanol from sugar, starch and lignocellulose-rich material (Figure 2.1). Currently, the USA and Brazil produce the most bioethanol in the world, from starch (e.g. corn) and saccharose (e.g. sugarcane) feedstocks. Second-generation bioethanol, produced from lignocellulosic-rich feedstock, is a potentially valuable alternative to crop-based feedstocks (Barampouti *et al*., 2019). Currently, producing bioethanol from MSW involves many technical and economic challenges. The major barriers identified are the cost of the enzymes, the heat duty for the process and the intensive energy needs of distillation (Barampouti *et al*., 2019). Despite these barriers, MS-OFMSW has the potential to be a suitable feedstock for bioethanol production, as recently shown by a demonstration plant operating in Spain (Moreno *et al*., 2021) indicating that bioethanol production from MS-OFMSW could be technologically and economically feasible on the commercial scale in the near future. However, because of high variability in the quality and material content of MS-OFMSW, an evaluation of the nutritional characteristics (carbohydrates, fats and proteins) and potential process inhibitors and contaminates is essential to fully understand the potential for ethanol production from this material.

Biodiesel consists of fatty acid methyl esters, and most of its production worldwide is concentrated in the EU and the USA, where vegetable oil is the main feedstock (Barampouti *et al*., 2019). Biodiesel is mainly obtained by the transesterification of fat and vegetable oils in the presence of a catalyst, leading to the production of ethyl or methyl esters (Figure 2.1).

MS-OFMSW can contain up to 13% fat/oil (Barampouti *et al*., 2019), which is relatively low when compared with other feedstocks currently being used (Karmakar *et al*., 2010). Fat content and calorific value are two of the main feedstock characteristics that determine the yield and energy of the biodiesel produced (Karmakar *et al.*, 2010). The production of biodiesel from MS-OFMSW is not usually considered, as its fat content is lower than that of source-segregated wastes, which are rich in fat. Kannengiesser *et al*. (2015) studied the production of biodiesel using a percolated form of feedstock in a composting facility in Germany. Their investigations show that, although the process was technically possible, the amount of biodiesel produced was not economically viable.
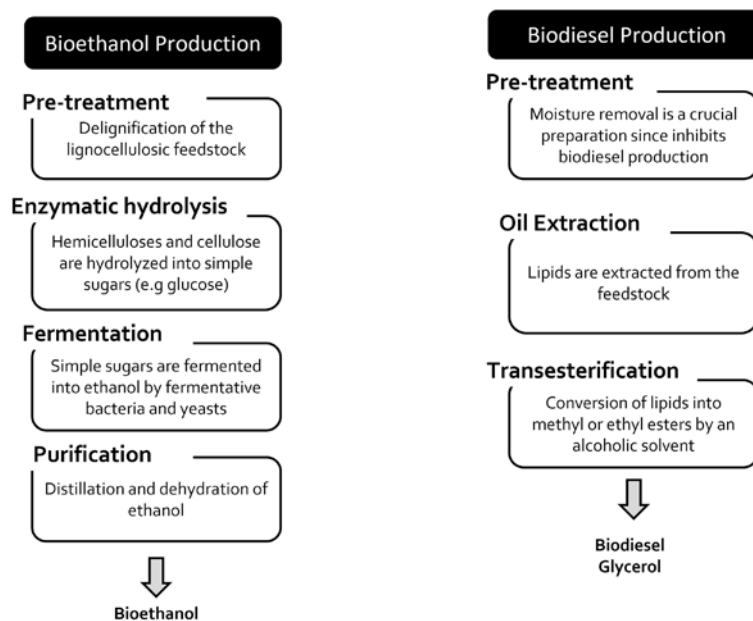
Figure 2.1. Bioethanol and biodiesel production from fermentation and transesterification processes.

2.5 Thermal Treatment of MS-OFMSW

Thermal processing involves converting MSW into energy, heat and fuel (gas, liquid or solid). Also known as waste-to-energy technology, it comprises incineration, gasification and pyrolysis. Incineration is a widely known thermal process commonly used to convert waste to energy. However, the thermal conversion of waste can be seen as less desirable than biological conversion because of social reluctance and the higher potential for the generation of gaseous pollutants (Beyene *et al*., 2018).

Pyrolysis and gasification have advantages over traditional incineration in terms of higher energy efficiency, the generation of higher-value products and better pollution control (Matsakas *et al*., 2017).

Gasification and pyrolysis are thermal processes that convert carbon-based material into combustible gases (e.g. syngas), hydrocarbons/tar (oil) and char/ash at high temperatures (Beyene *et al*., 2018). Gasification occurs in an oxygen-limited environment, whereas pyrolysis occurs in the absence of oxygen (Beyene *et al*., 2018). Syngas can be converted directly into energy or converted into a building block for different chemical energy intermediate products such as biodiesel and bioethanol (Palacio *et al*., 2019). Ultimate (percentages of carbon, oxygen, nitrogen, sulfur, hydrogen) and proximate (calorific value, ash, moisture, fixed carbon and volatile matter) analyses determine the suitability of the feedstock for valuable gas production. In gasification, a higher carbon and oxygen content is desirable, whereas large amounts of nitrogen and sulfur can lead to emissions of nitrogen and sulfur oxides. Furthermore, the ash and volatile matter content of the feedstock will determine the production of char and tar, respectively.

2.6 Research Gaps and Project Objectives

There is a lack of research and industrial focus in Ireland on the potential to recover and reuse MS-OFMSW. However, decreasing landfill capacity and new EU targets to reduce the landfilling of biodegradable waste require the in-depth evaluation of high-value options. Despite much research across Europe, knowledge of the heterogeneity and characteristics of the residual organic waste stream in Ireland is crucial, as, to date, no in-depth characterisation study of MS-OFMSW has been carried out. The aim of this project was to characterise MS-OFMSW and BSRW through an analysis of their potential for energy recovery, for biogas and biofuel production and as soil improvers (Table 2.1).

Historical data and previous projects conducted by Enrich Environmental informed the choice of potential processes for each component of the residual organic waste and helped to identify the diagnostic parameters that allow the generation of high-value end materials (Table 2.1).

The main objectives of the VALOR work were to:

- characterise residual organic waste (MS-OFMSW and BSRW) in relation to physical properties, particle size distribution and content of impurities (Chapter 4);
- evaluate bromatological properties and biomethane potential to establish the suitability of residual organic waste for the production of biofuels (Chapters 5 and 6);
- conduct elemental, ultimate and proximate analyses to establish the potential of residual organic waste for the production of energy (Chapter 5) and high-added-value products, such as bio-oil and biochar, through a pyrolysis experiment (Chapter 7);
- assess the use of BSRW as a soil amendment (Chapter 5) and validate the impacts on water quality and the benefits to soil and plants in land remediation field trials (Chapter 8).

Table 2.1. Selected diagnostic parameters for the valorisation of residual organic waste

End use/product	Diagnostic parameters	Recovery process	Initial target material
Energy production	Calorific value	Thermal process	BSRW 10–40 mm
Biofuels	Methane potential	AD	MS-OFMSW
	Cellulose/hemicellulose and lignin	Fermentation	BSRW
	Fats		
Soil improver	Stability	Land reclamation	BSRW 0–10 mm
	Ecotoxicity		
	Phytotoxicity		

3 Residual Organic Waste Sampling

Residual organic waste (MS-OFMSW and BSRW) was sampled at Enrich Environmental in 2019 during the summer (May and June) and winter (November and December). Three samples from each of the waste streams, MS-OFMSW and BSRW, were collected in each season (Table 3.1). The sampling design was based on the *Protocol for the Evaluation of Biodegradable Municipal Waste Sent to Landfill*, published by the Irish Environmental Protection Agency (2011). The European standards for biofuel sample preparation (EN 14780:2011) and for sampling of waste materials (EN 14899:2005) were also consulted. The sampling was designed to allow for an evaluation of a range of processes and parameters related to the recovery of residual organic waste.

Each MS-OFMSW sample was collected over a 2- to 4-day period, depending on the frequency of truck deliveries, by sampling from 10 trucks. A composite sample from each truck (≈20 kg) was collected after the waste had been emptied into the reception area and comprised 30 random grab samples (increments of 0.5–1 kg). Truck samples were mixed in a designated location in the enclosed area to form a primary sample. The primary sample was reduced in size for laboratory preparation and analysis using the coning and quartering technique (EPA, 2011).

Approximately 5 kg of the sample was used on the sampling day to determine the bulk density and moisture content of the waste. A sample of 10 kg was separated into smaller samples for further analysis and storage at –20°C, and approximately 10 kg was dried for the purpose of a characterisation analysis of the impurities.

BSRW samples were collected as outlined in EPA (2011). The samples were generated by taking 15 increments of 2 kg, collected from each bay, to provide a composite sample of 30 kg. Increments were sampled randomly so that they were representative of the whole batch. Each composite sample was mixed and reduced in volume using the coning and quartering technique. Based on particle size, two fractions, 10–40 mm and 0-10 mm, were produced by screening the samples with a 10 mm sieve. Approximately 2 kg of the sample was used immediately to determine the bulk density and moisture of BSRW, in both fractions. Part of the remaining sample was separated into smaller samples for further analysis, stored at –20°C and dried for particle size and impurity characterisation.

It is important to note that, when composting MS-OFMSW, the oversize material (above 40 mm) from the processing of MS-OFMSW and/or green

Table 3.1. Overview of MS-OFMSW and BSRW samples collected in each season

Waste type	Number of samples	Sample reference numbers	Season
BSRW	6	070519/090419 BSRW	Summer
		040619/040519 BSRW	
		210619/210519 BSRW	
		291019/021019 BSRW	Winter
		251119/111019 BSRW	
		021219/161019 BSRW	
MS-OFMSW	6	070519/020519 MS-OFMSW	Summer
		040619/020619 MS-OFMSW	
		240619/200619 MS-OFMSW	
		231019/161019 MS-OFMSW	Winter
		251119/221119 MS-OFMSW	
		021219/271119 MS-OFMSW	

For laboratory logistics purposes, samples were given reference numbers.

waste is reused as a bulking agent in the biological treatment of MS-OFMSW (Graça *et al*., 2021).

3.1 Historical Data

Enrich Environmental has undertaken extensive characterisation of the physical and chemical properties of municipal residual waste (MS-OFMSW and BSRW) for internal controls. These data were gathered to build knowledge of the materials being studied and identify current knowledge gaps in relation to the characterisation of MS-OFMSW and BSRW.

The examination of historical data collected by Enrich Environmental also served as a starting point for the VALOR project in evaluating high-value recovery processes for residual municipal waste. A total of 15 MS-OFMSW (Table 3.2) and 31 BSRW (Tables 3.3 and 3.4) composite samples collected between 2012 and 2016 underwent in-depth chemical and physical characterisation covering a wide range of parameters. Analyses were conducted by a third-party laboratory. Organic matter was determined by loss on ignition (LOI) and used to estimate organic carbon. Total nitrogen and carbon contents were determined using an elemental analyser. Total heavy metal contents were determined by digestion followed by inductively coupled plasma (ICP) determination. PAH contents were determined by solvent extraction followed by gas chromatography mass spectroscopy (GCMS). Total element contents were determined by digestion followed by ICP determination.

This prior characterisation indicated that MS-OFMSW is suitable for other biological treatment processes (such as fermentation and digestion) as a result of its moisture and organic matter. Composted material (BSRW) would be more suitable as an organic amendment for soil remediation and/or thermal processing, as indicated by the amount of nutrients and organic matter (Table 3.3). However, the diagnostic features that were needed to establish the suitability of these waste materials for material recovery through other processes, such as energy and/or biofuel production, were not available. The historical data also showed that PAHs were detected

Table 3.2. Historical data on average physical and chemical properties analysed in MS-OFMSW samples (*n* = 15)

Parameter (DM)	Average ± standard error
Moisture	56.6±6.5
Organic matter	41.2±11.2
Organic carbon	23.9±6.5
Total heavy metals (mg/kg)	
Copper	164.0±124.3
Zinc	453.5±208.3
Lead	273.8±391.8
Cadmium	0.7±0.2
Nickel	58.8±37.4
Chromium	108.2±79.9
Mercury	0.5±0.8
PAHs (mg/kg)	
Total PAHs [EPA16][a]	9.4±6.2
Naphthalene	0.4±0.2
Acenaphthylene	0.2±0.0
Acenaphthene	0.4±0.2
Fluorene	0.4±0.2
Phenanthrene	1.3±0.8
Anthracene	0.4±0.2
Fluoranthene	1.1±0.9
Pyrene	0.9±0.6
Benzo[a]anthracene	0.6±0.5
Chrysene	0.8±0.5
Benzo[b]fluoranthene	0.7±0.5
Benzo[k]fluoranthene	0.6±0.4
Benzo[a]pyrene	0.7±0.5
Indeno[1,2,3-cd]pyrene	0.7±0.6
Dibenz[a,h]anthracene	1.3±0.9
Benzo[g,h,i]perylene	0.7±0.6

[a]The 16 selected PAHs.
DM, dry matter.

in residual organic waste; however, the average concentrations were within the recommended levels for source-segregated organic waste (Regulation (EU) 2019/1009 of the European Parliament and of the Council). Polychlorinated biphenyls (PCBs) were not detected in MS-OFMSW (data not shown) or BSRW samples (Table 3.4).

Table 3.3. Historical data on average chemical properties and nutrients analysed in BSRW 0–10 mm samples (*n*=31)

Parameter (DM)	Average ± standard error
Total nitrogen (%)	2.0±0.3
Organic matter (%)	41.6±7.0
Organic carbon (%)	24.2±4.1
Total calcium (%)	7.1±2.1
Total magnesium (%)	0.6±0.1
Total phosphorus (%)	0.4±0.006
Total potassium (%)	0.7±0.1
pH	6.8±0.4
Conductivity (mS/cm)	2.9±0.6

DM, dry matter.

Table 3.4. Historical data on average potential contaminant concentrations in BSRW 0–10 mm samples (*n*=31)

Parameter (DM)	Average ± standard error
Total heavy metals (mg/kg)	
Copper	284.6±180.2
Zinc	647.3±189.9
Lead	227.0±147.8
Cadmium	1.4±0.5
Nickel	74.8±82.5
Chromium	83.1±42.3
Mercury	0.4±0.2
PAHs (mg/kg)	
Total PAHs [EPA16][a]	5.0±4.5
Naphthalene	0.1±0.1
Acenaphthylene	0.1±0.0
Acenaphthene	0.1±0.2
Fluorene	0.2±0.2
Phenanthrene	1.2±1.1
Anthracene	0.3±0.7
Fluoranthene	0.8±0.5
Pyrene	0.7±0.4
Benzo[a]anthracene	0.4±0.4
Chrysene	0.5±0.6
Benzo[b]fluoranthene	0.4±0.5
Benzo[k]fluoranthene	0.2±0.3
Benzo[a]pyrene	0.2±0.2
Indeno[1,2,3-cd]pyrene	0.2±0.2
Dibenz[a,h]anthracene	0.2±0.2
Benzo[g,h,i]perylene	0.2±0.2
Polychlorinated biphenyls (PCBs) (µg/kg)	
Total PCBs [EC7][b]	<2
PCB-28	<0.5
PCB-52	<0.5
PCB-101	<0.5
PCB-118	<0.5
PCB-153	<0.5
PCB-138	<0.5
PCB-180	<0.5

[a]**The 16 selected PAHs.**
[b]**The seven priority PCBs.**
DM, dry matter.

4   General Characterisation of Residual Organic Waste

A general characterisation of residual organic waste (MS-OFMSW and BSRW) was initially conducted to inform the follow-up studies of the materials' behaviour and properties.

The aims were to:

- characterise the physical properties (moisture and bulk density) of the residual organic waste samples collected in the summer and winter;
- determine the particle size distribution of the residual organic waste and evaluate the content of physical impurities, to assess the suitability of valorisation processes and the pre-treatment options that might be needed.

4.1   Physical Characterisation of Residual Organic Waste

The analysis of the MS-OFMSW samples showed that they had an average moisture content of 46.3% and an average bulk density of 780.3 g/L (Table 4.1), whereas BSRW samples had an average moisture content of 22.0% and a density of 416 g/L (Table 4.2). Analysis of variance (ANOVA), a statistical tool that determines if the statistical means of two groups are different, was conducted to determine if the moisture content (%) and bulk density (g/L) differences between the winter and summer samples were significant. A significant difference between the two means indicates

Table 4.1. Moisture content and bulk density of the MS-OFMSW samples collected in 2019

MS-OFMSW samples	Season	Moisture (%)	Bulk density (g/L)
070519/020519	Summer	43.5±1.5	809±50
040619/020619	Summer	47.1±3.0	814±39
240619/200619	Summer	50.5±0.7	789±63
231019/161019	Winter	46.8±3.3	733±42
251119/221119	Winter	45.3±3.5	756±31
021219/271119	Winter	44.3±2.6	781±69
Average		46.3±2.3	780.3±28.5
Summer		47.0±2.9 a	804±10.8 a
Winter		45.5±1.0 a	757±19.6 b

Mean values followed by the same letter are not statistically significantly different at _p_=0.05.

Table 4.2. Moisture content and bulk density of the BSRW samples collected in 2019

BSRW samples	Season	Moisture (%)	Bulk density (g/L)
070519/090419	Summer	21.5±1.4	457±17
040619/040519	Summer	24.6±2.6	423±56
210619/210519	Summer	24.8±5.1	449±13
291019/021019	Winter	14.3±0.4	403±18
251119/111019	Winter	22.1±0.5	384±22
021219/161019	Winter	24.4±1.9	382±15
Average	Both	22.0±3.6	416±29
Average	Summer	23.6±1.5 a	443±14.5 a
Average	Winter	20.3±4.3 a	390±9.5 b

Mean values followed by the same letter are not statistically significantly different at _p_=0.05.

a measurable difference between the groups and that, statistically, the probability of obtaining that difference by chance is 5%, represented by $p < 0.05$. The moisture content of the winter and summer samples for both residual waste materials was not significantly different. However, the bulk density of the MS-OFMSW and BSRW summer samples was higher than that of the winter samples. Residual waste mainly comprises organic waste; however, the variability in waste composition throughout the year and the ratio of organic matter to the content of impurities such as glass, plastics and metals could explain the differences in bulk density (Campuzano and González-Martínez, 2016).

4.2   Particle Size Distribution

The particle size distribution of the residual waste was determined using three MS-OFMSW and four BSRW samples (Figure 4.1). Particle size distribution was carried out on a dry matter (DM) basis, in triplicate, using a series of sieves with decreasing apertures (31.5 mm, 16.0 mm, 10.0 mm, 8.0 mm, 5.0 mm, 4.0 mm and 2.0 mm), based on the standards AfOR MT PC&S:2002 and CEN/TS 16202:2013. The MS-OFMSW samples showed relatively low variability in particle size distribution, except for the fraction that was greater than 31.5 mm. This was expected because of the mechanical and sorting treatments that municipal residual waste undergoes before the MS-OFMSW fraction is generated.

Higher variability in particle size distribution in the BSRW samples could be related to the composting process, where mechanical handling of the drier material and, perhaps, more substantial use of bulking

agents (oversize green waste) occurs. In BSRW samples, as 59% of the material was ≥ 10 mm, 41% was < 10 mm.

4.3   Impurity Content of Residual Organic Waste

Both the organic material content and the impurity content of the residual organic waste (MS-OFMSW and BSRW) were determined simultaneously with the determination of the particle size distribution of the three MS-OFMSW samples and four BSRW samples. The results are presented as % weight per weight (w/w) on a DM basis. The determination of foreign material content in municipal waste is often overlooked because of its low added value and limited reuse options. To understand the potential for the valorisation of the residual organic waste (MS-OFMSW and BSRW) and potential pre-treatment options, the physical impurities in the material were classified into the selected categories shown in Table 4.3. The categories were chosen based on their potential for removal, such as inert material that could be removed with density separators and metal that could be removed using magnetic conveyor belts. Moreover, the breakdown of combustibles into paper and plastic is relevant to energy recovery, since plastic content increases waste's energy value but paper content increases moisture retention.

