CIRCULAR ECONOMY:

CARBON, NUTRIENTS AND SOIL

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International Solid Waste Association

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The International Solid Waste Association (ISWA) is a global, independent and non-profit making association, working in the public interest to promote and develop sustainable waste management.

ISWA has members in more than 60 countries and is the only worldwide association promoting sustainable, comprehensive and professional waste management

ISWA's objective is the worldwide exchange of information and experience on all aspects of waste management. The association promotes the adoption of acceptable systems of professional waste management through technological development and improvement of practices for the protection of human life, health and the environment as well as the conservation of materials and energy resources.

ISWA's vision is an Earth where no waste exists. Waste should be reused and reduced to a minimum, then collected, recycled and treated properly. Residual matter should be disposed of in a safely engineered way, ensuring a clean and healthy environment. All people on Earth should have the right to enjoy an environment with clean air, earth, seas and soils. To be able to achieve this, we need to work together.

Executive summary

In June 2014 the ISWA Board established the ISWA Task Force on Resource Management. This report is one of six reports prepared by the Task Force and describes the potential value that can be recovered from organic wastes. It focusses specifically on the carbon and plant nutrient content in organic wastes and how they can be recycled to create high value products, contribute towards feeding an ever-growing global population, as well as help conserve resources and improve soils. It focusses on OECD countries, although the principles outlined in this report are global.

Organic wastes are those that are derived from living things, both plants and animals. Within OECD countries, an estimated 177 million tonnes of organic municipal waste is generated annually, of which only 66 million tonnes is recycled through composting and anaerobic digestion. Assuming an overall maximum capture rate of 70%, this means that potentially 124 million tonnes a year of municipal organic waste could be collected for biological treatment, which equates to an additional 58 million tonnes a year over and above what is currently collected. The potential for organic commercial and industrial wastes, crop residues and manures is largely unknown but is likely to be considerable and well in excess of the municipal waste fraction.

The resources contained within this 124 million tonnes of municipal organic waste are significant, holding anywhere between 0.1 to 3 million tonnes of nitrogen and 4 to 41 million tonnes of carbon. This carbon and nutrients can be extracted, modified, or transformed into a range of different products which can be classed into three main categories:

- high value, low volume products – these are bio-based fine and speciality chemicals which are used in relatively small amounts for high-technology applications;
- medium value, medium volume products – these include commodity chemicals, bioplastics, biogas, struvite, fibreboard and cellulose; and
- high volume, low value products - these are primarily compost and digestate, resulting from composting and anaerobic digestion processes, respectively.

The global market potential for these products is potentially massive, with estimates in the USD billions annually. In most cases, the economic competitiveness of manufacturing these bio-based products from secondary waste-derived resources will be linked to the relative cost of manufacture of primary resources from petroleum-based precursors. The current low price of crude oil, coupled with subsidies for fossil fuels, established supply networks and economies of scale for primary resources all weigh against the development of new infrastructure and processing capacity to exploit secondary waste-derived resources. Policy and fiscal incentives to stimulate demand and overcome investment and technical barriers to supply could usefully be developed in order to 'unblock' this significant economic potential.

Similarly, extant waste legislation also serves to act as a barrier towards integrating waste-derived resources into a materials-based economy, both logistically and economically. This uncertainty needs to be addressed through an enabling legislative framework coupled with the development of new quality specifications and end-of-waste criteria throughout the biomass value chain.

Although compost and digestate currently command relatively low prices compared with other bio-based products, they represent significant sources of carbon and plant nutrients that can benefit both crops and soils. Overall, across OECD countries, it is estimated that 66 million tonnes of waste was composted/anaerobically digested in 2013, which would result in approximately 22 million tonnes a year of compost/digestate being produced. Although agriculture is the dominant market sector, the potential maximum supply of all manufactured compost/digestate falls well below the theoretical agricultural land bank needed to accommodate these products.

The nutrient value of compost and digestate can be calculated relative to its equivalent for inorganic fertilizer. Across the OECD, taking into account actual compost/digestate production, somewhere in the region of USD 121 million in nutrient value is currently being realised annually, which could increase to USD 227 million per annum if all municipal organic wastes were captured for recycling.