On average, 43% of the MS-OFMSW consisted of material that was organic in origin, while 31% was inert material and 25% was combustible material, on a DM basis (Figure 4.2). On a fresh weight basis (as received by Enrich Environmental), impurities correspond to approximately 25% of the total weight.
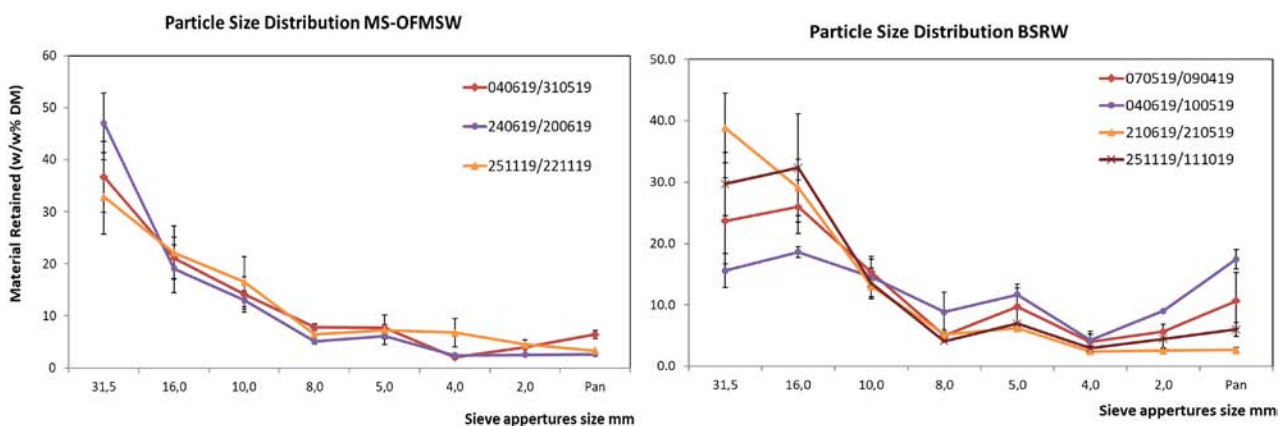
Figure 4.1. Particle size distribution in MS-OFMSW and BSRW samples (% weight per weight (w/w) DM).

Table 4.3. Selected impurity categories

Impurity class	Description
Inert	Sum of glass, metal and stones/ construction and demolition material
Combustible	Sum of paper and plastic
Glass	Glass
Metal	Hard metal (nails, screws), aluminium foil, coins, batteries
Stones/construction and demolition (C&D) waste	Stones, construction and demolition material (brick, ceramic)
Plastic	Hard and film plastic, Styrofoam, rubber, latex
Paper	Absorbent paper, wipes, printing paper
Others	Textile, bone, WEEE, toys, unusual items such as credit cards

IMPURITIES IN MS-OFMSW (W/W% DM)

Figure 4.2. Average distribution of materials of organic origin and impurities (e.g. inert, combustible and other impurities) in MS-OFMSW samples (% w/w DM).

IMPURITIES IN BSRW 10-40 MM (W/W% DM)

Figure 4.3. Average distribution of materials of organic origin and impurities (e.g. inert, combustible and other impurities) in the BSRW 10–40 mm fraction (% w/w DM).

IMPURITIES IN BSRW 0-10 MM (W/W% DM)
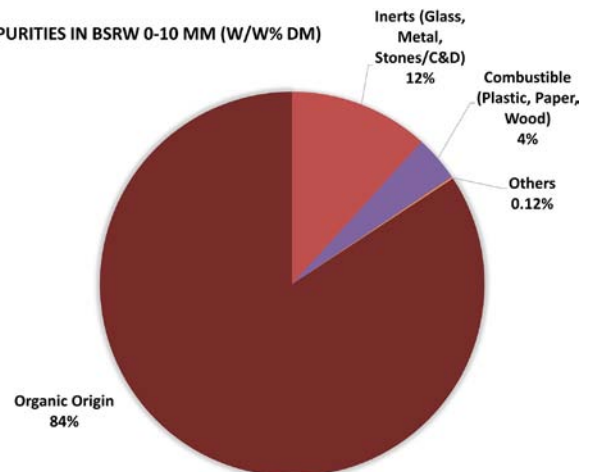
Figure 4.4. Average distribution of materials of organic origin and impurities (e.g. inert, combustible and other impurities) in the BSRW 0–10 mm fraction (% w/w DM).

The physical impurities of BSRW are presented according to the reuse options evaluated, i.e. as the 10–40 mm fraction, which was evaluated for energy production, and the 0–10 mm fraction, which was evaluated as a soil improver. In the 10–40 mm fraction of BSRW, 53% of the material was of organic origin, whereas the overall proportions of inert material and combustibles were similar, at 24% and 22%, respectively (Figure 4.3). The 0–10 mm fraction of BSRW had a much lower impurity content, and on average 84% of the material was organic in origin (Figure 4.4).

The characterisation of impurities in the residual organic waste (MS-OFMSW and BSRW) is presented in Tables 4.4–4.6. On a DM basis, glass and paper account for the largest proportions of physical impurities in MS-OFMSW and BSRW 10–40 mm, whereas the metal and plastic fractions constitute smaller proportions. Residual organic waste is derived from non-recycled household waste and, therefore, plastic, glass, paper and other materials are expected. However, the quantities of these non-organic materials in the residual organic waste remain under-investigated, largely because of their

Table 4.4. Composition of impurities in three MS-OFMSW samples

Impurity class	Mass of impurity (% w/w DM)			
	040619/310519 Average (±std)	240619/200619 Average (±std)	251119/221119 Average (±std)	Overall mean Average (±std)
Glass	18.2±2.9	16.1±4.8	26.2±3.4	20.2±4.3
Plastic	8.1±1.4	7.1±1.5	5.4±2.4	6.9±1.1
Metal	3.2±1.4	1.3±0.8	4.1±2.7	2.9±1.2
Stones/C&D	10.4±3.8	7.2±2.8	6.8±4.3	8.1±1.6
Paper	13.9±1.0	25.0±4.8	15.0±5.0	18.0±5.0
Others	1.81±1.6	1.8±2.2	0	1.2±0.8

C&D, construction and demolition.

Table 4.5. Composition of impurities in four BSRW 10–40 mm fraction samples

Impurity class	Mass of impurity (w/w% DM)				
	070519/090419 Average (±std)	040619/100519 Average (±std)	210619/210519 Average (±std)	251119/111019 Average (±std)	Overall mean Average (±std)
Glass	14.9±1.1	14.0±2.4	13.7±1.4	15.2±2.2	14.5±0.7
Plastic	5.2±1.1	5.4±1.6	3.0±1.2	8.7±3.0	5.6±2.0
Metal	1.8±1.2	3.8±0.8	2.7±1.8	2.1±1.1	2.6±0.8
Stones/C&D	5.7±2.0	5.5±1.5	7.0±0.5	10.1±2.2	7.1±1.8
Paper	6.5±3.5	8.0±1.2	8.5±0.4	19.7±4.0	10.7±5.3
Others	2.1±1.7	0.8±0.5	0.1±0.1	1.5±0.2	1.1±0.7

C&D, construction and demolition.

Table 4.6. Composition of impurities in four BSRW 0–10 mm fraction samples

Impurity class	Mass of impurity (% w/w DM)				
	070519/090419 Average (±std)	040619/100519 Average (±std)	210619/210519 Average (±std)	251119/111019 Average (±std)	Overall mean Average (±std)
Glass	7.0±1.8	11.0±2.7	10.6±2.0	2.9±1.4	7.9±3.3
Plastic	1.3±0.1	1.6±0.3	1.0±0.2	0.8±0.2	1.2±0.3
Metal	0.2±0.1	1.2±0.7	0.3±0.2	0.1±0.03	0.5±0.4
Stones/C&D	3.1±0.9	4.8±0.9	4.1±0.5	1.8±2.2	3.5±1.1
Paper	0.5±0.4	4.3±1.1	3.2±0.3	2.8±1.1	2.7±1.4
Others	0.1±0.1	0.4±0.4	0	0	0.12±0.2

C&D, construction and demolition.

low market or reusable values. Our results confirmed recent reports indicating that glass is the most common type of physical impurity in residual organic waste (Montejo *et al*., 2010; Sharifi and Renella, 2015). Glass and hard plastic are currently recyclable materials. Glass represented the highest proportion of recyclable material in the residual organic waste, followed by paper. Distinguishing between recyclable and non-recyclable paper was not possible to quantify; however, during visual sorting of the waste it was observed that most of the paper was non-recyclable, such as absorbent paper (e.g. blue paper or kitchen paper) and wipes.

The plastic in the MS-OFMSW and BSRW (Figure 4.5) was sorted into four categories: hard plastic, plastic film, plastic wrap and others such as latex, rubber and Styrofoam. The majority of plastics in the samples were hard plastics, followed by plastic wrap, plastic
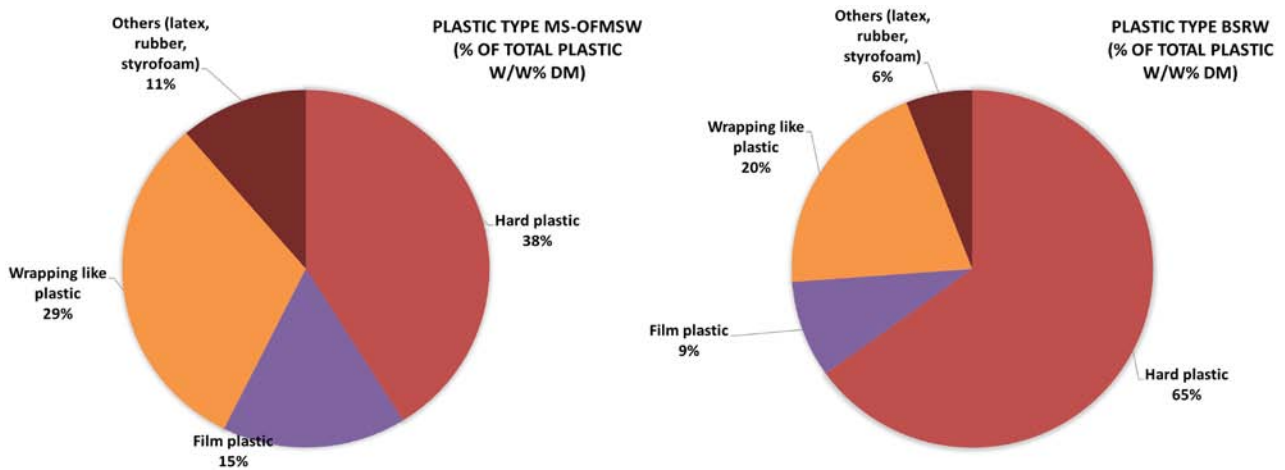
Figure 4.5. Average distribution of different types of plastic in residual organic waste (% w/w DM).

film and others. However, the distribution of plastic types was different in all the samples collected, which may be explained by the heterogeneity of these materials and the non-uniform distribution of plastics in residual organic waste.

Macro- and microplastic contents were evaluated based on particle size. Macroplastics ($>5\,mm$) constituted more than 95% (w/w DM) of the plastic screened out of the residual waste, whereas microplastics ($<5\,mm$) made up 1–5% (w/w DM).

When the BSRW 0–10 mm fraction is proposed for use as a soil amendment, impurities removal is required, using for example density or ballistic separation techniques. Such processes are currently in place in countries where BSRW is used as a soil amendment, for example in Portugal at the Braval Ecoparque. This waste treatment facility produces commercial compost from BSRW that complies with national legislation for organic amendments (Decreto-Lei No. 103/2015, 2015), which sets a maximum impurity limit value and compost quality standards.

5 Evaluation of High-value Options for Residual Organic Waste

This chapter investigates the potential higher-value uses for residual organic waste identified in Chapter 2. It includes details of analyses carried out to determine the suitability or unsuitability of residual organic waste for each use. An in-depth evaluation of the residual organic waste was conducted to determine the most suitable options for MS-OFMSW and BSRW valorisation.

5.1 Use of MS-OFMSW and BSRW for Biofuel Production

There is limited information available on the suitability of MS-OFMSW and BSRW for use as biofuels. Initially, composite samples of the materials collected in season 1 (summer) (see Table 3.1) were analysed for extractives, carbohydrates and lignin, and two further samples of MS-OFMSW were also subsequently examined. Screening for bromatological properties of both residual organic wastes, in particular for carbohydrate and fat contents, is useful for understanding their potential use for biofuel (bioethanol and biodiesel) production and as added-value products.

The water and ethanol extractants comprised a range of fractions such as non-structural sugars, chlorophyll and waxes, and inorganic salts, such as sulfates and phosphates (Sluiter *et al*., 2008). Extractives in the MS-OFMSW samples accounted for on average

35.5%, in line with values reported by Farmanbordar *et al*. (2018). As expected, BSRW yielded a lower proportion of extractives (Figure 5.1). During composting, readily available nutrients, carbohydrates and easily degraded molecules are used by microorganisms. The organic and mineral contents of composted material are therefore more resilient and recalcitrant to extraction with water and/or ethanol (Iiyama *et al*., 1995).

The sugar (25%) and lignin (16%) contents varied between samples and did not show clear trends in relation to the composting treatment of BSRW (Figure 5.1). The bromatological characteristics of the residual organic waste are likely to be linked to its composition and seasonal variability (Pecorini *et al*., 2020). The process for composting MS-OFMSW often involves the utilisation of oversize material that can change the lignin content by introducing external woody material (Graça *et al*., 2021).

The sugars in the residual organic waste samples were mainly hexoses (20–30%), with glucan constituting 80% of the total measured sugars (Figure 5.2). The sugar content determines the suitability of waste for bioethanol production. Recent studies evaluating bromatological composition reported that sugars are the main chemical component of MS-OFMSW (Campuzano and González-Martínez, 2016; Pecorini *et al*., 2020; Zamri *et al*., 2021), and
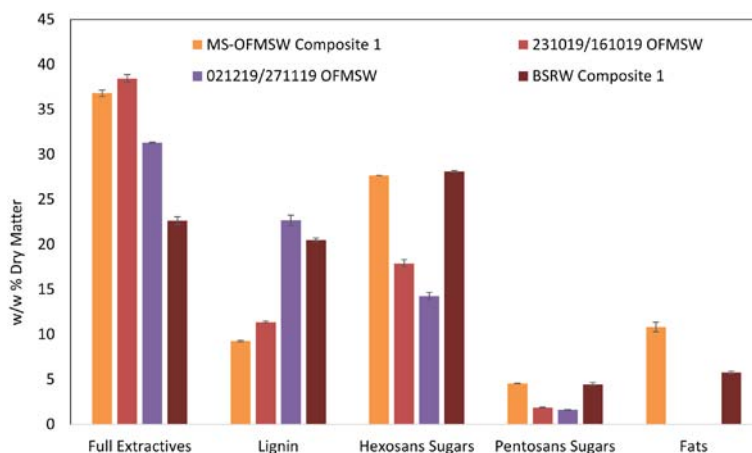
Figure 5.1. Bromatological analysis of MS-OFMSW and BSRW samples.
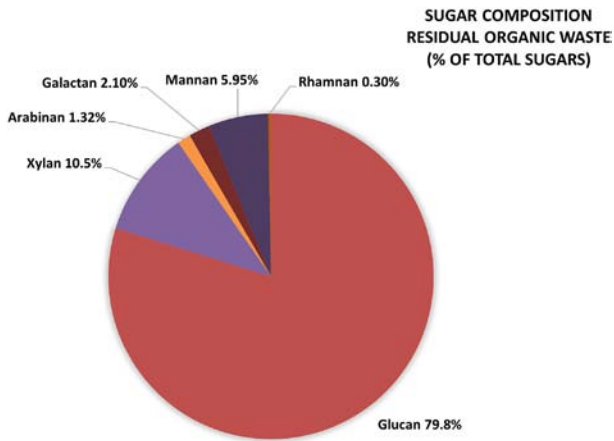
Figure 5.2. Composition of sugars (as a percentage of total sugars) in the residual organic waste (average of all MS-OFMSW and BSRW samples).

this was also found to be true here (Figure 5.1). Although the BSRW sugar content was similar to that of MS-OFMSW, the sugars in the former are likely to be recalcitrant and less prone to break down by enzymatic or thermal treatments. MS-OFMSW therefore represents an easily degradable sugar source with a high moisture content, which contributed to the choice of this material for bioethanol production.

Fat content is the main property required for biodiesel production, and the amount of fat in MS-OFMSW (10.8% DM) was almost twice that in BSRW (5.8% DM). Bromatological data show that the fat content of residual organic waste is highly variable. For example, source-segregated waste may contain a total of less than 4% fat (Pecorini *et al*., 2020), whereas the mean fat content of MS-OFMSW can be between 17.5% and 20% (Campuzano and González-Martínez, 2016; Paritosh *et al*., 2018). The production of biodiesel from residual organic waste is currently not considered a viable option because of immature technology and high production costs (Mizik and Gyarmati, 2021). Nevertheless, the bromatological analyses conducted here provide a valuable and in-depth assessment of mixed household organic waste that can be considered when deciding on a potential pathway for the sustainable use of this residual waste stream.

5.2 MS-OFMSW for Biomethane Production

The production of methane from MS-OFMSW is carried out globally. Our aim was to understand the potential of MS-OFMSW generated in Ireland to produce methane. In Ireland, only one facility, established in 2020, currently digests MS-OFMSW (https://www.energiagroup.com). Initial characterisation of MS-OFMSW samples showed moisture and organic compositions similar to that found elsewhere (Campuzano and González-Martínez, 2016) and indicated that MS-OFMSW produced in Ireland is a suitable feedstock for AD.

Biomethane potential analysis was carried out by the MaRei Research Centre, University College Cork (samples 070519, 040619 and 260619 MS-OFMSW), in accordance with the methodology described in Wall *et al.* (2013), and by NRM Laboratories, UK (samples OFMSW 251119 and 220221).

Under optimum incubation conditions, methane production reached a maximum value after 12 days of AD (Figure 5.3). The biomethane potential assay was conducted for a maximum of 28 days, representing the maximum digestion time in a commercial setting. A total of five MS-OFMSW samples were evaluated for biogas production.

The amount of methane generated ranged between 258 and 317 L CH_4/kg volatile solids (VS) (Table 5.1) and was similar to amounts reported in other recent studies using similar feedstocks (Scarlat *et al*., 2018; Moreno *et al*., 2021; Zamri *et al*., 2021). Biogas composition (methane and carbon dioxide) was evaluated in two samples (Figure 5.4). The ratio of methane to carbon dioxide in the biogas was, on average, 60:40, which is similar to that in biogas found in commercial plants (Pedro Machado, Braval Ecoparque, Portugal, 2019, personal communication) and reported elsewhere (Zamri *et al*., 2021). Hydrogen sulfide (H_2S) was not detected in the biogas, although, in a full-scale plant, trace amounts of nitrogen, ammonia, H_2S and water vapour would be expected (Migliori *et al*., 2019).

The results suggest that MS-OFMSW produced in Ireland is suitable for the production of biogas. In 2020, the first large-scale AD plant targeting MS-OFMSW commenced operation in Ireland, indicating that this material is a resource that can be used to generate green energy. However, the digestate from MS-OFMSW AD plants is unlikely to be used as a fertiliser because of the amount of impurities expected.
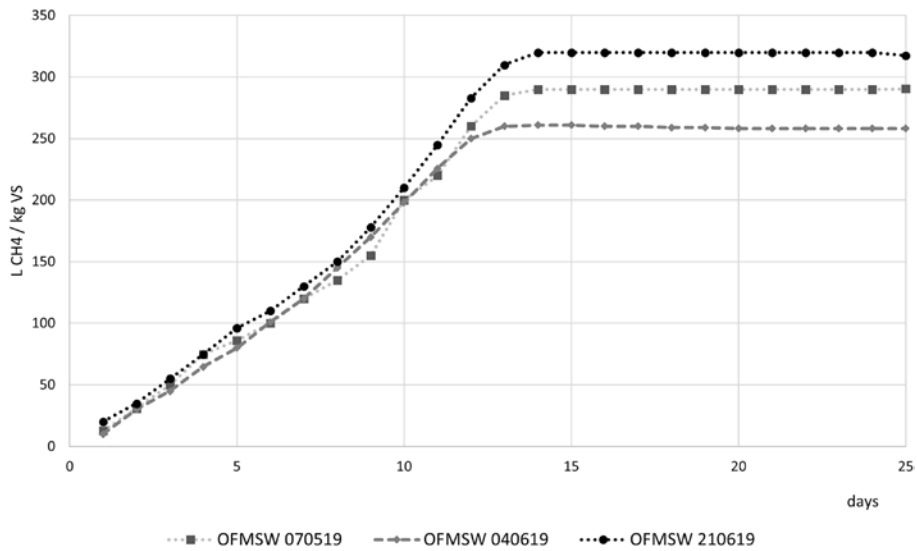
Figure 5.3. Specific methane yields from samples 070519, 040619 and 210619 MS-OFMSW over a period of 25 days at 37 °C.

Table 5.1. Biogas and methane (CH_4) yield from MS-OFMSW

MS-OFMSW samples	Volatile solids (VS) (%)	L gas/kg VS	L CH_4/kg VS	L gas/kg MS-OFMSW	L CH_4/kg MS-OFMSW
070519	28.01	483.8	290.3	136.4	81.9
040619	27.4	430.3	258.2	117.9	70.7
260619	27.5	529	317.4	145.5	87.3
251119	29.81	511	314	152	94
220221	30.8	485	298	149	92
Average ± standard error	28.7 ± 1.4	487.8 ± 33.4	295.6 ± 21.2	140.2 ± 12.3	85.2 ± 8.4
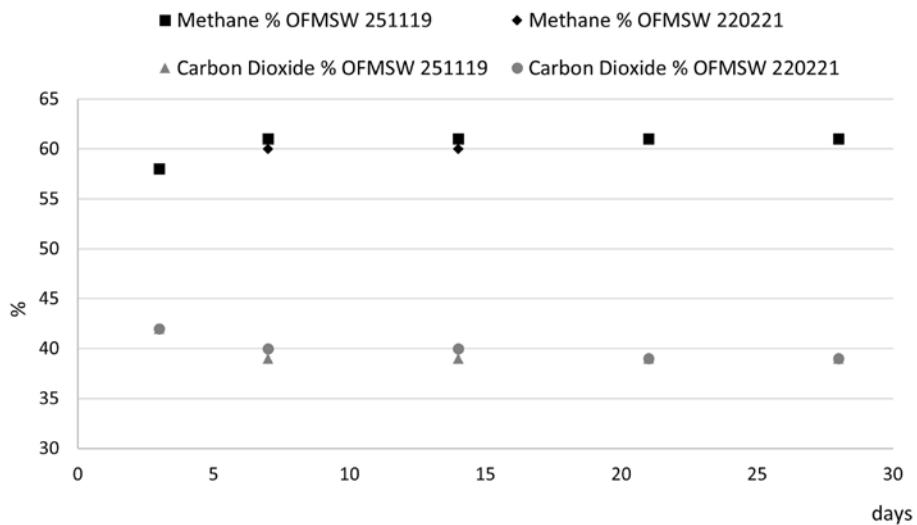
Figure 5.4. Changes in biogas composition during quantification of biomethane potential in MS-OFMSW samples.

5.3   MS-OFMSW and BSRW for Energy Production

Ultimate and proximate analyses of the residual organic waste (MS-OFMSW and BSRW) were carried out to understand the waste's potential for energy production. Because of its high moisture content, MS-OFMSW has less potential for energy production than BSRW, whereas the high ash content of BSRW presents a challenge. The BSRW 10–40 mm fraction was identified as a potential feedstock for energy production as a result of the high content of impurities and lower ash and moisture contents.

Six samples of BSRW 10–40 mm were analysed for ultimate and proximate analysis and calorific value (see Table 5.2), as were two composite samples of MS-OFMSW (see Table 5.3) and two composite samples of BSRW 0–10 mm (see Table 5.4). The two composite MS-OFMSW and BSRW samples comprised a homogeneous mixture of summer and winter samples.

The gross calorific value of the BSRW 10–40 mm fraction ranged between 13.1 and 15.6 MJ/kg (Table 5.2), presenting similar heating values to those reported in other studies (Agar *et al*., 2018; Yang *et al.*, 2018). On average, the ash and moisture contents of BSRW 10–40 mm were $26.0 \pm 6.6\%$ and $14.1 \pm 2.3\%$, respectively, considerably lower than the values for BSRW feedstock reported in previous studies (Yang *et al*., 2018; Kwapinska *et al*., 2020) and the MS-OFMSW and BSRW < 10 mm values

Table 5.3. Calorific value, proximate and ultimate analyses of MS-OFMSW (as sampled), taken as a summer and winter composite sample

Parameter (as sampled)	Summer	Winter
Ash (%)	24.4	21.8
Total moisture (%)	44.6	48.9
Volatile matter (%)	30.8	25.4
Sulfur (%)	0.2	0.4
Chlorine (%)	0.4	0.2
Gross calorific value (kJ/kg)	7391.0	7055.0
Net calorific value (kJ/kg)	5767.0	5405.0
Carbon (%)	19.7	20.2
Hydrogen (%)	2.5	2.1
Oxygen (%, dry analysis)	13.9	11.0
Nitrogen (%)	0.9	1.0

(Tables 5.3 and 5.4). Analysis of BSRW 0–10 mm showed that ash and moisture contents increased 1.5-fold and 1.3-fold, respectively, when compared with BSRW 10–40 mm, confirming that the < 10 mm fraction was responsible for most of the moisture and ash loading in BSRW. Analysis of seasonal variance using ANOVA, as described in Chapter 4, was carried out on the BSRW 10–40 mm samples collected in summer and winter. In summer, the feedstock had a significantly higher calorific value and chlorine content and a lower nitrogen content than in winter. Although caution should be applied in the interpretation of the seasonality analysis because of the small number of samples, the results demonstrate that seasonal

Table 5.2. Calorific value, proximate and ultimate analyses of BSRW 10–40 mm samples (as sampled)

Parameter (as sampled)	070519/090419	040619/040519	210619/210519	291019/021019	251119/111019	021219/161019
Ash (%)	18.9	27.6	19.0	22.4	31.4	36.9
Total moisture (%)	14.8	9.9	15.4	16.7	15.3	12.4
Volatile matter (%)	57.9	56.7	52.6	52.3	47.7	39.6
Sulfur (%)	0.24	0.25	0.29	0.28	0.38	0.44
Chlorine	0.92	0.82	0.78	0.49	0.39	0.35
Gross calorific value (MJ/kg)	15.4	15.6	15.0	14.5	13.1	13.2
Net calorific value (MJ/kg)	14.1	14.3	13.7	13.1	11.8	12.1
Carbon (%)	36.4	40.5	36.6	37.0	35.9	32.4
Hydrogen (%)	4.47	5.02	4.36	4.74	4.16	3.32
Oxygen (%, dry analysis)	28.2	16.9	27.2	20.6	13.0	14.7
Nitrogen (%)	1.2	1.49	1.31	1.67	1.85	1.67

Table 5.4. Calorific value, proximate and ultimate analyses of the BSRW <10 mm (as sampled), taken as a summer and winter composite sample

Parameter (as sampled)	Summer	Winter
Ash (%)	38.5	40.2
Total moisture (%)	19.3	18.2
Volatile matter (%)	30.3	34.7
Sulfur (%)	0.5	0.6
Chlorine (%)	0.7	0.3
Gross calorific value (kJ/kg)	11,940	9841
Net calorific value (kJ/kg)	10,882	8886
Carbon (%)	27.1	27.8
Hydrogen (%)	2.7	2.4
Oxygen (%, dry analysis)	12.7	11.0
Nitrogen (%)	1.7	1.7

changes in organic household waste can affect the calorific value of the feedstock. These changes need to be taken into consideration when designing further large-scale studies. The variability between summer and winter samples is likely to be linked to the organic waste's composition, as the impurity content (section 4.3) did not vary between seasons.

5.4 Use of BSRW as a Soil Amendment

To evaluate the use of BSRW as a soil amendment, the 0–10 mm fraction was used after any impurities had been manually removed. In a scenario where BSRW is generated in high quantities (section 6.3), the removal of impurities is crucial, and density and ballistic separators need to be used to achieve a usable and safe material with minimal physical

impurities. Although no European standards exist for soil improvers generated from mixed organic waste, the European Commission Working Document on Biological Treatment of Biowaste (European Commission, 2001) or Portuguese Decreto-Lei No 103/2015 (Ministério da Economia, 2015), which establishes compost classes and allows for the use of mixed organic waste, can be used as a guide for assessing the quality of BSRW as a soil improver. However, not all of the BSRW 0–10 mm fraction can be recovered as a soil amendment, since it contains glass, plastic, paper and other impurities that need to be removed (section 4.3).

The BSRW 0–10 mm fraction was proposed for use as soil improver, since it consists of more than 80% organic material and smaller amounts of impurities. Analyses of stability (EN 16087–1:2011), phytotoxicity (EN 16086–2:2011) and ecotoxicity were conducted along with an analysis of nutrients and metals.

Phytotoxicity trials were conducted using commercial cress and grass seeds in accordance with EN 16086–2:2011. Ten cress and 10 grass seeds were germinated in 50 mL plastic containers in duplicate, in a matrix of increasing concentrations of BSRW 0–10 mm blended with peat (volume per volume (v/v) of fresh material). Peat (100%) was used as a positive control. Cress seeds were germinated for 7 days (Figure 5.5) and grass seeds were germinated for 14 days (Figure 5.6). For the BSRW samples collected in the summer season, a wider range of BSRW–peat mixtures were included in the toxicity study to understand the effects of BSRW on plant growth. Results are expressed on a v/v of fresh material basis. The control showed ≥90% germination in all trials,
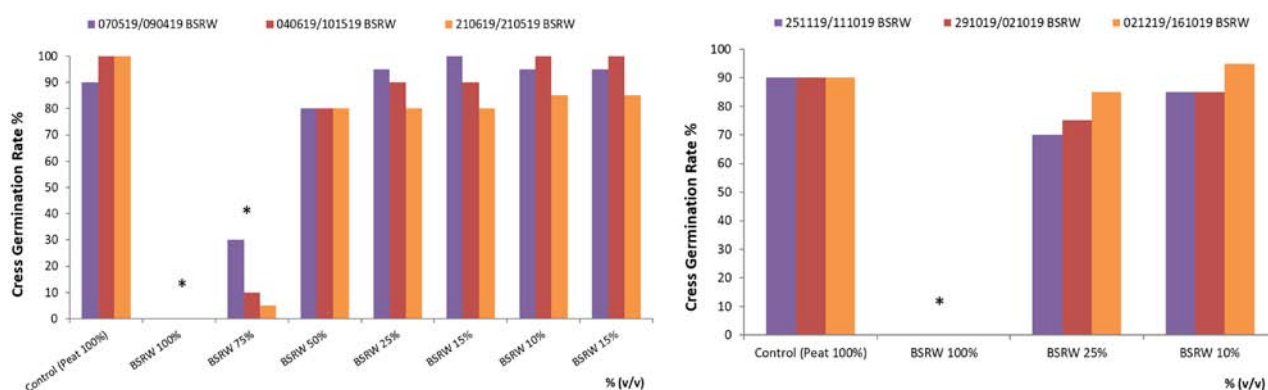
Figure 5.5. Cress seed germination rates using BSRW <10 mm in varying concentrations, day 7 of germination.

whereas no germination was observed in the 100% BSRW samples. The cress germination rate was ≥80% with BSRW incorporated at concentrations of 5–50% (v/v), indicating no toxic effects from BSRW up to 50% (Figure 5.5).

The germination rates of the grass seeds (Figure 5.6) were similar to those of the cress seeds, with BSRW concentrations ranging from 5% to 25%. Overall, the germination rates of the cress and grass seeds were severely affected only when BSRW was used at concentrations of 75% or 100%. It was expected that seed germination would be limited at concentrations of 75–100% BSRW. Pure BSRW, or green compost, is not suitable for seed germination because of its high electrical conductivity and salt content, both of which affect seed germination (see Chapter 3 and Table 3.3). This is in line with other studies performed on garden waste compost as a growing media (Prasad and Maher, 2001).

The ecotoxicity of BSRW was studied using the earthworm species *Dendrobaena veneta* (Kapanen and Itävaara, 2001). An avoidance test was initially conducted to determine whether garden soil (blended with 10% v/v horticultural sand) or peat was the more suitable control in the ecotoxicity trials (Loureiro *et al*., 2005). The earthworms did not show a preference for either substrate, and the mortality with both was equivalent to 20% (data not shown). Results are expressed on a v/v of fresh material basis. Two toxicity tests (Elliston and Oliver, 2019) were therefore conducted for the 0–10 mm BSRW fraction blended with either garden soil or peat. In the first test (toxicity test 1), soil (blended with 10% v/v horticultural sand) was used. BSRW was blended with the soil at

concentrations of 5–25% v/v of fresh material, and peat (blended with 10% v/v sand) was used as the control (Figure 5.7). In the second experiment (toxicity test 2), soil was replaced with peat (Figure 5.8). Each test was conducted in 1 L opaque plastic buckets, which were perforated to allow air exchange, using five worms and in triplicate. During the experiments, moisture was controlled by measuring the loss of weight from the bucket over the week and adding water if needed. The experiments were carried out in a room with controlled temperature (20–22°C). The worms were fed 2 g of cooked oats each week (Elliston and Oliver, 2019); the mortality of the earthworms was monitored for a period of 3 weeks.

The mortality values between replicate samples were highly variable, regardless of the substrate or concentration of BSRW. Figure 5.7 outlines mortality over a 3-week period for worms in soil and soil–BSRW mixtures. Mortality is slightly lower in the 75% soil–25% BSRW mixture than in the 100% soil samples, but lower concentrations of BSRW result in higher mortality. This anomalous result can possibly be explained by the variance in triplicate results and worm heterogeneity. When peat was used as the substrate (Figure 5.8), worm mortality was lower in 100% peat than in 100% soil. The three peat–BSRW mixtures resulted in lower mortality than 100% peat. The results suggest that the soil has a detrimental effect on the worms, but, for the peat mixtures at least, the addition of BSRW does not result in higher mortality.

Oxygen uptake rate (OUR) is the stability method used in the EU Fertiliser Regulation (EU, 2019). OUR is an indicator of compost stability and microbial activity. A threshold OUR of 25 mmol O_2/kg OM/hour
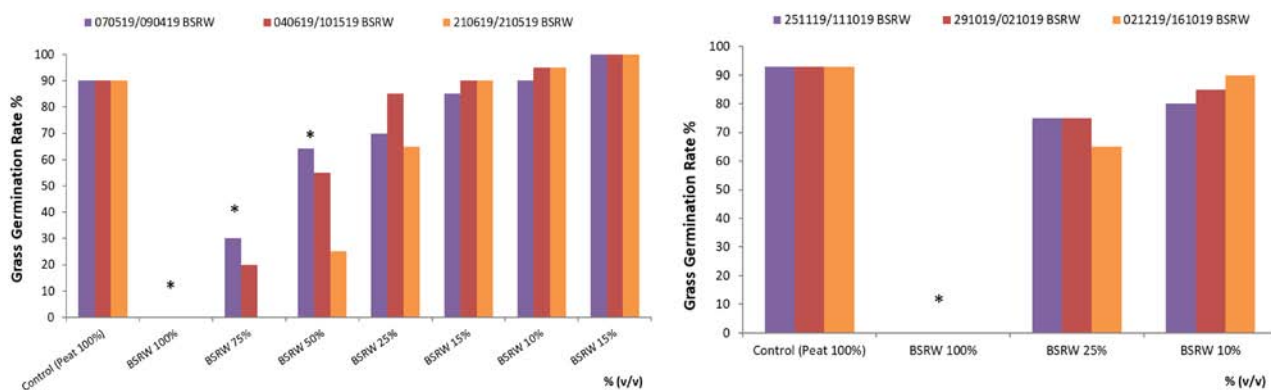
Figure 5.6. Grass germination rates using BSRW < 10 mm in varying concentrations, day 14 of germination.
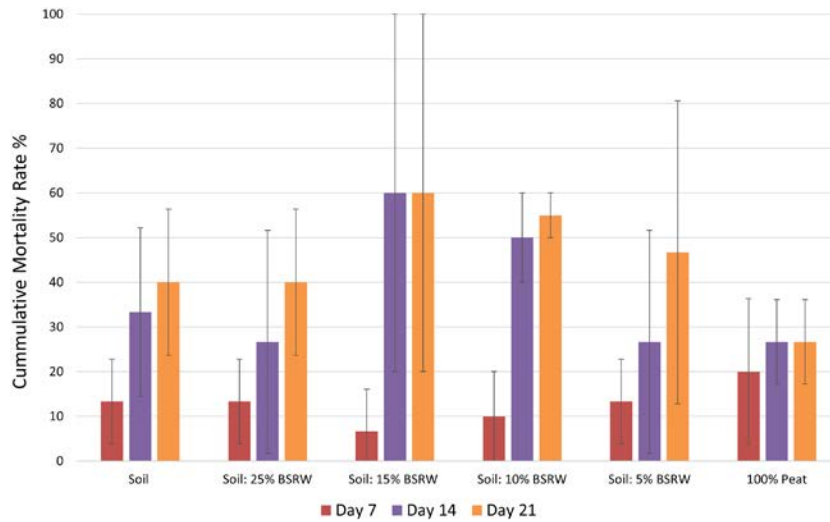
Figure 5.7. Cumulative worm mortality in toxicity test 1. Error bars represent standard deviations.
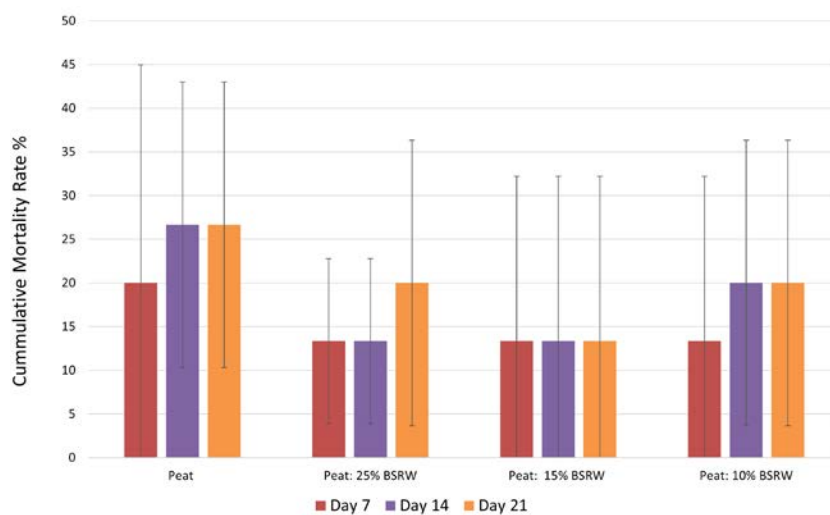
Figure 5.8. Cumulative worm mortality in toxicity test 2. Error bars represent standard deviations.

is recommended as an indicator of compost suitable for land application (EU, 2019; Foster and Prasad, 2021). All samples from the CLO fraction (derived from BSRW < 10 mm) presented an OUR below 25 mmol O_2/kg OM/hour, indicating that the BSRW is within the limits and presents a good source of active organic matter (Table 5.5).

The metal content of the BSRW samples was consistent with that in previous studies (Epelde *et al*., 2018) and similar to that reported for sewage sludge (Smith, 2009). We used the maximum acceptable metal concentration for sewage sludge for land application as a comparator in this work. As shown in Table 5.6, Metal concentrations in the BSRW samples

Table 5.5. Oxygen uptake rate measured in the BSRW samples

BSRW < 10 mm	OUR (mmol O_2/kg OM/hour)
070519/090419	17.5±0.09
040619/140519	15.1±0.14
210619/210519	17.8±0.30
291019/021019	15.2±0.39
251119/111019	20.7±0.96
021219/161019	14.9±1.30
Regulation (EU) 2019/1009 threshold value	25.0
Foster and Prasad (2021) threshold value	25.0

Table 5.6. Nutrient, organic matter and metal concentrations (n=3) measured in BSRW samples (values represent mean values±standard errors for each paramenter)

Parameters (DM)	070519/090419[a]	040619/040519[a]	210619/210519[a]	291019/021019[a]	251119/111019[a]	021219/161019[a]	Maximum permitted by S.I. No. 148/1998[b]
Organic matter (%)	48.9±0.9	59.8±1.60	59.6±1.2	49.5±1.4	58.9±4.2	51.5±0.3	
Total carbon (%)	30.91±1.56	31.11±2.07	24.21±0.14	32.9±0.5	33.34±0.36	29.16±0.47	
Total nitrogen (%)	2.21±0.11	2.37±0.24	1.88±0.09	2.36±0.08	2.09±0.08	1.98±0.05	
Carbon-to-nitrogen ratio	13.99±0.01	13.20±0.44	12.90±0.54	13.87±0.64	14.52±0.39	14.72±0.17	
Nutrients (g/kg)							
Phosphorus	4.83±0.20	4.17±0.14	4.33±0.05	3.84±0.07	4.21±0.12	4.27±0.20	
Potassium	3.87±0.13	3.20±0.06	3.42±0.11	3.09±0.04	3.38±0.09	3.50±0.03	
Magnesium	3.12±0.47	5.84±017	6.07±0.29	5.58±0.39	6.81±0.53	5.83±0.78	
Calcium	7.97±0.48	12.7±0.60	12.6±1.38	13.1±0.84	15.7±0.81	12.3±1.32	
Sodium	8.27±0.59	5.79±0.21	5.92±0.25	5.42±0.06	6.80±0.22	6.65±18	
Metals (mg/kg)							
Aluminium	11.05±0.76	11.29±0.90	10.90±0.36	14.82±0.25	20.39±1.16	17.44±0.43	–
Cadmium	5.78±0.74	3.21±0.07	2.22±0.08	6.88±0.66	2.83±0.20	3.01±0.34	20
Chromium	29.26±9.38	24.86±2.42	21.10±2.83	35.94±2.34	40.18±4.92	27.16±2.90	–
Copper	130.2±9.86	221.4±1.00	250.9±10.4	250.5±10.4	361.0±25.5	416.4±7.63	1000
Nickel	32.02±1.75	56.53±3.87	52.62±5.80	37.80±3.88	47.36±3.63	62.94±5.60	300
Lead	215.2±4.69	269.8±16.9	247.4±26.9	178.9±18.1	223.9±13.5	295.1±26.0	750
Zinc	389.9±5.09	569.9±41.9	536.8±36.9	580.5±30.6	687.1±42.7	526.9±27.4	2500

[a]Mean values ± standard errors are given for each parameter.