Although the nutrient value of compost and digestate can be calculated with relative ease, the benefit of organic carbon and its effect on soil organic matter is currently not valued in monetary terms. Soil organic matter represents a finite and vulnerable resource, acting as a substantial carbon sink. As most cultivated arable soils show signs of organic matter loss, this not only has the potential to reduce productivity, but also has important climate change implications.

An estimated five million tonnes of stable carbon (and ten million tonnes of carbon in total) is applied to OECD soils every year in the form of compost/digestate, which could rise to six million tonnes and 12 million tonnes, respectively, if all of the potential municipal organic waste was composted and/or digested. This could potentially make a significant contribution towards improving soil function and increasing the soil carbon pool.

The monetary value to farmers of improving soil structure and function through long term compost and digestate use could usefully be assessed, encompassing, for example, savings through reduced/ improved tillage, reduced irrigation, improved fertilizer utilization and reduced soil erosion. Integrating these benefits into national and regional agricultural policies (including subsidies) would create a powerful driver.

Compost and digestate quality is of the upmost importance. National quality standards and end-of-waste criteria overseen by an independent certification body is a necessary precursor for sustainable markets and end-user acceptance, as they ensure that only quality assured products are applied to soils. Standards and certification schemes exist in some, but not all, OECD countries.

The waste management sector has an important role to play in collecting, transporting and treating organic wastes, and currently possesses a range of technical competencies to carry this out effectively. In order to extract greater value from organic wastes and manufacture a range of high value products, these services will need to be developed and extended still further. The waste sector, however, cannot work in isolation: it will need to build partnerships with other complementary sectors and expand its core competencies, diversify its operational standards and occupational qualifications, and extend training across all professional levels. In addition, the waste sector will also need to increase and improve the scope of separate organic waste collections (in order to maximise quality and reduce variability), as well as improve pre-treatment methods. The latter is particularly important to remove contamination and provide feedstocks of the correct composition for use as raw materials (precursors) for conversion into higher value products. Further research and development is needed to improve the effectiveness of pre-treatment techniques, and to adopt those currently employed in comparable industry sectors. In addition, new industry quality specifications and end-of-waste criteria will need to be developed throughout the organics value chain. Managing variable, heterogeneous wastes remains a significant challenge for the sector.

In order to fully embrace the potential opportunities available through manufacturing higher value products, synergies could be realised by co-locating waste processing plants alongside more sophisticated biorefinery operations. This has the potential to realise significant capital and operational cost savings, which would allow for more cost effective cascading of resources.

In conclusion, the carbon and nutrient value in organic waste is currently being realised, at least in part. Significant potential exists to maximise collection and recovery of organic wastes across OECD countries, and to use these to manufacture high-value bio-based products, as well as recycling nutrients and improving soils through the application of quality compost and digestate. To realise this, co-locating treatment and manufacturing processes at single sites, overcoming technical, logistical and fiscal barriers, and valuing the benefits of improving natural capital (in particular soils) all need to be addressed.

Prepared by the ISWA task force on resource management

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Jane originally trained as a microbiologist, has a doctorate in biochemistry and an MBA. She trades as Carbon Clarity, provides consultancy and writing services, and is currently vice chair of the International Solid Waste Association's Biological Treatment Working Group.

Jane has authored a number of technical composting books and has presented at conferences in North America, Europe, Africa and Asia. She has recently launched Carbon Clarity Press, specialising in publishing resources to inspire sustainable living.

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Introduction

All life on earth is dependent upon carbon and nutrient cycling. Ecosystems rely upon the availability of organic and inorganic matter for assimilation into complex compounds by living organisms, followed by subsequent decomposition back into their constituent parts. Ever since humans started to grow crops and herd animals, these nutrient cycles have been distorted as new ecosystems are formed and the flow of carbon and nutrients changed. In most parts of the world today, agricultural systems provide both plant and animal matter for human consumption. These foodstuffs are often traded globally, resulting in the transport of carbon and nutrients between countries and continents.

Modern society is also wasteful, with an estimated 1.3 billion tons of food waste lost or wasted every year globally[1]. In addition, the gardens, parks and landscaped features that surround our homes and places of work generate significant quantities of botanical residues, all of which need to be managed. Collectively termed 'organic' wastes, these materials are natural in origin and contain significant quantities of carbon and plant nutrients; they are the focus of this report.

The disposal of organic wastes in landfill leads to the diversion of much of this carbon and nutrients away from ecosystems, rendering it practically unavailable for effective uptake and reuse. In addition, the uncontrolled decomposition of organic wastes in dumpsites and some landfills also leads to the emission of methane, which is a potent greenhouse gas and an acknowledged source of anthropogenic climate change.[2]

Coupled with concerns about waste disposal, is the desire to manufacture a range of products from bio-based, instead of petroleum-based, precursors. Bio-based products that are also biodegradable offer a tantalising opportunity to reduce society's dependence on fossil fuels and concurrently reduce quantities of disposed waste. When manufactured from secondary, rather than primary, raw materials, this has the potential to create a win-win situation, contributing towards the concept of a 'circular economy'[3].

In tandem with modern society's wasteful habits, is the need to increase agricultural productivity as well as stem the degradation of soils. Soils are a non-renewable resource and are currently under threat. From a human perspective, one of the most important functions soils play is as a medium in which to grow crops for human and livestock consumption. Projected population increases from 7.2 billion in 2013 to 9.6 billion by 2050[4] means that there will be greater pressure to increase outputs, whilst degradation processes will necessarily reduce the capacity of some soils to maintain current yields. To meet these demands, the Food and Agriculture Organization of the United Nations (FAO) has estimated that agricultural production must increase by 60 percent globally between 2005/2007 and 2050, increasing to almost 100 percent in developing countries.[5,6] This is a major challenge.

Pressure on agricultural land to produce more food to feed an ever-growing population, means that productivity rates and agricultural efficiencies need to increase, which has led to an increasing demand for fertilizers. Modern agricultural systems have relied on the use of inorganic fertilizers for decades, supplying the three primary plant nutrients, namely: nitrogen (N), phosphate (P_2O_5) and potash (K_2O). The FAO has estimated that world demand for total fertilizer nutrients is estimated to grow at 1.8 percent per annum from 2014 to 2018[7]. Some parts of the world are net importers of some nutrients, whilst others are net exporters. The challenge is to deliver the right quantities of fertilizers in the right place at the right time.

Inorganic nitrogen fertilizers are primarily made from ammonia, which is manufactured through synthetic chemistry by the Haber process. As most ecosystems are nitrogen-limited for growth, the widespread use of synthetic nitrogen fertilizers has uncoupled the rate of plant growth from the underlying natural rate of nitrogen fixation, meaning that crop yields have been significantly enhanced. However, the Haber process is energy intensive, meaning that the cost of nitrogen fertilizer is linked to the price of energy.

Phosphate fertilizer is obtained from mined phosphate rock, which is a finite resource. As mines are centred on a few geographical areas, many parts of the world rely upon imports. For example, the European Commission has estimated that the European Union relies upon imports for 92% of its use[8]. Although reserves of rock phosphate have been estimated to last somewhere between 300-400 years[9], the uneven spatial distribution of mines and underlying geopolitical uncertainty, has led the European Commission to place it on the list of critical raw materials[10]. Recycling of phosphorus is now receiving considerable attention, with many European countries establishing national phosphorus platforms.[11]

Recycling the carbon and nutrients in organic wastes therefore has a number of significant benefits, including:

- conserving resources;
- reducing the environmental impact of waste disposal;
- mitigating climate change;
- enhancing the functionality of soils;
- feeding an ever-growing global population; and
- decoupling product manufacture from petroleum precursors and the use of fossil fuels.

This report describes the ways in which carbon and plant nutrients in organic wastes can be recycled to meet these aspirations.