[b]Waste Management (Use of Sewage Sludge in Agriculture) Regulations, 1998.

were below threshold values for sewage sludge in Irish legislation (S.I. No. 148/1998).

Analysis of the summer and winter samples showed small variations in the properties of BSRW between seasons. Phosphorus content in BSRW samples was higher in the summer, whereas no other nutrients showed significant differences. For metal concentrations, winter BSRW samples showed higher contents of aluminium, chromium, copper and zinc; the other elements showed no statistically significant differences in concentrations between sampling seasons. Organic contaminants were not analysed in this work; however, historical data for PAHs and PCBs can be found in section 3.1. Research has demonstrated that composting is effective in the degradation of PAHs and PCBs from MS-OFMSW (Graça *et al*., 2021). However, concerns remain about the potential for soil and water contamination from the use of BSRW on land. These concerns are addressed in Chapter 9, where the leaching of metals and nutrients from the application of sewage sludge and BSRW are discussed, as is the potential for BSRW to increase background metal concentrations in soil.

6   Laboratory-scale Bioethanol Production with PERSEO Bioethanol®

The potential for bioethanol production from MS-OFMSW was investigated using a patented process involving a 50 L pilot reactor in the PERSEO Bioethanol® biorefinery facility in Valencia, Spain. To carry out this experiment, a 50 kg sample of MS-OFMSW was collected between October and November 2020 by sampling 10 delivery trucks. The impurities were removed by hand, accounting for 26% (on a fresh weight basis), and the sample was frozen before shipping. The sample was shipped by special carrier using 24-hour delivery. The composition analysis for this study was based on the previous bromatological analysis carried out (see Chapter 5). The process consisted of pre-treating the raw material (Figure 6.1) by removing impurities and simultaneous saccharification and fermentation (SSF) to produce bioethanol from the sugars contained in the substrate. Impurity content is not accounted for in the bioethanol production results presented. PERSEO Bioethanol® recommends a maximum impurity content of 10% for an optimum ethanol yield, which would necessitate the use of mechanical pre-treatment methods to remove impurities.

The pilot fermentation assay was carried out with milled MS-OFMSW (15.5 kg as received) and water (24.5 kg) to achieve a MS-OFMSW solid concentration of 20%. This was added to the 50 L reactor (Figure 6.2), with constant stirring at 150 rpm for 48 hours, along with additives (nutrients, enzymes, yeasts, acid-base) and under temperature- and pH-controlled conditions. The analysis of the bioethanol production over time in the reactor was carried out using high-pressure liquid chromatography.

The maximum concentration of bioethanol was reached after 40 hours of SSF (17.04 ± 0.16 mL/L) (Figure 6.3). Using the lower glucan content (12.7%) measured in VALOR project samples (section 5.1) to estimate the conversion of this polysaccharide into bioethanol, the conversion rate was 74%, which can be considered a typical value from this process. The production of bioethanol per tonne of MS-OFMSW can be estimated (Table 6.1) according to the lower and higher sugar content measured in the raw material. It was estimated that a production yield of between 35 and 70 L of bioethanol per tonne of MS-OFMSW (on a fresh material basis) could be produced using the PERSEO process, depending on the glucan content. The ethanol produced in this study was similar to that produced in the study by Moreno *et al*. (2021) using the same process.

To the best of our knowledge, no commercial biorefinery in Europe currently produces bioethanol from MS-OFMSW. Care must be taken when evaluating these findings, as this is a single study, and therefore the results presented should serve as a guideline for future investigation. The high initial investment required and the financial risks associated with the volatility of both the biofuel and the waste market represent major barriers to implementing this

Figure 6.1. Pre-treatment (milling and homogenisation) of the MS-OFMSW prior to fermentation.

Figure 6.2. Loading of the pilot reactor (left) and the resulting homogeneous aqueous organic mixture (right).
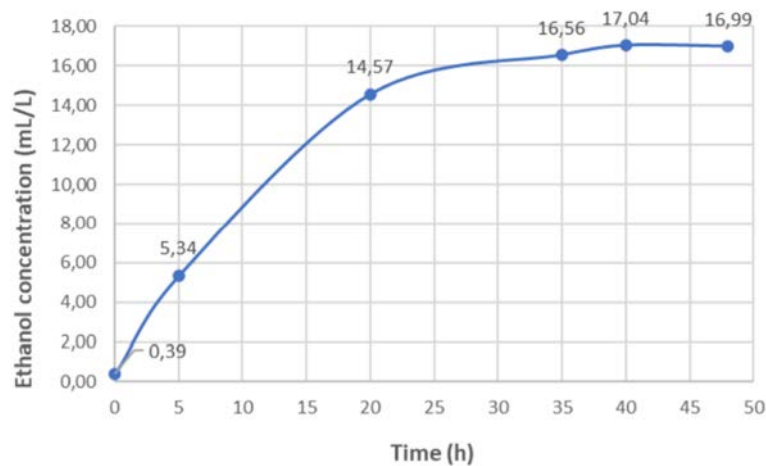
Figure 6.3. Changes in the bioethanol concentration in the 50 L reactor.

Table 6.1. Estimated ethanol production in the pilot-scale assay, assuming lower and higher glucan values measured in the MS-OFMSW samples by the VALOR project

Glucan content (%, DM)	Ethanol produced (L/t MS-OFMSW)	
	As analysed	DM basis
12.7	34.9	67.4
25.6	70.4	136.4

and other new technologies. Bioethanol is currently produced from starch- and sugar-based feedstocks with high conversion efficiencies. However, these feedstocks are often under scrutiny because of competition with food markets (Muktham *et al*., 2016). The EU's renewed emphasis on resource recovery and the pressure to increase the amount of bioethanol blended in petrol, along with tighter targets on the landfilling of organic waste, reinforce the need to conduct further pilot and large-scale experiments to ensure the reproducibility of the results achieved for bioethanol production and the commercial feasibility of the process using MS-OFMSW as a feedstock.

7   Laboratory-scale Pyrolysis Using the 10–40 mm Bio-stabilised Residual Waste Fraction as Feedstock

To evaluate the use of BSRW as a potential feedstock for energy production, our approach consisted of using the 10–40 mm fraction of BSRW for energy production and material recovery (e.g. biochar). This material contained lower moisture and ash contents and therefore had a higher energy potential.

The objectives of this experiment were to evaluate the suitability of BSRW 10–40 mm as a feedstock for pyrolysis and the reuse of the biochar produced for high-value applications. To investigate the production of high-quality biochar from the subsequent pyrolysis, we compared the biochar generated from the BSRW with compost oversize from the composting of source-segregated green waste. The BSRW 10–40 mm samples collected over the winter months were chosen for this pyrolysis experiment, as they were likely to have less favourable characteristics, such as lower heating value and higher moisture and ash contents, than those collected in summer. Compost oversize and the 1:1 (v/v) mixture of BSRW 10–40 mm and compost oversize were also pyrolysed. Prior to pyrolysis, because of the diversity of materials in the residue and the maximum reactor volume, samples were homogenised and particles reduced to a workable size using a blender. Inert materials (e.g. glass, metals, stones) were removed by hand, taking into account that only small amounts of material could be pyrolysed. The moisture and ash contents of the samples were measured prior to pyrolysis (Table 7.1). Pyrolysis was carried out using laboratory-scale equipment in accordance with a procedure optimised by the University of Limerick (Kwapinska et al., 2020).

For the BSRW 10–40 mm samples (Figure 7.1), the char yield ranged between 43.6% and 51.2%, whereas the char yield from the pyrolysis of wood with or without BSRW 10–40 mm was between 45.9% and 48.8%. A limitation inherent to this study was the preparation of the feedstock prior to pyrolysis (e.g. inert material removal, size reduction, sample storage), which led to changes in the moisture and ash contents (Table 7.1). Inert content removed from the BSRW 10–40 mm fraction before pyrolysis corresponded to 22.4–24.2% DM, with the main components removed being glass and construction and demolition waste. These materials had to be removed because of the limited sample size that could be pyrolysed by the laboratory system. In a pilot-scale system, the removal of impurities should be further tested to better understand the efficiency of the BSRW 10–40 mm fraction as a pyrolysis feedstock. The removal of impurities in this scenario should be considered. Since biochar density is low compared with inerts that remain after the pyrolysis process, such as stones, glass and metals, further processing of biochar is facilitated. In the laboratory-scale process, inert material needed to be removed prior to pyrolysis. Despite this limitation, the aim of the study was to generate feedstock with a moisture content of < 30% to make the process technically feasible for the BSRW 10–40 mm fraction.

Compost oversize generated the largest gas yield (52.7% w/w DM) and the smallest oil yield (1.4% w/w DM) of all the feedstocks examined (Figure 7.1), indicating that this material could be used to produce

Table 7.1. Moisture and ash contents of feedstock samples immediately prior to pyrolysis

Pyrolysis feedstock		Moisture (%)	Ash (%, fresh sample)	Ash (%, DM)
BSRW 10–40 mm	251119/111019	26.7	20.8	28.4
	021219/161019	15.1	27.0	31.8
	291019/021019	23.4	21.2	27.7
Compost oversize		51.7	8.0	16.6
1:1 (v/v) mixture of BSRW and compost oversize		39.1	13.5	22.1
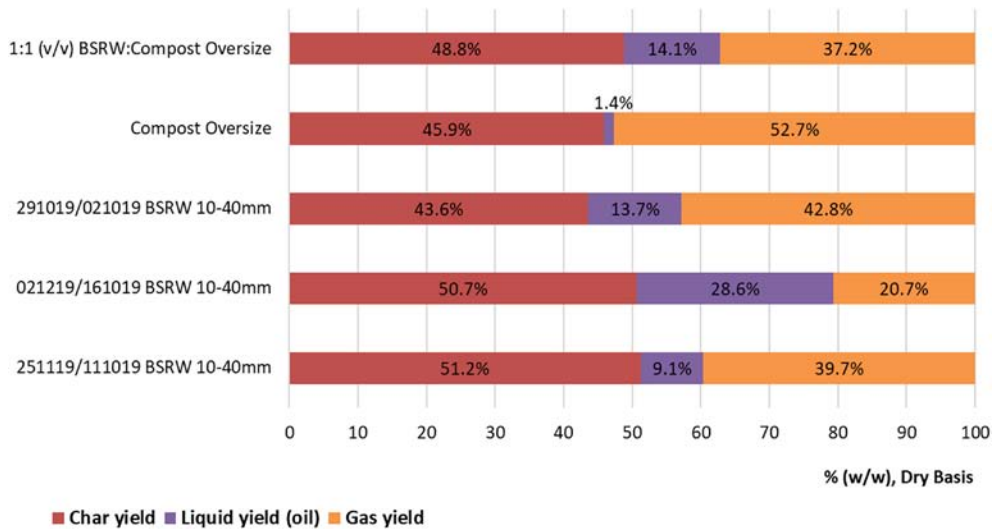
Figure 7.1. Average product distribution from pyrolysis of samples of BSRW 10–40 mm, compost oversize and 1:1 (v/v) mixture of BSRW and compost oversize at 700°C for 10 minutes.

gas and char. As reported by Kwapinska *et al*. (2020), oil generation depends on the gas treatment and the reactor size. In pilot-scale experiments, it is expected that the oil content measured will be higher than that in large-scale plants, since in the latter the gas travels a longer distance before cooling down and will be subject to further treatment, such as cracking, reducing oil generation.

The syngas collected from the pyrolysis of BSRW had a relatively similar composition across the samples, regardless of the use of compost oversize (Figure 7.2). The combustible fraction of syngas, made up of

hydrogen (H_2), methane (CH_4) and carbon monoxide (CO) and hydrocarbons, equated to approximately 60% of the syngas total composition. As a result of analytical limitations, the chlorinated compounds and ammonia (NH_3) content in the syngas were not determined.

The syngas obtained from the pyrolysis of the BSRW 10–40 mm fraction showed a heating value of 18 MJ/m³. By contrast, samples of compost oversize generated syngas with a lower calorific value. The composition and heating value of the syngas from the pyrolysis of organic municipal waste depends on
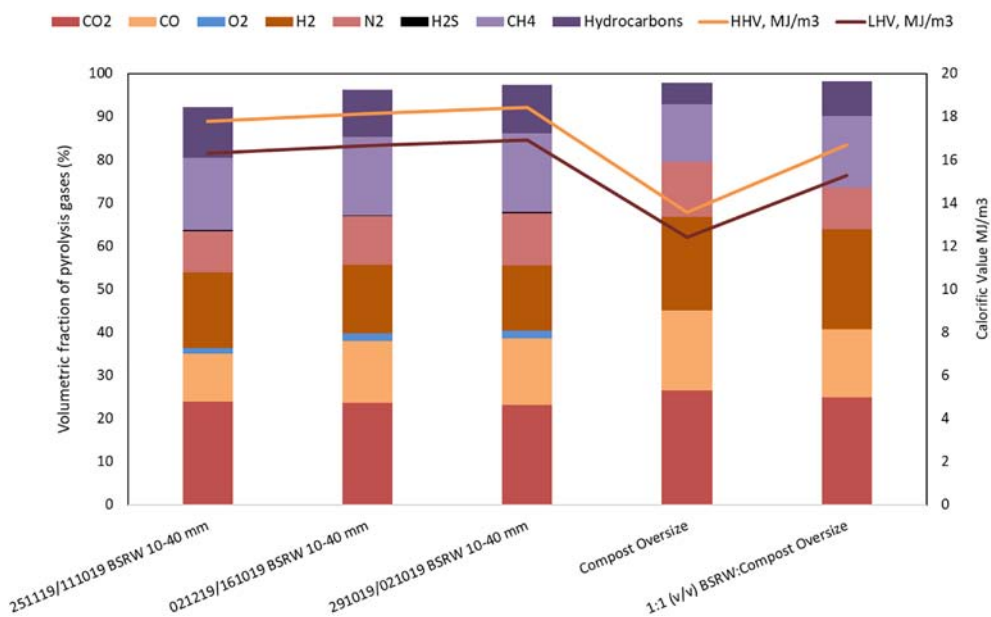
Figure 7.2. Pyrolysis gas composition and calorific value of syngas.

the temperature of the process (Yang *et al*., 2018; Palma *et al*., 2020) and the pre-treatment of the organic waste (Agar *et al*., 2018). Previous studies have shown that, when organic waste is subject to composting, the gas yields and calorific value improve with the reduction in moisture content (Agar *et al*., 2018; Palma *et al*., 2020). Our study confirmed that BSRW 10–40 mm shows significant potential for recovery by pyrolysis following the in-vessel composting treatment.

This process would contribute to the generation of electricity from waste materials, which would otherwise be landfilled, and would also generate other valuable products, such as bio-oil and biochar.

The biochar generated by the pyrolysis of BSRW was evaluated for its suitability for use in agriculture/on land and as an adsorbent. The European Biochar Certificate standards and Regulation (EU) 2019/1009 (EU, 2019) were used to assess biochar quality in relation to heavy metal content (Table 7.2) and assess the potential uses of the biochar product.

Previous studies show that biochar produced from residual waste could be used as a soil amendment and carbon-sequestering material (Jindo *et al*., 2020). Biochar is also utilised in an extensive range of applications such as an animal feed additive, a slurry treatment, an additive in AD, a low-cost adsorbent for water, waste water and gas treatments, and a fuel-like material (Bartoli *et al*., 2020; Gwenzi *et al*., 2021).

In this study, the biochar generated by the pyrolysis of the BSRW 10–40 mm fraction was tested for its suitability for use on land, and the Brunauer–Emmett–Teller (BET) surface area was determined to assess its

potential use as an adsorbent. Biochar pH, electrical conductivity, and organic matter and macronutrient (nitrogen, phosphorus, potassium, magnesium and calcium) concentrations are important parameters for assessing suitability for agricultural use (Table 7.3). Biochar is generally alkaline, which is linked to feedstock characteristics and pyrolysis temperature and also affects the material carbon structure (Tomczyk *et al.*, 2020). The alkaline pH of the biochar and the calcium, potassium and magnesium cation contents provide an opportunity to use this material as a liming agent (Bolan *et al*., 2022). The carbon content of the BSRW 10–40 mm biochar ranged between 30% and 34%, whereas carbon in the biochar from samples with compost oversize increased to >50%. If used in soil, biochar is unlikely to contribute to the meaningful supply of nutrients; however, its carbon content and high stability have been shown to contribute to soil sequestration of carbon (Callegari and Capodaglio, 2018; EBC, 2020).

The BET surface area ranged between 17.3 and 32.8 m^2/g (Table 7.3), which is consistent with the biochar surface areas obtained from other organic amendments (Jin *et al*., 2014) and MSW (Ndirangu *et al*., 2019) prior to activation. Previous studies have shown that biochar produced from OFMSW is suitable for removing organic pollutants from landfill leachate (Jin *et al*., 2014; Jayawardhana *et al*., 2019). The performance of adsorption experiments would be important to provide a better understanding of the efficiency of removal of organic and inorganic pollutants from waste water.

The metal content of the biochar generated from the pyrolysis of BSRW complies with the metal

Table 7.2. Metal concentrations allowed in biochar according to the European Biochar Certificate and Regulation (EU) 2019/1009

Metal (DM mg/kg)	European Biochar Certificate		Regulation (EU) 2019/1009
	Agriculture	Material (fuel/adsorbent)	
Arsenic	13	15	40
Cadmium	1.5	5	2
Chromium	90	250	Na
Copper	100	250	300
Lead	150	250	120
Mercury	1	1	1
Nickel	50	250	50
Zinc	400	750	800

Table 7.3. Elemental composition, metal content and BET surface area of biochar produced

% (fresh matter)	251119/111019: BSRW 10–40 mm	021219/161019: BSRW 10–40 mm	291019/021019: BSRW 10–40 mm	Compost oversize	1:1 (v/v) BSRW and compost oversize
pH	10.6	10.2	10.6	9.8	10.2
EC (µs/cm)	1427	1979	1845	527	1979
Organic matter	39.2	25.8	43.9	67.7	50.4
Moisture	2.3	2.1	2.5	2.1	2.3
Ash	62.3	52.8	55.6	37.2	58.4
Sulfur	1.03	1.96	0.78	0.22	0.45
Carbon	30.6	34.1	29.9	58.0	51.1
Nitrogen	0.62	0.93	0.98	0.88	1.05
Phosphorus	0.69	0.65	0.78	0.19	0.54
Potassium	1.78	1.74	1.54	1.86	1.81
Magnesium	1.12	1.00	0.91	0.2	0.45
Calcium	14.7	8.8	9.1	2.9	6.1
BET surface area (m²/g)	26.1	32.8	17.9	17.3	27.4
Arsenic	5.5	8.4	3.8	2.8	9.3
Cadmium	1.3	1.5	1.3	0.5	8.5
Chromium	30.5	34.1	87.9	5.1	68.7
Copper	341	464	175	27.5	186
Lead	163	60.5	53	17	49.1
Mercury	<0.1	<0.1	<0.1	<0.1	<0.1
Nickel	45.7	69.9	27.2	7	38.4
Zinc	492	470	447	100	368

EC, electrical conductivity.

concentrations permitted by the European Biochar Certificate and Regulation (EU) 2019/1009 in biochar produced from source-segregated wastes (Table 7.2), meaning that the biochar generated is suitable for both land and non-land applications. Organic pollutants were not evaluated in the biochar samples produced; however, the PAH and PBC contents of MS-OFMSW are relatively low (section 3.1) and subject to degradation during the composting process (Graça *et al.*, 2021). The pyrolysis process uses high temperatures, which transforms undesirable materials such as plastics, non-recyclable paper and textiles. Furthermore, the inert content remaining in the biochar (glass, metals, stones) is easily removed with density separation at a commercial level.