Organic wastes

Definition of organic wastes

The term 'organic waste' is ill-defined and can mean different things to different people. Within the context of this document, 'organic wastes' have been assumed to include bio-wastes defined in the EU Waste Framework Directive 2008/98/EC (namely, biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants), as well as other wastes that are similar in nature to bio-wastes, such as manures and crop residues. Sewage sludges are specifically excluded. Notably, bio-wastes are primarily generated in urban areas.

Organic wastes supply chains

Organic wastes may arise at any point following growth of a plant or animal, to final end use by a consumer. By their nature they are recycled through natural biologically-mediated decomposition processes (either aerobically or anaerobically), or burnt to release the energy stored in them.

Some crop residues (such as straw and bagasse) and livestock manures, may be recycled *in situ* at the places where they arise, such as farms. Crops and livestock transported off-farm, will be either consumed directly or processed prior to consumption. Some of this material will be wasted pre-consumption, some at the point of consumption, and some post-consumption. These wastes are generally collected and recycled *ex situ*, or disposed of (e.g. through landfill or incineration).

Another important source of organic wastes are non-crop plants, which arise in urban gardens and parks, or through landscaping activities and the like. These are often referred to as 'green wastes' or 'garden wastes'. Some will be recycled *in situ*, either through home or on-site composting, chipping or mulching activities. Others will be collected and recycled *ex situ* at composting, anaerobic digestion or biomass facilities.

This is a complex pathway that has been summarised conceptually in Figure 1.

Quantities and composition of organic wastes

Estimated quantities

Significant quantities of organic wastes are generated annually. These are summarised in Table 1.

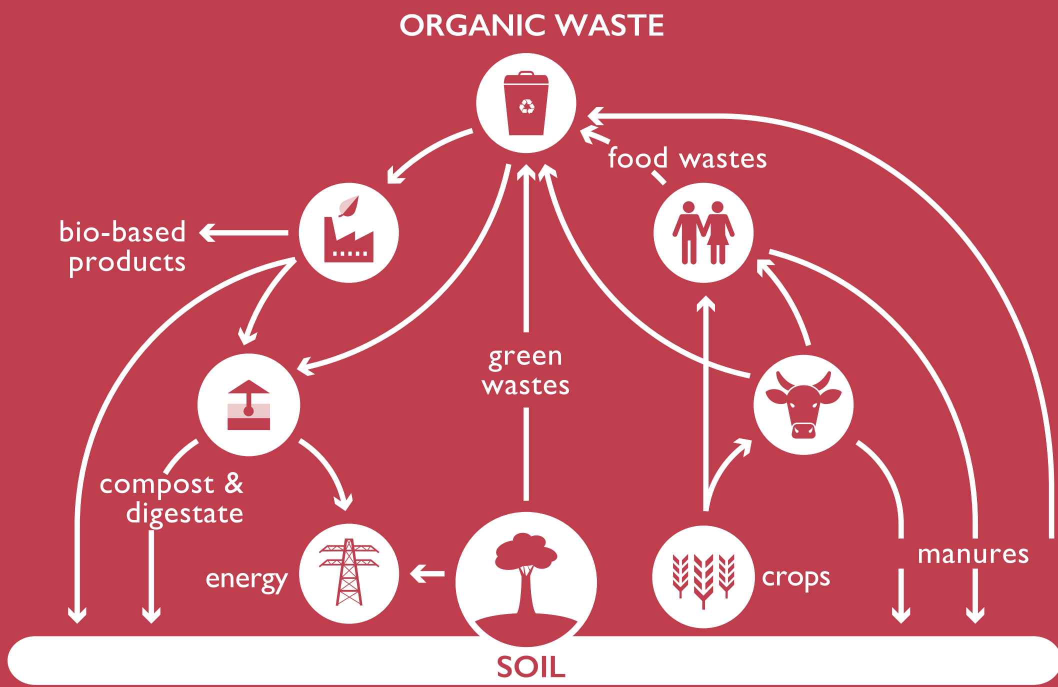
One of the major barriers to effective waste analysis is the reliability and variability of data. As countries quantify and define wastes in different ways, this means that like-for-like comparisons between countries, regions and continents is difficult.