8   Validation of the Use of Bio-stabilised Residual Waste as a Soil Amendment

8.1   Case Study I: BSRW in Soil Manufacturing for Landfill Final Capping

In 2013, Enrich Environmental set up a trial, in partnership with an industrial site where extracted waste has been deposited and that is regulated by the EPA, to determine the suitability of manufactured topsoil as a capping material on a licensed site. The main objectives of this trial were to:

- determine if BSRW can be incorporated with subsoil to create a suitable topsoil for landfill capping;
- determine the suitability of BSRW for growing grass for use in landfill restoration;
- investigate the potential environmental risks of using topsoil manufactured from BSRW for landfill restoration.

Three cells were established at the landfill site, situated away from ongoing restoration works and gas collection infrastructure. The control cell contained topsoil (200 mm) that was being used for restoration elsewhere at the site; a test cell contained manufactured soil (200 mm), comprising subsoil (used *in situ*) and 30% (v/v) BSRW 0–10 mm; and a third cell contained only subsoil (Figure 8.1). For the purpose of this study, only topsoil and manufactured soil were investigated. The manufactured soil properties are presented in Table 8.1. *In situ* topsoil used properties are presented in Table 8.3, referring to 2013 data.

In 2019, soil and grass samples were collected from the topsoil and manufactured soil cells to conduct a long-term evaluation, using earlier data for comparison. No chemical fertiliser or organic amendment applications had been applied to the plots.

Figure 8.1. View of the three landfill capping cells at installation and establishment of grass in 2013.

Table 8.1. Properties of manufactured soil comprising subsoil used *in situ* and 30% (v/v) BSRW

Soil parameter (DM)	Manufactured soil – test cell
Texture	
Clay (%)	23
Silt (%)	31
Sand (%)	46
Texture class	Clay loam
pH and organic matter, nutrient and metal contents	
Soil pH	8.1
Organic matter (%)	11.3
Total nitrogen (%)	0.65
Available phosphorus (mg/L)	57.6
Available phosphorus (mg/L)	1214.6
Available phosphorus (mg/L)	206.9
Carbon-to-nitrogen ratio	10.1
Total zinc (mg/kg)	212
Total copper (mg/kg)	74.7
Impurities	
Visible (> 2 mm) (% w/w)	0.18
Plastics (> 2 mm) (% w/w)	0.03

In this experiment, BSRW was the only ingredient used in the manufacturing of the topsoil (cell 2).

As expected when manufacturing a semi-natural ecosystem, the amount of available nutrients had decreased since the start of the experiment in 2013. Nevertheless, the manufactured soil (cell 2) contained higher levels of available nutrients than the topsoil (cell 1) (Table 8.2), which could contribute to maintaining the long-term growth of grass. The manufactured soil showed a higher available nutrient content in 2013 and in 2019 than the topsoil. Organic amendments increase the availability of nutrients in the soil and also improve the capacity of the soil to retain nutrients by natural cycling. This is due to the introduction of beneficial microorganisms and improvements in soil aggregation (Domínguez *et al*., 2019).

The organic matter level was 45% higher in the manufactured soil than in the topsoil and did not change in the 6-year period of the trial (2012–2019). This suggests that the addition of organic matter from BSRW could remain in a non-disturbed system in the long term and contribute to the accumulation of soil carbon.

Grass nutrient uptake in 2013 and 2019 was similar in the manufactured soil and topsoil (Table 8.3). The manufactured soil (with BSRW) used for final capping supplied approximately the same amount of nutrients for grass growth and for topsoil after 1 year and after 6 years. Metal concentrations in the grass in 2019 were lower overall than in 2013, regardless of the soil used. The range of metal concentrations in grass in the trial were in the lower ranges of reference values for metals found in herbage elsewhere (Ross *et al*., 2007). Concentrations of nickel and chromium in the grass from both cells increased from 2013 to 2019, which could potentially be explained by deposition onto herbage; nevertheless, the herbage values for these metals in the trial were low relative to reference values.

This 6-year field trial demonstrated that 0–10 mm BSRW blended with subsoil can be used to manufacture a soil capable of supporting vegetative growth over a prolonged period of time. The grass produced in the manufactured soil cell was of similar composition and nutritional content to grass produced on agricultural grasslands. This study showed that the use of BSRW improved the soil organic matter content and sequestered organic carbon in the soil over the long term.

Table 8.2. Soil parameters of the topsoil (cell 1) and manufactured soil (cell 2) in 2013 and 2019 in the BSRW long-term landfill final capping trial

	Topsoil		Manufactured soil	
Soil parameters	**2013**	**2019**	**2013**	**2019**
Organic matter (% DM)	7.00	6.02	11.3	11.7
Available phosphorus (Morgan's mg/L)	3.40	2.90	57.6	34.6
Available potassium (Morgan's mg/L)	61.5	46.4	1214.6	130
Available magnesium (Morgan's mg/L)	70.3	57.7	206.9	235

Table 8.3. Grass parameters analysed for the topsoil (cell 1) and manufactured soil (cell 2) in 2013 and 2019 in the BSRW long-term landfill final capping trial

Grass parameters (DM)	Topsoil		Manufactured soil		Range in rural herbage[a]	Maximum allowed in animal feed[b]
	2013	2019	2013	2019		
Total nutrients (%)						
Nitrogen	4.87	1.85	4.79	1.79		
Phosphorus	0.39	0.27	0.31	0.25		
Potassium	4.48	1.36	3.64	1.07		
Sulfur	0.35	0.17	0.33	0.18		
Metals (mg/kg)						
Copper	19.5	5.50	19.4	5.10	2.49–29.9	50
Zinc	85.8	21.7	53.2	25.1	14.7–114	100
Lead	1.66	0.53	1.83	0.75	0.47–84	5
Nickel	1.90	3.30	3.60	4.00	1.0–13.1	–
Cadmium	0.23	0.09	0.19	0.15	0.1–1.43	0.5
Mercury	0.00	0.02	0.01	0.01	0.07–0.2	–
Chromium	0.60	3.50	0.70	2.60	1.0–24.5	–

[a]**Ross** *et al.***, 2007.**

[b]**Commission Regulation (EU) No 1275/2013 of 6 December 2013.**

8.2 Case Study II: Restoration of Soils and Water Quality Evaluation

The restricted use of BSRW is linked to the potential for organic and inorganic contamination. Nevertheless, BSRW has the potential to be reused and recycled within a circular economy context. For instance, controlled use on land would offset carbon emissions by diverting the organic material from incineration or landfill, resulting in a carbon-positive soil additive. A leachate trial was established to evaluate the potential for metal and nutrient leaching through land application of BSRW and sewage sludge.

The aim was to assess the risk of using BSRW as a soil amendment (0–10 mm fraction) by monitoring runoff from the test site for metal and nutrient content. Leaching trials were conducted over 6 months on a forest soil (20 cm depth, approximately 200 kg) with a history of Sitka spruce plantation (approximately 20 years). Four treatments were established in duplicate: (1) control, (2) sewage sludge chemically stabilised (10 t/ha DM), (3) BSRW at 10 t/ha DM and (4) BSRW at 25 t/ha DM. Adapted water storage tanks (1000 L capacity) were set up to conduct the experiment (Figure 8.2). Commercial grass seeds were used and sowed at a rate in line with the

supplier's instructions. BSRW impurities were removed manually prior to its use in the trial. BRSW and sewage sludge were incorporated at 10 cm depth.

Leachate was collected every week for the first 2 months and monthly thereafter. Rainfall data were collected from the Met Éireann website using the Dunsany Weather Station, approximately 1 km from the trial site (Figure 8.3). Sewage sludge was sourced from a waste water treatment plant and chemically stabilised using lime (10% v/v), simulating the main pre-treatment used in Ireland for sewage sludge applied to land. This material acted as a comparison for BSRW in the experiment, as its current legal status allows for controlled land spreading. Assessments of the quality of the collected leachate were based on Irish regulations on surface water quality (S.I. No. 77/2019 and S.I. No. 272/2009).

The stabilisation of sewage sludge with lime resulted in a pH indicating very high alkalinity (Table 8.4). The total nitrogen and phosphorus concentrations in the sludge were also higher than in the BSRW, consistent with previous studies (Alvarenga *et al.*, 2017). The metal levels in both organic amendments were below the maximum permitted by the Irish Waste Management (Use of Sewage Sludge in Agriculture) Regulations, 2001 (S.I. No. 267/2001) (Table 8.4).

Figure 8.2. View of the water tanks used for the leachate experiment.
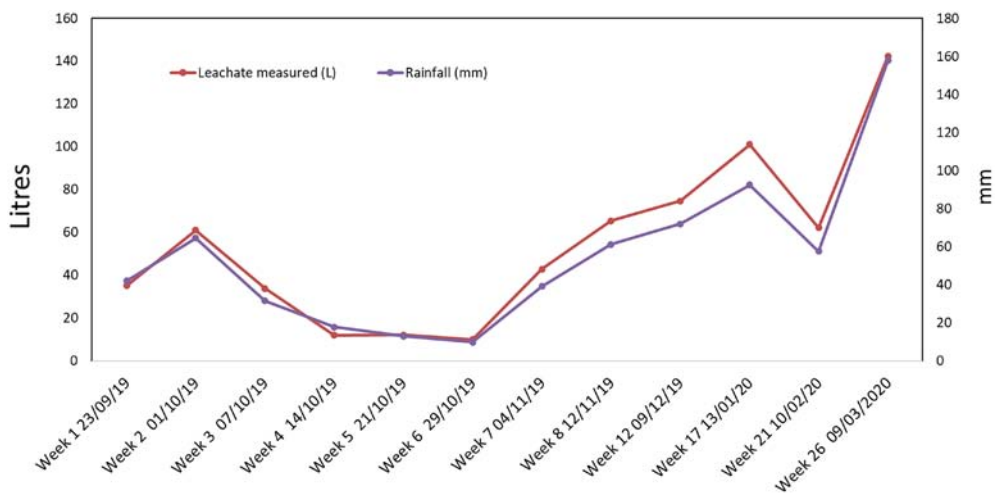
Figure 8.3. Rainfall (mm) and leachate (L) collected for 6 months.

A soil under Sitka spruce plantation known to be acidic with low nutrient availability (Harrison *et al.*, 1995) was selected to assess the application of BSRW for non-agricultural land use compared with regulated application of sewage sludge.

The effects of BSRW on soil properties were similar to those of sewage sludge (Table 8.5). The application of both organic amendments increased pH, electrical conductivity and available nutrients. The application of 25 t BSRW/ha increased the organic matter

Table 8.4. Properties of the BSRW and sewage sludge used in the leachate trial

Material properties	BSRW[a]	Stabilised sewage sludge[a]	Maximum permitted by S.I. No. 267/2001[b]
pH	7.77±0.01	12.86±0.05	
Electrical conductivity (µs/cm)	1912±0.67	2957±0.73	
Organic matter (%, DM)	47.61±0.31	53.23±0.61	
Total carbon (%, DM)	30.09±0.41	23.53±0.16	
Total nitrogen (%, DM)	2.30±0.05	3.74±0.11	
Nutrients (mg/kg, DM)			
Phosphorus	4738.7±100.0	22,895.4±936.0	
Potassium	4275.7±22.1	516.6±4.2	
Magnesium	9266.0±103.0	3140.4±4.9	
Sodium	7854.6±85.1	1948.8±60.1	
Calcium	20,687.6±145.5	11,195.6±108.8	
Metals (mg/kg, DM)			
Aluminium	17,769.7±118.5	3641.6±120.4	–
Cadmium	9.02±0.39	10.71±0.29	20
Chromium	43.77±5.18	20.65±2.54	–
Copper	494.6±14.2	392.8±6.1	1000
Nickel	66.91±6.12	17.88±0.77	300
Lead	317.5±28.3	90.5±3.5	750
Zinc	1018.9±40.3	344.1±8.7	2500

[a]**Mean values ± standard errors are given for each parameter.**

[b]**Waste Management (Use of Sewage Sludge in Agriculture) (Amendment) Regulations, 2001.**

and carbon contents in the soil; however, applying sewage sludge and BSRW at the lower rate of 10 t/ha had no effect on these soil parameters. Sewage sludge contained more total nitrogen than BSRW; nevertheless, the application of 10 t BSRW/ha resulted in similar levels of nitrogen in the soil (0.31%) as the application of sewage sludge, whereas the application of 25 t BSRW/ha resulted in 1.6 times more nitrogen in the soil than the application of sewage sludge (Table 8.5). This suggests that nitrogen in sewage sludge is more soluble and more likely to be lost from soil by runoff or leaching than nitrogen in BSRW. Both organic amendments increased the levels of available phosphorus and potassium in the soil. Although no significant differences were detected, the higher application concentration of BSRW showed a tendency to increase the availability of these nutrients in the soil.

The Waste Management (Use of Sewage Sludge in Agriculture) Regulations (S.I. No. 148/1998) was referred to in order to understand the risk of soil metal build-up after the application of organic amendments. The background metal concentrations observed in the control soil were found to be close to the threshold

values, and the concentrations of cadmium and nickel exceeded the values (Table 8.5). According to the Soil Geochemical Atlas of Ireland (Fay *et al*., 2007), naturally high background levels of cadmium and nickel can be attributed to limestone shale bedrock, whereas areas with long-term activity (Dublin, Meath, Cork and Wexford) present higher background levels of heavy metals in soil. In the present study, the forest site was in County Meath, potentially explaining the metal concentrations in the control soil. As expected, once sewage sludge and BSRW had been applied (Table 8.5), the metal concentrations increased, with some of these exceeding the maximum allowance. The application of sewage sludge and BSRW at the same rate (10 t/ha) generally resulted in similar increases in soil metals, demonstrating similar metal loads from these materials.

Herbage yield showed responses to the application of sewage sludge and BSRW, but the nutritional profile of herbage remained mainly unaltered by the four soil treatments (Table 8.6). Although increases in soil metal concentrations were observed, no effects of the metals in the herbage samples were detected, indicating

Table 8.5. Soil properties and metal concentrations in the soil after amendments were applied

Soil properties	Control[a]	Sewage sludge 10 t/ha[a]	BSRW 10 t/ha[a]	BSRW 25 t/ha[a]	Maximum permitted by S.I. No. 148/1998[b]
pH	5.65±0.04 a	8.24±0.19 b	7.78±0.12 c	8.22±0.06 b	
Electrical conductivity (µs/cm)	38.9±0.55 a	371.8±22.7 b	284.1±12.1 c	641.3±54.8 c	
Organic matter (%, DM)	8.90±0.70 a	9.04±0.14 a	8.82±0.27 a	11.36±0.16 b	
Total carbon (%, DM)	3.42±0.06 a	4.01±0.27 a	4.18±0.23 a	5.49±0.22 b	
Total nitrogen (%, DM)	0.29±0.02 a	0.32±0.03 ab	0.35±0.01 b	0.51±0.02 c	
Carbon-to-nitrogen ratio	12.6±0.31 a	12.51±0.73 a	11.99±0.49 ab	10.83±0.36 b	
Available nutrients (Morgan's extraction) (mg/L)					
Phosphorus	8.00±0.60 a	25.3±1.25 b	26.9±4.70 b	33.6±3.80 b	
Potassium	42.7±1.40 a	52.3±1.50 b	71.0±18.1 b	162±52.5 b	
Magnesium	83.4±1.00 a	90.2±4.95 a	111±17.6 a	179±39.0 a	
Metal (DM, mg/kg)					
Cadmium	3.93±0.04 a	5.67±0.52 b	4.50±0.38 c	5.22±0.15 bc	1.00
Chromium	38.16±0.72 a	30.76±0.14 b	28.74±2.23 b	30.46±1.69 b	–
Copper	41.74±0.78 a	47.87±1.22 b	59.72±0.47 c	103.73±6.95 d	50.0
Nickel	33.19±0.95 a	36.78±0.99 b	36.31±0.80 b	41.29±2.06 c	30.0
Lead	24.24±0.26 a	24.99±1.62 a	32.17±3.56 b	42.49±0.58 c	50.0
Zinc	110.68 ± 0.45 a	116.70±1.74 b	141.91±1.01 c	225.46±3.95 d	150.0

Different letters represent statistically significant ($p < 0.05$) differences between the soil treatments. The same letter represents no statistical difference between the soil treatments. For example, the pH 5.65 value (marked with 'a') is significantly different from the pH 8.24 and pH 7.78 values (marked with 'b' and 'c', respectively); pH 8.24 and pH 8.22 are not significantly different, so they are marked with the same letter ('b').

[a]**Mean values ± standard errors are given for each parameter.**

[b]**Waste Management (Use of Sewage Sludge in Agriculture) Regulations, 1998.**

that the metals were bound to the organic matrix and not bioavailable for plant uptake. The high pH of the sewage sludge treatment could also have reduced metal availability in these plots. These results are in line with those discussed in section 6.1, with metal levels in grass samples being lower than reference values found in herbage elsewhere (Ross *et al*., 2007).

Leachate quality was evaluated for 6 months (26 weeks) and analysed for ammonium, nitrate, reactive phosphorus, pH and metals. Assessments of the water quality of leachate were based on the Irish regulations on surface water (S.I. No. 77/2019, S.I. No. 272/2009), drinking water (S.I. No. 122/2014) and urban waste water treatment (S.I. No. 254/2001). The pH value and the concentrations of nitrate (Figure 8.4) and of the metals chromium, cadmium, arsenic and nickel (Figure 8.5) were below the maximum permitted in inland waters, and mercury was not detected (<0.05 mg/L) in any sample. Concentrations of all variables decreased over the time of the experiment apart from a spike in zinc that coincided with high rainfall in the final 3 weeks of the experiment (Figure 8.3).

Ammonium was detected in week 1 only (Figure 8.4) and was above 0.2 mg/L in the leachate from the organic amendment treatments. The leachate from the sewage sludge treatment showed ammonium levels 2.8-fold and 1.5-fold higher than those from the 10 t BSRW/ha and 25 t BSRW/ha, respectively. The extreme leaching of ammonium in this situation is related to the forms of nitrogen in the sewage sludge, with high availability and a susceptibility to leaching.

Reactive phosphorus was the only element tested that exceeded the threshold values for inland waters (Figure 8.4), and the levels of phosphorus leaching from the control treatment were higher than in the organic amendment treatments for the first 5 weeks. The application of organic amendments to a forest soil improved phosphorus retention, suggesting strong phosphorus retention in sewage sludge and compost (Stutter, 2015). To avoid excessive phosphorus leaching directly into nearby water bodies, a buffer zone would be recommended in accordance with current sewage sludge legislation.

Table 8.6. Herbage yields and nutritional profiles of grass samples from soil treated with sewage sludge and BSRW and from control plots

Herbage yield and nutrients (DM)	Control[a]	Sewage sludge 10 t/ha[a]	BSRW 10 t/ha[a]	BSRW 25 t/ha[a]	Maximum allowed in animal feed[b]
Yield (t/ha)	1.22±0.29 a	2.40±0.19 a	1.40±0.04 b	2.00±0.16 a	
Nitrogen (%, DM)	2.29±0.10 ab	2.39±0.01 a	2.10±0.02 b	2.11±0.02 b	
Phosphorus (%, DM)	0.41±<0.01 a	0.41±0.02 a	0.40±0.01 a	0.40±0.01 a	
Potassium (%, DM)	2.52±0.01 a	2.42±0.15 a	2.52±0.12 a	2.51±0.01 a	
Calcium (%, DM)	0.69±0.02 a	0.68±0.04 a	0.66±0.03 a	0.68±0.01 a	
Magnesium (%, DM)	0.15±<0.01 a	0.14±0.01 a	0.14±0.01 a	0.15±<0.01 a	
Sodium (%, DM)	0.03±0.01 a	0.02±0.02 a	0.02±<0.01 a	0.02±0.02 a	
Sulfur (%, DM)	0.16±<0.01 a	0.22±<0.01 b	0.21±0.01 ab	0.27±<0.01 c	
Manganese (mg/kg, DM)	34.6±<0.15 a	37.6±<0.40 b	34.3±1.35 ab	35.9±0.70 ab	
Iron (mg/kg, DM)	120.5±12.5 a	203.5±21.5 a	107.1±8.90 a	145.5±4.50 a	
Boron (mg/kg, DM)	7.55±0.35 a	6.90±0.20 a	7.00±<0.01 a	7.70±0.30 a	
Molybdenum (mg/kg, DM)	7.96±0.30 a	9.25±0.57 a	8.09±0.14 a	5.50±0.06 b	
Metal (DM, mg/kg)					
Cadmium	0.29±0.03 a	0.26±0.01 a	0.25±0.01 a	0.20±0.01 a	0.50
Chromium	0.85±0.05 a	1.00±0.10 a	0.80±<0.01 a	0.90±0.10 a	–
Copper	9.20±3.40 a	5.95±0.25 a	5.55±0.25 a	5.10±<0.01 a	50.0
Nickel	2.50±0.20 a	2.95±0.15 a	2.40±<0.01 a	2.30±0.01 a	–
Lead	0.60±0.24 a	1.22±0.38 a	0.56±0.13 a	0.61±0.05 a	5.0
Zinc	29.90±1.20 a	35.65±0.25 a	36.15±2.05 a	34.75±0.05 a	100.0
Mercury	<0.01	<0.01	<0.01	<0.01	–

Different letters represent statistically significant ($p < 0.05$) differences between the soil treatments. The same letter represents no statistical difference between the soil treatments.

[a]**Mean values ± standard errors are given for each parameter.**

[b]**Maximum allowed according to Commission Regulation (EU) No 1275/2013 of 6 December 2013.**

The results suggest that BSRW can be used as soil amendment without major concerns for soil heath. The main environmental concern regarding water quality is the potential for ammonium, nitrate and orthophosphate to leach into adjacent water bodies. BSRW is preferred to lime-treated sewage sludge, since the leaching of nitrogen is minimised with the former (Rigby *et al.*, 2016), allowing for a more efficient use of nitrogen as a fertiliser and avoiding contamination of water bodies. This study supports findings from previous studies, i.e. that the leaching of heavy metals is unlikely to constitute a risk to water quality, since heavy metals and organic pollutants are strongly bound to soil organic matter (Smith, 2009). Its metal content could make BSRW less suitable for application in certain Irish soils that have naturally high background concentrations, so as to reduce the risk of heavy metal accumulation; however, no leaching or bioavailability effects were detected during this study.

8.3 Case Study III: 0–10 mm Fraction of BSRW as a Suitable Organic Soil Amendment for the Direct Revegetation of a Bauxite Residue Disposal Area

The alumina from bauxite ore is extracted using the Bayer process. The use of caustic soda in this process results in the remaining bauxite residue exhibiting highly alkaline, sodic and saline characteristics. In industrial-scale facilities, this residue can be generated at a rate of approximately 1 million tonnes per annum and, because of its chemical nature, it does not support plant growth. Companies managing bauxite residue disposal areas (BRDAs) are required to ensure that respective environmental standards set in the Industrial Emissions Directive (Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010) are complied with through approved restoration and closure plans. The bio-remediation of bauxite residue to convert it
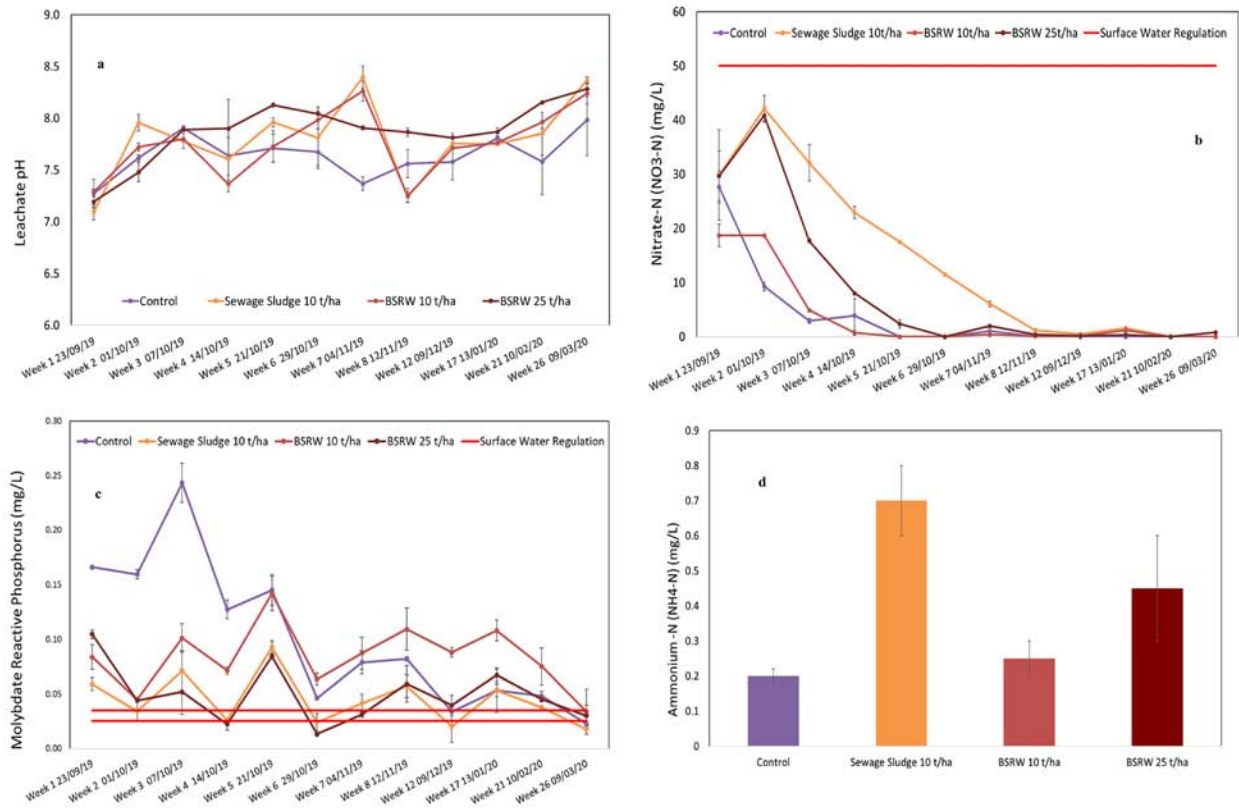
Figure 8.4. Effects of applying lime-treated sewage sludge at 10 t/ha and BSRW at 10 t/ha and 25 t/ha to forestry plantation soil on (a) leachate pH, (b) nitrate concentrations and (c) reactive phosphorus concentrations recorded over a 6-month monitoring period in the experiment; (d) ammonium concentrations detected in week 1 are also shown. When available, Surface Water Regulation thresholds are represented with red lines for comparison. Error bars represent standard deviations.

into a well-structured soil for direct revegetation is challenging and requires specialist soil management and restoration plans (Di Carlo *et al*., 2019).

The VALOR project team, supported by the project steering committee and project industry partner Enrich Environmental, was given approval from the EPA for a large-scale field trial on a BRDA, licensed by the EPA. The licensed facility has successfully demonstrated direct revegetation of a BRDA through previous studies undertaken with the University of Limerick and ongoing rehabilitation of the BRDA managed by Enrich Environmental (McMahon, 2017). The currently established, demonstrated and approved method for direct revegetation of the BRDA at the licensed facility utilises sand and gypsum and commercial compost as the organic amendment.

The aims of this trial were:

- to verify the suitability of BSRW as an alternative to the current commercial composts that

were used to demonstrate successful direct revegetation of a BRDA;
- to investigate the concentration of metals, persistent organic pollutants (POPs) and nutrients in BRSW and commercial compost, amended bauxite residue and runoff water.

To investigate both approaches, two identical trial areas were set up, following the standard management approach to direct revegetation but varying the type of organic amendment used. The test area was amended with BSRW and the control area was amended with commercial compost.

A trial area of 4100 m² was identified on the BRDA (Figure 8.6). The area was divided into two equal-sized plots: a control plot where commercial compost was applied and a test plot with BSRW. Both plots were managed in the same way, and commercial compost and BSRW were applied at the same rate (Table 8.7).
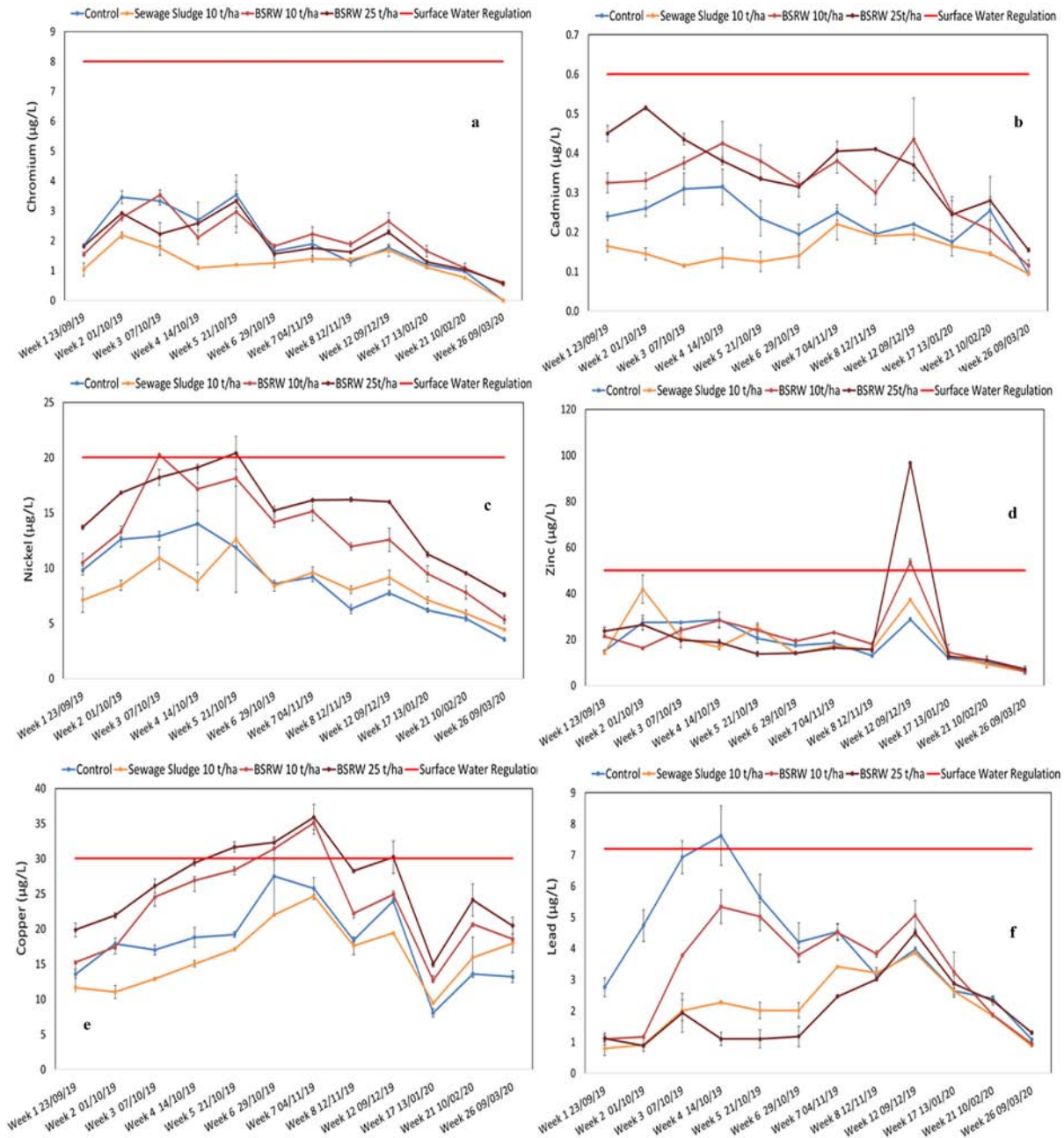
Figure 8.5. Variation (µg/L) in (a) chromium, (b) cadmium, (c) nickel, (d) zinc, (e) copper and (f) lead in the collected leachate over 26 weeks. The red lines represent the limit values for metals stipulated in Irish legislation on surface waters (S.I. No. 77/2019: European Union Environmental Objectives (Surface Waters) (Amendment) Regulations 2019). Error bars represent standard deviations.

To ensure accurate surface water runoff sampling, a separate collection system for each plot was installed with flow measurement. Both plots were engineered to have a gentle gradient to ensure that all runoff was directed towards collection channels (Figure 8.6). Runoff water was captured in these downstream channels and diverted to attenuation sumps for sampling, one for each plot.

The plots were separated using the physical boundary of a bank of bauxite residue to prevent cross-contamination. An upstream perimeter drain was installed to divert potential external surface water and ensure that only test and control plot surface water was captured. After the attenuation sumps, all runoff water from the plots was diverted to the existing surface water channels and captured and treated in the onsite treatment system. On both plots,
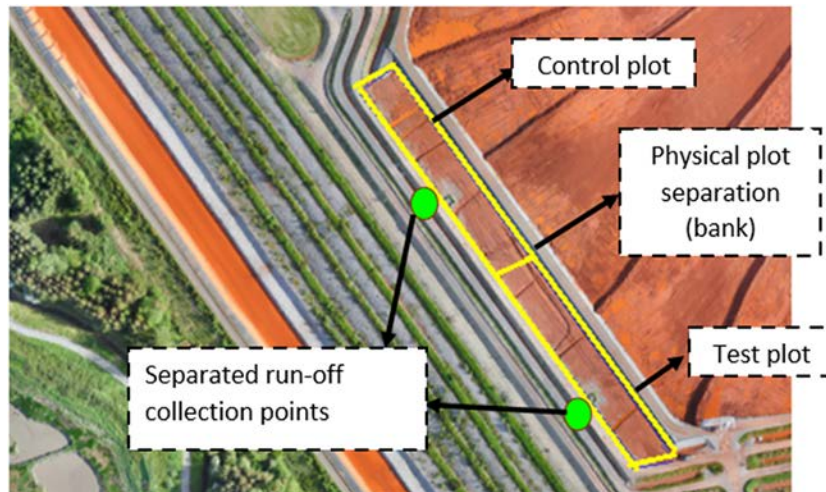
Figure 8.6. Aerial view of the trial area (within the yellow border).

Table 8.7. Proportion of amendments incorporated into the two plots, control and test blends (% v/v, incorporation depth 300 mm)

	Test	Control
Bauxite residue	42%	
Gypsum	3%	
Sand	25%	
BSRW	30% (150 tonnes)	Not applicable
Commercial compost	Not applicable	30% (150 tonnes)

a specialised blend of salt-tolerant grass species (30% dwarf perennial, 30% strong creeper, 25% perennial grass, 8% Timothy perennial grass, 2% creeping bent, 2.5% white clover and 2.5% red clover) was sown at a rate of 100 kg/ha to create a multi-species grass sward.

The physical and chemical characteristics of the bauxite residue are presented in Table A1.1 (Appendix 1) and have been extensively studied in Ireland and abroad (Di Carlo *et al*., 2019). Owing to the mineral-rich nature of the bauxite residue and the organic matter of the composts used, metals, PAHs and PCBs were identified as the most appropriate parameters to monitor in this trial. Analyses were conducted on the bauxite residue amendments (commercial compost and BSRW) (Table A1.2), unamended bauxite residue, residue amended with BSRW and commercial compost (Table 8.8). The runoff water from the test and control plots was also analysed (Table 8.9). The methodology is presented in Appendix 2.

Surface runoff from each plot was sampled at the corresponding collection points. The initial plan was to sample weekly for the first 2 months of the trial. Afterwards, leachate was to be collected monthly from month 3 to month 6 and bimonthly from month 6 to month 12. However, in practice the sampling of runoff (Table 8.9) was dictated by the weather conditions. Runoff from the plots was very low, especially in the first few months, which coincided with the summer period. Advanced flow measurement devices (flumes) and telemetry equipment were installed and calibrated using water tankers on site. Having initially anticipated that runoff would be low, flumes that could measure flow as low as 0.9 L/s were installed (Van Walt Flumes, equipment ref. 13.17.04). However, runoff from the trial was always below the level of detection. Potentially, the area of each plot, 2050 m², and the high water retention capacity of the bauxite residue influenced the ability of the equipment installed to detect runoff.

Organic contaminant (PAH and PCB) concentrations were all below the limit of detection in the test and control soil mixtures (reported on a "fresh basis", as some of the small organic analytes such as naphthalene are highly volatile, and the drying of samples could have affected the results).

The data generated and presented in this report demonstrate that there was no distinguishable difference in the qualitative or quantitative results for metals, POPs or nutrients associated with the test and control plots. The BSRW has been shown to support

Table 8.8. Bauxite residue properties without organic amendments (BRDA: no compost), with commercial compost (control plot) and with the addition of BSRW as a soil improver (test plot)

Soil parameter (DM)	BRDA: no compost	Control plot: current approach	Test plot: BSRW
pH	8.5	8.7	8.3
Electrical conductivity (µs/cm)	2.14	3.20	3.40
Organic matter (DM, %)	6.56	9.98	11.98
Total nitrogen (DM, %)	< 0.02	0.14	0.30
Available nutrients (DM)			
Phosphorus (mg/L)	3.0	27.0	34.0
Calcium (g/L)	12.6	11.8	16.1
Potassium (mg/L)	98.6	968	586
Magnesium (mg/L)	26.2	330	182
Sodium (g/L)	12.2	8.9	8.3
Exchangeable calcium (mg/kg)	< 10	< 10	< 10
Exchangeable potassium (mg/kg)	94	755	493
Exchangeable magnesium (mg/kg)	13	224	140
Exchangeable sodium (mg/kg)	4360	3689	3826
Cation exchange capacity (meq/100 g)	10.4	11.7	11.8
Metals (DM)			
Copper (mg/kg)	33.9	45.6	43.5
Zinc (mg/kg)	41.2	75.7	83.8
Lead (mg/kg)	40.6	42.0	48.4
Arsenic (mg/kg)	23.4	19.1	19.2
Cadmium (mg/kg)	0.12	0.28	0.43
Nickel (mg/kg)	11.6	13.6	14.2
Chromium (mg/kg)	835	681	544
Mercury (mg/kg)	< 0.2	< 0.2	< 0.2
Titanium (g/kg)	23.2	18.8	18.5
Iron (g/kg)	339	307	290
Aluminium (g/kg)	59.4	56.8	55.8

the faster and visually more vigorous establishment of vegetation (Figure 8.7).

Table 8.9 outlines the runoff properties of 10 samples taken on different dates throughout the experiment (September 2021 to March 2022). The results from the test (BSRW) and control (the commercial compost, values of which are in bold) plots were compared with each other and with international threshold concentrations. All variables for the test and control plots were statistically analysed for differences between sample means, where $n = 10$ for the test plot and $n = 10$ for the control plot (except for iron, magnesium, nickel, titanium and mercury, where $n = 9$ for both test and control plots). Data were tested for normality using the Shapiro–Wilks test. All variables, excluding pH, had a non-normal distribution. The Mann–Whitney *U*-test was used to

test data for non-normal distributions, and pH was tested using a *t*-test with α = 0.05 set for both tests. Of the 18 variables, 12 showed no significant difference, whereas a statistically significant difference ($p < 0.05$) was found for nitrate, conductivity, chromium, copper and zinc. Nitrate concentrations were 1 mg/L in both test and control plots, with the exception of the point sampled on 8 October 2021, where the nitrate concentration was higher in BSRW runoff (2.1 mg/L) than in runoff from the control plot (1 mg/L). Runoff conductivity decreased throughout the experiment, with the BSRW (test) plot at 962 µs/cm in September 2021 compared with the control plot at 797 µs/cm. From 8 October 2021, runoff conductivity was always higher in the control than in the test. Chromium concentrations in the runoff from the plots were generally similar. BSRW (test) plot runoff presented

Table 8.9. Results from runoff experiments from test site (compost recovered from BSRW) and control site (commercial compost)

Parameter	07.09.21	08.10.21	15.10.21	22.10.21	28.10.21	19.11.21	02.12.21	12.01.22	11.02.22	22.02.22	Thresholds
pH	7.3 (**7.3**)	7.2 (**7.7**)	7.6 (**7.7**)	6.7 (**7.3**)	6.6 (**7**)	7.4 (**8**)	8 (**8.6**)	7.8 (**8.2**)	7.2 (**7.9**)	7.7 (**8.2**)	6.5–9.5[a]
BOD (mg/L)	8 (**6**)	9 (**5**)	9 (**19**)	8 (**5**)	5 (**12**)	15 (**2**)	3 (**2**)	3 (**5**)	3 (**2**)	4 (**5**)	25[b]
Nitrate (mg/L)	1 (**1**)	2.1 (**1**)	1 (**1**)	1 (**1**)	1 (**1**)	1 (**1**)	1 (**1**)	1 (**1**)	1 (**1**)	1 (**1**)	50[a]
Ammonium (mg/L)	0.67 (**0.02**)	0.03 (**0.04**)	0.03 (**0.03**)	0.26 (**0.13**)	0.14 (**0.09**)	0.02 (**0.02**)	0.02 (**0.02**)	0.02 (**0.06**)	0.02 (**0.29**)	0.02 (**0.02**)	300[a]
Orthophosphate (mg/L)	0.53 (**0.02**)	0.02 (**0.02**)	0.02 (**0.02**)	0.12 (**0.02**)	0.05 (**0.02**)	0.02 (**0.02**)	0.02 (**0.02**)	0.23 (**0.02**)	0.02 (**0.02**)	0.02 (**0.02**)	0.3[c]
Conductivity (µs/cm)	962 (**797**)	219 (**504**)	126 (**471**)	63 (**312**)	40 (**259**)	114 (**223**)	113 (**223**)	194 (**288**)	112 (**296**)	308 (**432**)	2500[a]
Aluminium (µg/L)	0.78 (**0.69**)	268 (**127**)	359 (**390**)	146 (**265**)	68.9 (**262**)	1370 (**629**)	186 (**527**)	192 (**617**)	185 (**1100**)	312 (**540**)	200[a]
Arsenic (µg/L)	0.01 (**0.01**)	1 (**5**)	1 (**5**)	1 (**1**)	1 (**1**)	10 (**10**)	10 (**10**)	5 (**5**)	5 (**10**)	10 (**10**)	10[a]
Cadmium (µg/L)	0.02 (**0.02**)	0.2 (**0.4**)	0.2 (**0.4**)	0.2 (**0.2**)	0.2 (**0.2**)	2 (**2**)	2 (**2**)	0.4 (**0.4**)	0.4 (**2**)	2 (**2**)	5[a]
Chromium (µg/L)	0.02 (**0.02**)	5 (**1**)	5 (**1**)	5 (**5**)	5 (**5**)	13.7 (**3**)	2 (**2**)	1 (**1.4**)	1 (**22.6**)	2 (**2**)	50[a]
Copper (µg/L)	0.19 (**0.02**)	16.5 (**3.8**)	15.2 (**5.5**)	23 (**1**)	13.6 (**4.1**)	65.2 (**2**)	16.7 (**4.1**)	9.2 (**1**)	16.2 (**243**)	12.7 (**2**)	2[a]
Iron (µg/L)	0.17 (**0.8**)	61.5 (**18.7**)	177 (**44.6**)	160 (**143**)	96.5 (**316**)	4030 (**906**)	81.6 (**347**)	81.8 (**277**)	34.1 (**N/A**)	69.5 (**460**)	200[a]
Lead (µg/L)	0.01 (**0.01**)	1 (**5**)	1 (**5**)	1 (**1**)	1 (**1**)	10 (**10**)	10 (**10**)	5 (**5**)	5 (**10**)	10 (**10**)	10[a]
Magnesium (µg/L)	7.89 (**1.35**)	790 (**829**)	833 (**510**)	746 (**449**)	471 (**458**)	1720 (**737**)	1310 (**640**)	2940 (**2460**)	N/A	5300 (**3450**)	80,000[c]
Nickel (µg/L)	0.005 (**0.00**)	3 (**2**)	3 (**2**)	3 (**3**)	3 (**3**)	5 (**5**)	5 (**5**)	2 (**2**)	2 (**53.5**)	5 (**5**)	20[a]
Titanium (µg/L)	0.01 (**0.001**)	7.6 (**1**)	16 (**5**)	11.2 (**18**)	9.5 (**35.6**)	338 (**110**)	6.2 (**27.5**)	6.5 (**48**)	N/A	6.3 (**58.4**)	100[c]
Zinc (µg/L)	0.07 (**0.005**)	268 (**4.5**)	261 (**2.2**)	431 (**47.5**)	366 (**46.3**)	510 (**14.5**)	143 (**10.6**)	84.7 (**2.3**)	85.4 (**134**)	50.3 (**3**)	1000[a]
Mercury (µg/L)	0.03 (**0.02**)	0.02 (**0.01**)	0.02 (**0.01**)	0.02 (**0.02**)	0.02 (**0.02**)	0.02 (**0.02**)	0.02 (**0.02**)	0.02 (**0.01**)	0.01 (**N/A**)	0.02 (**0.02**)	0.08[c]

Control site values are in brackets in bold.

[a] European Union (Drinking Water) Regulations 2014, S.I. No. 122 of 2014. Available online: https://www.irishstatutebook.ie/eli/2014/si/122/made/en/pdf (accessed 6 January 2023).

[b] Appendix A4.1 Key Wastewater Treatment Standards Report. Downloadable from: https://assets.gov.ie/120810/d2fc6fd6-8767-4074-925f-55358beaaaeb.pdf (accessed 10 February 2023).

[c] EU Groundwater Directive (Directive 2006/118/EC). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32006L0118 (accessed 6 January 2023).

Figure 8.7. Photos, taken on 5 May 2022, of grass growing on (a) the test plot and (b) the control plot.

higher chromium concentrations at three sampling points, whereas the control plot (commercial compost) presented a higher concentration at one sampling point. Copper and zinc concentrations in the runoff from the test plot were generally higher than those from the control plot, with the exception of the sample taken on 11 February 2022, where copper and zinc in the control plot runoff showed values of 243 µg/L and 134 µg/L, respectively.

Of the 18 properties analysed, pH, biochemical oxygen demand (BOD), nitrate, ammonia, conductivity, arsenic, cadmium, chromium, nickel and magnesium were below international water quality thresholds for both the test (BSRW) and the control (compost) plots. Chromium, lead, titanium, mercury and zinc concentrations were also below international thresholds. Aluminium exceeded international thresholds, but there was no statistically significant difference between the test and control plots for this element. Copper exceeded international limits, but the results were skewed by "outliers" on 19 November 2021 and 11 February 2022, and the mean concentration for the control plot (26.65 µg/L) was larger than that for the test plot receiving BSRW

(18.85 µg/L) on all sampling dates. Iron exceeded the international threshold on 1 day (19 November 2021), but this value was also considered an outlier for both plots. With the outlier date excluded, the mean concentration of iron was larger for the control plot receiving the standard compost treatment (178.57 µg/L) than for the BSRW plot (81 µg/L). The potential carbon benefit from remediating the test plot with the 0–10 mm fraction of BSRW is presented in Table A1.2.

This study demonstrated no distinguishable differences between amending bauxite residue with BSRW and amending it with commercial compost. Although this work does not establish the long-term effects of the organic amendments in bauxite restoration, it does demonstrate that BSRW is an effective replacement for commercial compost and that the runoff water quality is comparable. BSRW treatment results in improved vegetative cover, and the comparison with the commercial compost, and the environmental factors studied, indicate that BSRW is a suitable replacement in the closure plans for licensed facilities, subject to ongoing monitoring.

9   Plastic in Marketable Compost and Soil

The use of compost manufactured from source-segregated waste is regulated by legislation, such as Regulation (EU) 2019/1009 (EU, 2019), and quality control procedures. This ensures that contaminants, such as impurities (e.g. glass, plastic and metal) and heavy metals, if present, are compliant with acceptable threshold limits to prevent their use from posing any risk to the environment and/or human/animal health. Plastic contamination in compost and digestate is of concern because of the environmental risks it poses and rising concerns about its potential effects on human health. Plastic particles found in the soil vary in size, density, shape and chemical composition. Compost is a potential source of plastic contamination when applied to soils, which is leading to mistrust from users and a low market valued product (Foster and Prasad, 2021).

Few studies identify and quantify plastic contamination in marketed compost and soil improvers or establish the likelihood that this type of contamination will enter the soil environment from such sources. Compost produced from biowaste and green waste showed less than 25 microplastic particles per kg, considerably less than in most digestate samples (Weithmann *et al.*, 2018; Braun *et al*., 2021). Feedstock contamination, mass reduction during processing and/or procedures taken by compost procures to remove the plastic from the feedstock (e.g. remove plastic from feedstock before further treatment) are suggested as reasons for the variability in the amount of plastic between compost and digestate samples.

A study of sewage sludge showed that it contained microplastics ranging from 4196 to 15,385 particles/kg (Mahon *et al*., 2016). In agricultural farmland, Piehl *et al*. (2018) estimated 206 macroplastic particles/ha and between 158,100 and 292,400 microplastic particles/ha.

The screening of source-separated waste for micro-/macroplastic contaminants is necessary to establish whether soil improvers prepared from these feedstocks are potential pathways of soil contamination.

This chapter focuses solely on the quality of compost produced from source-segregated green waste and food waste. The aims are to:

- provide an initial assessment of plastic contamination in compost produced from source-segregated waste (e.g. green waste and food waste);
- quantify the presence of macroplastics (e.g. >5mm) and microplastics (between 5 and 2mm) in compost;
- assess plastics in soil samples amended with compost.

Therefore, compost samples were collected from the processing of green waste and food waste (Figure 9.1). Green waste comprises source-segregated garden and landscaping waste. This segregation is done at a number of civic amenity centres in Ireland. Food waste is source segregated by households or at commercial properties using the "brown bin" system. The waste is collected from brown bins and delivered to a composting facility. Household brown bins are used to collect both garden waste and food waste.

9.1   Quantification of Plastic in High-quality Compost

An initial assessment of plastic contamination in compost was performed using observational methods. Three food waste compost (FC) samples (FC1, FC2, FC3) and four green waste compost (GC) samples (GC1, GC2, GC3, GC4) were obtained from composting facilities in Ireland. The plastic in the source-segregated compost was characterised and quantified following the PAS100: 2011, AfOR MT PC&S methodology, using a series of sieves with varying aperture size (10mm, 5mm, 4mm and 2mm), to quantify the presence of plastic fragments >5mm and between 5 and 2mm. Samples were analysed in triplicate. Field samples were taken as a composite sample, walking the field in direction W and taking 20 cores of 10cm depth, in accordance with Teagasc guidelines.

Figure 9.1. (a) Shredding of source-segregated green waste at processing facility and (b) source-segregated food waste.

The amount of plastic present in the compost samples was highly variable, although the proportion of plastic in the GC was relatively lower than that in the FC (Figure 9.2). This may be because packaging commonly used to store food is often thrown into bins containing spoiled/leftover food. Recently, Braun *et al.* (2021) reported large variation in the amount of plastic in quality compost samples, with no differences found between green waste and food waste compost. In our study, we also detected large variation in plastic content in the analysed samples. For plastic fragments of > 2 mm (% w/w) the level detected was within the threshold values stipulated in Regulation (EU) 2019/1009 (EU, 2019) and Irish Standard 441:2012 except for the FC3 sample. FC3 results showed that 80–100% of the plastic found in the compost samples measured between 5 and 10 mm.

In five compost samples, the plastics found were classified by type: hard, film and plastic wrap. This classification was by visual inspection to facilitate the analysis and was intended to give an indication of the types of plastics placed in the brown bin. This analysis can inform stakeholders on how to improve organic waste separation. A large variety of plastics were found in the compost samples; in particular, FC. GC samples showed a lower load of plastic units overall (Figure 9.3). In GC samples, plastic film dominated hard plastic and plastic wrap, making up 66–72% of the plastic analysed. Both plastic film and hard plastic were found in FC samples, without a clear trend of which type would be more abundant. FC1 showed a higher abundance of hard plastic, whereas FC2 showed a higher abundance of plastic film (Figure 9.3).
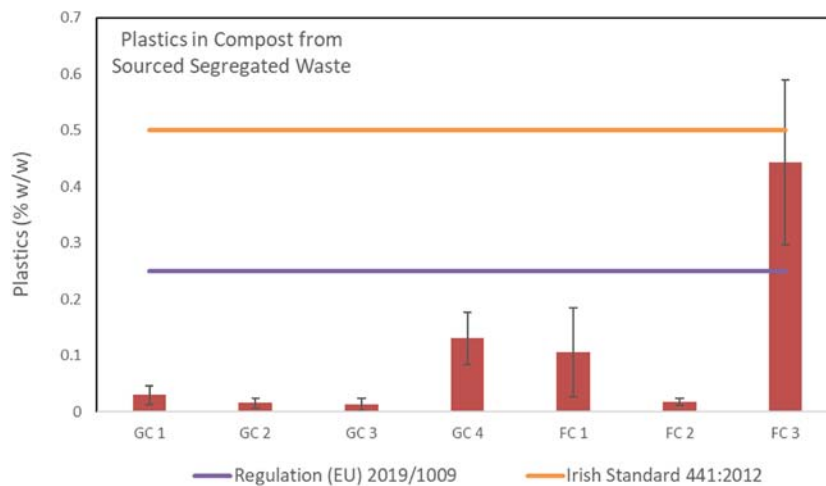
Figure 9.2. Proportion (% w/w DM) of plastics in compost samples from source-segregated GC and FC.
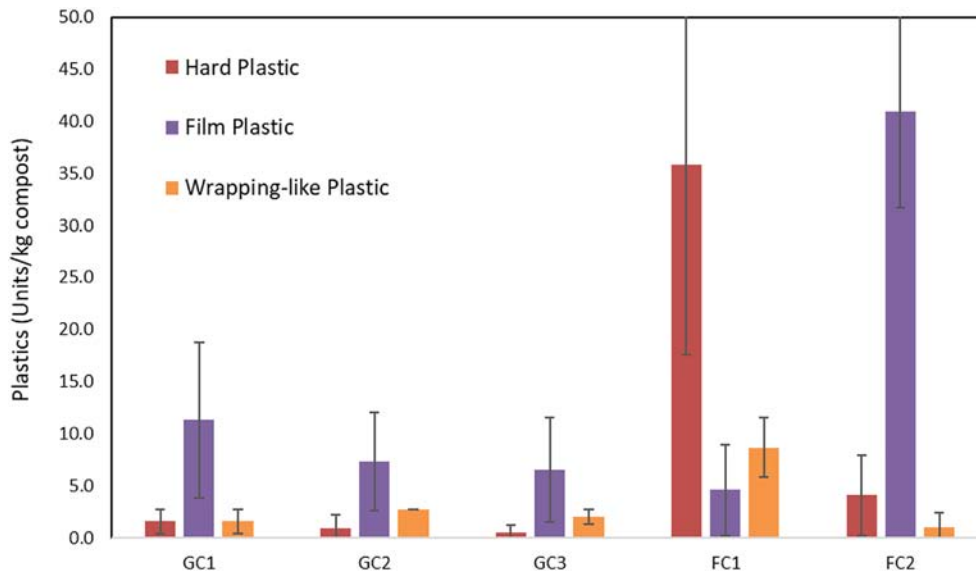
Figure 9.3. Units of plastic (plastic units/kg compost DM), separated in the assessed plastic types in samples from GC and FC.

Overall, plastic was found in green and food waste compost samples, with relatively higher proportions in the latter. Changes introduced in September 2021 mean that soft plastics are now allowed in the recycling bin, which is expected to greatly improve the quality of the green waste and food waste being segregated for composting (MyWaste, 2021). The origin of the waste (green versus food waste) appears to influence the quantity and type of plastic that the final compost contains.

Another consideration is the type of mechanical treatment the waste will undergo prior to the composting process. Both green and food waste go through a shredding stage where the plastic in the waste can be shredded into smaller pieces. Because of the small particle size of the plastic detected in the samples, it is unlikely that all of this material can be effectively removed from the finished compost. The elimination of plastic from the organic waste fraction is therefore necessary at the household level. Indeed, Foster and Prasad (2021) recommend (1) raising awareness within households about reducing the disposal of plastics in the brown bin and providing a better understanding of the value of food and green compost and (2) carrying out brown bin inspections and inspections of the green waste at local waste amenities to assist in reducing plastic contamination.

9.2 Screening of Plastics in Agricultural and Landscape Soil Samples

Agricultural soil samples, with and without a history of compost application, were analysed for their plastic content (> 2 mm). However, difficulties were encountered in sourcing samples from agricultural land with a long history of compost application. Nevertheless, samples were available from a farm which had two adjacent fields, one of which had a long history of FC application (10 t/ha every 5 years) and the other had no history of compost application. A plastic assessment was performed in accordance with the PAS100: 2011, AfOR MT PC&S methodology, and samples were assessed in triplicate. No plastic was detected in the samples taken from the soil with no history of compost application, whereas the samples from the field that received compost had a plastic content which ranged from 0.018% to 0.236% w/w DM. These results demonstrate that food compost is a source of plastics to agricultural soil.

Care must be taken when drawing conclusions from these particular results, as the experiment involved the comparison of just two fields; however, recent work has also confirmed that compost application can be a source of plastic in soils (Piehl *et al.*, 2018; Weithmann *et al.*, 2018; Braun *et al.*, 2021).

9.3 Characterisation of Plastics by Infrared Spectroscopy

To better understand the type of plastic polymers that were found in the soil samples, some plastic from a GC sample (GC4) and a horticultural soil sample where compost had been used were analysed using attenuated total reflectance (ATR) Fourier-transform infrared (FTIR) spectroscopy. FTIR spectroscopy can identify plastic polymers based on their characteristic infrared (IR) spectra, while the addition of ATR helps to identify plastic polymers with high accuracy (Jung *et al.*, 2018). A total of 26 pieces of plastic were analysed using this method (Table 9.1).

FTIR spectroscopy is becoming more prevalent in identifying plastic types from environmental samples; however, it has limitations for analysing plastic from high organic matter samples, such as compost and soil, because of the adsorption of organic matter onto the plastic particles.

Only two plastic polymers were detected in the soil sample, polypropylene and polystyrene, whereas a wider range of plastics were detected in the compost sample, including polypropylene, low-density polyethylene and polyethylene terephthalate (Table 9.1).

The classification of plastic conducted by ATR FTIR spectroscopy revealed more detailed information about the plastic types found in compost and soil samples beyond the basic categories of hard, soft or

Table 9.1. Plastic polymers identified by ATR FTIR spectroscopy

Type	Abbreviation	Compost	Topsoil
Polypropylene	PP	5	1
Low-density polyethylene	LDPE	3	0
High-density polyethylene	HDPE	1	0
Polystyrene	PS	2	1
Polyvinyl chloride	PVC	0	0
Polyethylene terephthalate	PETE	2	0
Latex	Latex	1	0
Unknown		6	4

plastic wrap. It also showed that visual assessment of plastic content can be biased, and certain types may not be able to be identified by ATR FTIR spectroscopy. Although the use of IR techniques in the classification of plastics in environmental samples is a recent development, a larger monitoring programme to quantify and characterise plastic contamination should be put in place, using both visual and laboratory methods. This programme would need to address the difficulties of sourcing samples from appropriate sites and the variation that can arise from such analytical methods, but it would be crucial that the compost quality be monitored in line with the National Waste Action Plan (Department of Communications, Climate Action and Environment, 2020).

10 Conclusions and Recommendations

The aim of this study was to characterise residual organic waste, namely MS-OFMSW and BSRW, to identify the potential of using residual organic waste for energy recovery, for biogas and biofuel production, and as a soil improver.

Chapter 4 presented the data on the characterisation of residual organic waste in Ireland from industry partners, and then evaluated biological and thermal processes for their potential suitability for obtaining added-value materials from this waste stream. It also considered the lack of data available on the physical parameters and impurity content (e.g. glass, plastics, metals, stones) of the waste, which contributes to the selection of suitable recovery and pre-treatment processes that need to be applied.

Glass content was the main impurity found in the residual organic waste studied, constituting up to 22% (DM) of BSRW. Because of its density, glass accounts for a higher proportion than other impurities, whereas plastics, which represented 6.5% (DM) of BSRW, are more visible and bulkier. This work has established that glass and other impurities such as plastic act as barriers to the reuse of residual organic waste. Independent of the choice of valorisation process, the residual organic waste stream would need to undergo a pre-treatment step to remove undesirable materials.

Chapter 5 concluded that the production of biomethane and the production of bioethanol were the main biological recovery processes best suited to MS-OFMSW. AD plants for MS-OFMSW have been used in many countries, including Ireland. The potential for producing biomethane from MS-OFMSW was 300 L CH$_4$/kg VS, similar to results reported in other studies and by commercial facilities. The implementation of AD is potentially more feasible than the production of bioethanol.

Chapter 6 considered the implementation of commercial bioethanol production in a demonstration plant in Spain. Using the PERSEO Bioethanol® method, in the range of 35–70 L bioethanol/t MS-OFMSW (on a fresh material basis) was produced and, although at an early stage, with future investment and increasing demand for ethanol

from the energy sector, bioethanol production from MS-OFMSW could become more feasible.

BSRW was suitable for testing two main recovery processes that were selected on the basis of physical composition (e.g. material of organic origin versus impurity content). The BSRW 10–40 mm fraction was evaluated as a potential pyrolysis feedstock for energy and biochar production (thermal process).

Chapter 7 considered the use of BSRW 10–40 mm, which showed significant potential for recovery via pyrolysis after undergoing in-vessel composting and feedstock conditioning (e.g. size reduction and inert removal). This process generates syngas, which can be transformed into electricity, and biochar, which can be used in land applications, in waste water treatment or as fuel.

Chapter 8 validated the use of the BSRW 0–10 mm fraction as a soil amendment, as it is composed of 84% organic material (DM). However, the material would still need to undergo a refining process before being used to remove impurities. The case studies presented in this work showed that the production of a soil amendment from BSRW 0–10 mm can be achieved and used in soil remediation and restoration under similar conditions to those for sewage sludge. The case studies conducted as part of the VALOR work showed that the main concern regarding water quality is the potential leaching of nitrogen and phosphorus to adjacent water bodies. The leaching of heavy metals is unlikely to constitute a risk to water quality, since heavy metals are strongly bound to soil organic matter. The 6-year field trial demonstrated that 0–10 mm BSRW blended with subsoil created soil that supported vegetative growth over a prolonged period of time.

A change in policy towards including circular economy considerations in the waste management sector is needed to encourage the reuse of residual organic waste. Biological processes showed the potential to generate biofuels and contribute towards minimising Ireland's fuel imports. Further pilot-scale pyrolysis studies of the BSRW 10–40 mm fraction should be conducted to confirm the quantities of the products

being generated and further characterise the technical viability. Nevertheless, the AD of MS-OFMSW and the reuse of the BSRW 0–10 mm fraction as a soil improver for soil remediation and restoration represent two potential recovery processes that could be implemented as part of an organic waste policy in the near future, using VALOR project data as a basis for formulating the potential regulatory framework.

10.1   Conclusions

- Biological treatments, soil improvers, biofuels and thermal treatments were all identified as offering opportunities to add value to residual organic waste and ensure alternatives to landfill.
- Sampling and characterisation were undertaken to provide specific information on both the physical and chemical composition of MS-OFMSW and BSRW in Ireland.
- Both MS-OFMSW and BSRW are heterogenous, containing varying proportions of organic material, plastic, glass, stones and paper. Given the diverse nature of the material, no single treatment option was identified as being suitable for a stand-alone added-value proposition.
- The 0–10 mm fraction of the BSRW demonstrates similar performance to sewage sludge when used as a soil improver.
- The 0–10 mm fraction of BSRW was successfully used to ensure direct revegetation of a BRDA, while also diverting carbon-rich material from landfill, transforming it into a climate positive activity. The potential carbon benefit of the newly established soils was estimated at 343 tonnes of CO_2 equivalents per hectare.
- Glass is the most common type of impurity found in both MS-OFMSW and BSRW.
- The potential for biomethane production from MS-OFMSW was 300 L CH_4/kg VS; the fact that only one AD plant in Ireland operates on this feedstock indicates the presence of economic barriers to the development of this technology.
- Initial characterisation of MS-OFMSW indicates that its use for bioethanol production may be possible. Using the PERSEO Bioethanol® approach resulted in the production of bioethanol in the range of 35–70 L/t MS-OFMSW (on a fresh material basis). However, technology for handling such heterogenous material remains in its infancy.

- The chemical compositions of MS-OFMSW and BSRW indicate that the production of biodiesel from either would not be suitable.
- In 2018, 138,000 tonnes of BSRW was landfilled; had the 41% of this that is less than 10 mm been used as a soil improver, Ireland's recycling rate would have been increased by between 1% and 2%.
- The quality of compost produced from food waste is significantly influenced by the presence of impurities in brown bins.
- All residual organic waste could be diverted from landfill first by recovering energy through AD or fermentation and then by in-vessel composting and post-composting separation into 0–10 mm and 10–40 mm fractions. The 0–10 mm fraction would need to be further refined to remove impurities for recycling and could then be used as a soil improver, while the 10–40 mm fraction would be suitable for pyrolysis, producing energy and biochar.

10.2   Recommendations

- Differentiation is needed between the BSRW that is stabilised and disposed of in landfill and the 0–10 mm subfraction of BSRW which is subject to additional screening to remove impurities and ensure its suitability for use as a soil improver. It is estimated that on a w/w basis approximately 30–40% could be diverted from landfill.
- Active soil organic matter and microbial activity are essential elements of a healthy soil system. The 25 mmol O_2/kg OM/hour OUR limit described in the EU Fertiliser Regulation (EU, 2019) should be the stability reference for CLO (0–10 mm BSRW) destined for use as a soil improver.
- Improvements in the glass separation rate that could help to reduce its content in BRSW should be investigated.
- A regulatory framework should be developed for using CLO (0–10 mm BSRW) in a controlled and verifiable manner, similar to the nutrient management regime under which sewage sludge is applied to land.
- The carbon sequestration arising from the use of CLO as a soil improver should be considered by policymakers when devising new national policy.
- Financial incentives are needed to support the development of AD infrastructure for MS-OFMSW.

- Additional work is needed to further explore the potential use of MS-OFMSW in bioethanol production.
- A system for penalising people who routinely place items unsuitable for composting in the brown bin should be rolled out to reduce the impurities in food waste compost.
- The current treatment of residual organic waste could be improved based on the waste's characteristics. When separated into two fractions, 0–10 mm and 10–40 mm, BSRW showed potential to be recovered for use in energy and biochar production and as a soil amendment. Further characterisation of this waste stream is needed, as is the promotion of a viable circular economy approach to waste management.
- The choice of suitable processes for the valorisation of residual organic waste and the generation of added-value products must take into consideration unwanted materials (e.g. impurities) and include an appropriate pre-treatment stage. The results presented in this study show that alternative fuels and energy can be produced from residual organic waste. This would contribute to maximising the benefits from Ireland's waste output.
- BSRW 0–10 mm can be used as a soil improver for soil remediation, restoration and non-agricultural production, whereas BSRW 10–40 mm showed significant potential for pyrolysis

treatment, resulting in the generation of energy and added-value products, such as biochar and bio-oil.
- The characterisation of the potential high-value recovery processes for the valorisation of MS-OFMSW and BSRW should be used to contribute to more informed policy and waste management decisions.
- Larger-scale studies are needed to better inform the MS-OFMSW pre-treatment stages and to optimise biofuel and energy production. VALOR project results from field trials conducted with BSRW as a soil amendment could be the basis for informing policy that encourages the use of residual organic waste for soil remediation and restoration, and the development of a regulatory framework for the use of BSRW as a soil amendment.
- The use of BSRW as a soil amendment could be valuable for increasing the long-term soil organic matter status in a non-disturbed system. Its use in non-farming systems could also contribute to promoting carbon sequestration in degraded soils. When residual organic waste is landfilled or incinerated, the carbon is released into the atmosphere.
- Better household/consumer knowledge about compost production and how mismanaged plastic disposal can affect compost quality and result in soil contamination is needed.

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Abbreviations

AD	Anaerobic digestion
ANOVA	Analysis of variance
ATR	Attenuated total reflectance
BET	Brunauer–Emmett–Teller
BOD	Biochemical oxygen demand
BRDA	Bauxite residue disposal area
BSRW	Bio-stabilised residual waste
CLO	Compost-like output
DM	Dry matter
EPA	Environmental Protection Agency
FC	Food waste compost
FTIR	Fourier-transform infrared
GC	Green waste compost
ICP	Inductively coupled plasma
IR	Infrared
MS-OFMSW	Mechanically separated organic fraction of municipal solid waste
MSW	Municipal solid waste
OUR	Oxygen uptake rate
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
RDF	Refuse-derived fuel
SSF	Simultaneous saccharification and fermentation
VALOR	Valorisation Alternatives to Landfill for Organic Residues
VS	Volatile solid
v/v	Volume per volume
WEEE	Waste electrical and electronic equipment
w/w	Weight per weight

Appendix 1   Bauxite Residue Experimental Data

Table A1.1. Characteristics of the bauxite residue

Parameters (DM)	Bauxite residue average
Soil pH	10.2
Organic matter (%)	6.7[a]
Electrical conductivity (µS/cm)	2830
Total nitrogen (%)	<0.02
Phosphorus (mg/L)	<2.5
Potassium (mg/L)	59.2
Magnesium (mg/L)	<5
Sodium (mg/L)	4805
Calcium (mg/L)	<503

[a]Note that the loss on ignition method overestimates organic matter in the bauxite residue because of the loss of structural water at 550°C.

Source: personal communication.

Table A1.2. Properties of the BSRW and commercial compost used in the BRDA trial

Parameter (DM)	BSRW (soil improver)	Commercial compost
pH	7.6	8.7
Electrical conductivity (mS/cm)	6.44	4.7
Carbon (%)	27.8	19.2
Organic matter (%)	60.9	44.7
Nutrients (%)		
Nitrogen	2.49	1.70
Phosphorus	0.35	0.45
Potassium	0.77	1.73
Magnesium	0.47	0.97
Sulfur	0.64	0.44
Calcium	4.40	6.01
Sodium	0.64	0.53
Metals (mg/kg)		
Cadmium	1.4	1.0
Chromium	27.8	36.3
Lead	191.0	57.6
Mercury	0.2	0.3
Nickel	51.4	26.1
Zinc	630.0	396.0
Copper	157.0	122.0
PCB EC7 (µg/kg fresh)	<2	<2
PAH EPA16 (mg/kg fresh)	1.67 (DM: 1.87)[a]	<1
OUR (mmol O_2/kg OS/hour)	23.6	24.1
E. coli (CFU/g)	<10	<10
Salmonella	Not detected	Not detected
Impurities (>2 mm) (%)	1.80	<0.1

[a]DM calculated from the dry matter value. All other results for PAHs and PCBs are below the limit of detection.

Table A1.3. Organic contaminants measured in the bauxite residue without organic amendments (BRDA: no compost), after adding commercial compost (control area) and after adding BSRW as a soil improver (test area)

Organic contaminants (fresh basis)	BRDA (no compost)	Control area (current approach)	Test area (BSRW)
PAHs (mg/kg)			
Total EPA 16 PAH	< 1	< 1	< 1
Naphthalene	< 0.05	< 0.05	< 0.05
Acenaphthylene	< 0.05	< 0.05	< 0.05
Acenaphthene	< 0.05	< 0.05	< 0.05
Fluorene	< 0.05	< 0.05	< 0.05
Phenanthrene	< 0.1	< 0.1	< 0.1
Anthracene	< 0.05	< 0.05	< 0.05
Fluoranthene	< 0.1	< 0.1	< 0.1
Pyrene	< 0.1	< 0.1	< 0.1
Benzo[a]anthracene	< 0.1	< 0.1	< 0.1
Chrysene	< 0.1	< 0.1	< 0.1
Benzo[b]fluoranthene	< 0.1	< 0.1	< 0.1
Benzo[k]fluoranthene	< 0.1	< 0.1	< 0.1
Benzo[a]pyrene	< 0.1	< 0.1	< 0.1
Indeno[1,2,3-cd]pyrene	< 0.1	< 0.1	< 0.1
Dibenz[a,h]anthracene	< 0.1	< 0.1	< 0.1
Benzo[g,h,i]perylene	< 0.1	< 0.1	< 0.1
PCBs (µg/kg)			
Total PCBs [EC7]	< 2	< 2	< 2
PCB-28	< 0.5	< 0.5	< 0.5
PCB-52	< 0.5	< 0.5	< 0.5
PCB-101	< 0.5	< 0.5	< 0.5
PCB-118	< 0.5	< 0.5	< 0.5
PCB-153	< 0.5	< 0.5	< 0.5
PCB-138	< 0.5	< 0.5	< 0.5
PCB-180	< 0.5	< 0.5	< 0.5

Appendix 2   Summary of Methods

Table A2.1. Summary of methods

Method	Brief description	References
Analysis of soils, herbage, residues, organic amendments and solid biofuels		
Determination of moisture	Sample dried at 105°C The difference in mass before and after is used to calculate sample moisture %	EN 14774-2:2009: Solid Biofuels – Determination of Moisture Content – Oven Dry Method
Determination of impurities	Physical impurities and stones are determined after dry sieving	CEN/TS 16202:2013: Sludge, Treated Biowaste and Soil – Determination of Impurities and Stone AfOR MT PC&S: Method to Determine Particle Size Distribution of Compost and its Physical Contaminant and Stone Contents
Determination of pH	1:2.5 ratio – deionised water	EN 13037:2009: Soil Improvers and Growing Media – Determination of pH Agricultural Development and Advisory Service, 1986. *The Analysis of Agricultural Materials*. Ministry of Agriculture, Fisheries and Food. Reference Book 427 S.I. No. 605/2017: European Union (Good Agricultural Practice for Protection of Waters) Regulations 2017
Determination of electrical conductivity	1:2.5 ratio – deionised water	EN 13038:2009: Soil Improvers and Growing Media – Determination of Electrical Conductivity
Determination of organic matter content	Sample is ignited at 550°C The difference in mass before and after the ignition is used to calculate the loss on ignition	EN 15935:2010: Sludge, Treated Biowaste, Soil and Waste – Determination of Loss on Ignition
Extractable phosphorus (Olsen)	Sodium bicarbonate pH 8.5 Flow injection analysis/colorimetry	Agricultural Development and Advisory Service, 1986. *The Analysis of Agricultural Materials*. Ministry of Agriculture, Fisheries and Food. Reference Book 427
Exchangeable cations – cation exchange capacity	Ammonium acetate/potassium chloride ICP-OES discrete analyser	Agricultural Development and Advisory Service, 1986. *The Analysis of Agricultural Materials*. Ministry of Agriculture, Fisheries and Food. Reference Book 427
Determination of total carbon and total nitrogen	Dry combustion Elemental analyser	ISO 10694:1995: Soil Quality – Determination of Organic and Total Carbon after Dry Combustion (Elementary Analysis)
Determination of available calcium and sodium	Ammonium nitrate 1M Atomic absorption	Horneck, D.A. *et al*., 1989. *Methods of Soil Analysis Used in the Soil Testing Laboratory at Oregon State University*. Corvallis, Oregon Agricultural Development and Advisory Service, 1986. *The Analysis of Agricultural Materials*. Ministry of Agriculture, Fisheries and Food. Reference Book 427

Table A2.1. Continued

Method	Brief description	References
Determination of total major and minor metal elements	The sample is digested, and elements dissolved in the acid are analysed by ICP-OES/ICP-MS	EN 15297:2011: Solid Biofuels – Determination of Minor Elements
Determination of PAHs and PCBs	GC-MS	EN 16167: 2012–08: Sludge, Treated Biowaste and Soil – Determination of Polychlorinated Biphenyls (PCB) by Gas Chromatography with Mass Selective Detection (GC-MS) and Gas Chromatography with Electron-capture Detection (GC-ECD)
		FprCEN/TS 16181: 2012–03: Sludge, Treated Biowaste and Soil – Determination of Polycyclic Aromatic Hydrocarbons (PAH) by Gas Chromatography (GC) and High Performance Liquid Chromatography (HPLC)
Specific analysis conducted in MS-OFMSW and BSRW		
Bromatological analysis (MS-OFMSW and BSRW)	Analysis of sugars, fats, lignin, and water/ethanol extractives (MS-OFMSW and BSRW)	Sluiter, A. *et al.*, 2005. *Determination of Extractives in Biomass: Laboratory Analytical Procedure (LAP)*. Technical Report NREL/TP-510-42619. National Renewable Energy Laboratory
		Sluiter, A. *et al.*, 2006. *Determination of Sugars, By-products, and Degradation Products in Liquid Fraction Process Samples: Laboratory Analytical Procedure (LAP)*. Technical Report NREL/TP-510-42623. National Renewable Energy Laboratory
		Sluiter A. *et al.*, 2008. *Determination of Structural Carbohydrates and Lignin in Biomass*: *Laboratory Analytical Procedure (LAP)*. Technical Report NREL/TP-510-42618. National Renewable Energy Laboratory
Determination of biomethane potential (MS-OFMSW)	Measurement of maximum vol. methane produced per g/VS substrate: optimum conditions	Wall, D. *et al.*, 2013. The potential for biomethane from grass and slurry to satisfy renewable energy targets. *Bioresource Technology* 149: 425–431
Determination of calorific value (MS-OFMSW and BSRW)	Measurement of the energy liberated by complete oxidation of unit mass or volume of a fuel	EN 14918:2009: Solid Biofuels – Determination of Calorific Value
Ultimate analysis (MS-OFMSW and BSRW)	Determination of carbon, hydrogen, nitrogen and sulfur	EN 15407:2011: Solid Recovered Fuels – Methods for the Determination of Carbon (C), Hydrogen (H) and Nitrogen (N) Content
		ISO 16994:2016: Solid Biofuels – Determination of Total Content of Sulfur and Chlorine
Proximate analysis (MS-OFMSW and BSRW)	Determination of moisture, volatile matter, fixed carbon, and ash	ISO 18122:2015: Solid Biofuels – Determination of Ash Content
		ISO 18123:2015 – Determination of the Content of Volatile Matter
		EN 14774–2:2009: Solid Biofuels – Determination of Moisture Content – Oven Dry Method
Stability of composted materials (BSRW)	Determination of microbial activity in a sample by estimating the respiration rate	EN 16087–1:2011: Soil Improvers and Growing Media – Determination of the Aerobic Biological Activity – Part 1: Oxygen Uptake Rate (OUR)
Phytotoxicity of composted materials (BSRW)	Determination of decrease (or the absence) of germination of cress on soil improvers or growing media in comparison to a control sample	EN 16086–2:2011: Soil Improvers and Growing Media – Determination of Plant Response – Part 2: Petri Dish Test Using Cress

Table A2.1. Continued

Method	Brief description	References
Ecotoxity of composted materials (BSRW)	Determination of the mortality of earthworms in soil improvers or growing media in comparison to a control sample	Elliston, T. and Oliver, I.W., 2019. Ecotoxicological assessments of biochar additions to soil employing earthworm species *Eisenia fetida* and *Lumbricus terrestris*. *Environmental Science and Pollution Research International* 27: 33410–33418
		OECD, 2016. *OECD Guideline for the Testing of Chemical: Earthworm Reproduction Test (*Eisenia fetida/ Eisenia andrei*). Test Guideline 222. Organisation for Economic Co-operation and Development
Water analysis		
Determination of pH and conductivity	Direct pH and conductivity measurement	APHA 23rd edition 2017 4500-H+
		APHA 23rd edition 2017 Method 2510
Determination of BOD 5-day total		Methods for the Examination of Waters and Associated Materials, HMSO 1988 5 Day BOD 11 7522120, American Public Health Analysis of Water and Wastewater 5210 and 4500-C Association (APHA) 23rd edition 2017
Determination of nitrate, ammonium orthophosphate	Automated colorimetry	APHA 23rd edition 2017
Determination of total metals	ICP-MS	US EPA 200.7
		CSN EN ISO 11885
		US EPA 6010
		SM 3120
		CSN 75 7358

Appendix 3   Potential Carbon Mass Balance Estimate

Table A3.1. Carbon sequestration estimates for remediated BRDA

Tonnes of organic matter per hectare in BRDA	600
DM of CLO	75%
Tonnes of DM per hectare in BRDA	450
Organic content of CLO	40%
Tonnes of organic matter per hectare	180
Average carbon content of organic matter	58%
Tonnes of carbon per hectare	104.4
Conversion taking into account atmospheric losses	90%
Tonnes of stable carbon per hectare	93.96
CO_2 equivalent for carbon[a]	3.66
CO_2 equivalent saving associated with 1 hectare of BRDA restoration	344

[a]**https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator (accessed 10 February 2023).**

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, sriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

> Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
> Sceitheadh fuíolluisce uirbigh;
> Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
> Foinsí radaíochta ianúcháin;
> Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

> Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
> Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
> Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
> Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
> Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
> Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
> An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

> Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
> Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
> An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
> Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

> Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
> Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

> Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
> Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;

> Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

> Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
> Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
> Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
> Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
> Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

> Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
> Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

> Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
> 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 um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

> Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
> An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
> Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
> Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

> Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

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

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht 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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