Notably, there is a lack of meaningful data on commercial and industrial waste arisings, composition and growth. Whilst some will be classified as municipal solid waste (MSW), it is probable that a significant proportion is under represented or fails to be reported in official data. A recent report by the OECD highlighted this difficulty, especially for manufacturing and related sector food wastes, due to difficulties in defining and quantifying food wastes[13]. Similarly, data on manures and crop residues within OECD countries are not readily available. Consequently, this report necessarily focusses solely on MSW.

Waste composition

International data on waste composition are scant, although the World Bank has presented some global and regional estimates.[16] They suggested that, globally, the largest fraction of MSW is the organic fraction at 46% by mass (in 2009). This includes food scraps, yard (leaves, grass, brush) waste, wood and process residues.

Fig. 1 | Simplistic representation of organic waste origins and recycling routes



Tab. 1 | Estimated organic waste arisings

WASTE TYPE	REGION	ESTIMATED ANNUAL ARISING (TONNES)	REFERENCE YEAR	NOTES	REFERENCE
Municipal waste[a] (total of organic & non-organic)	OECD countries	656 million	2013	Total municipal waste figures include household and those similar to household waste. Data on waste composition are not available.	12
Organic fraction of MSW	OECD countries	177 million	2013	Estimate based on the organic fraction comprising 27% (see below).	Derived from OECD data, *ibid*
Animal and mixed food waste; vegetal wastes	EU28	94 million	2012	Food waste data for OECD are lacking due to differences in the way it is classified.[13]	14
Manures	EU28	16 million	2012	Difficult to measure quantities e.g. manures deposited in-field and those in housing/enclosures.	*Ibid*
Crop residues	Global	4 billion	2001	Difficult to measure quantities e.g. those left in-field and those collected for recycling/disposal.	15

[a] The OECD defines municipal waste as waste originating from: households, commerce and trade, small businesses, office buildings and institutions (schools, hospitals and government buildings), selected municipal services, i.e. waste from park and garden maintenance, waste from waste from street cleaning services. It includes waste collected through door-to-door traditional collection (mixed household waste), and fractions collected separately for recovery operations (through door-to-door collection and/or through voluntary deposits). It excludes waste from municipal sewage network and treatment, and; municipal construction and demolition waste. For a full definition see.[12]

The proportion of organic waste in the MSW stream is dictated by a number of different factors, such as *inter alia* demography (city vs. rural dwelling), climate (which affects green waste arisings), food preparation and eating habits, and wealth (the latter affecting quantities of food waste arisings). This means that the relative proportions of food waste to green waste in the organic fraction will vary considerably between OECD countries.

Overall, the organic fraction of municipal waste is generally higher in low income countries (64%) compared with high income countries (28%)[16]. For OECD countries, the World Bank has estimated it to be an average of 27% (although this varies significantly from 14%-56%); this fraction has been used as the basis for the calculations in this report. Data on the relative proportion of food-to-garden-to-other organic wastes are not available.

Although OECD countries have proportionally less organic waste as a fraction of their MSW, they represent the largest quantities in absolute terms, as OECD countries generate 44% of the world's total MSW (the largest fraction of any region analysed by the World Bank).

The lack of reliable data on commercial and industrial waste, crop residue and manure arisings also means that meaningful insight into this sector's potential value is difficult to estimate.

Waste growth

The estimated quantities of MSW shown in Table 1 do not take into account year-on-year increases in waste arisings. This is a significant issue, especially in those parts of the world experiencing economic growth and increasing consumer prosperity. Overall, for OECD countries, the World Bank has estimated that by 2025, OECD countries will generate 1.74 million tonnes of MSW a day, compared with 1.57 million tonnes in 2012[b] – this represents an increase of 11%. The relative proportion of organic waste is projected to remain the same at about 27%, although this does mean that absolute quantities will continue to increase.

[b] The report was published in 2012, however, it relied upon data sources derived from years prior to this. The baseline year in the report is therefore unclear.

Current and potential organic waste recycling

OECD data indicate that approximately 10% of MSW collected in 2013 was either composted or anaerobically digested[c], which is equivalent to 66 million tonnes. This implies that there is an additional 17% of organic municipal waste that was not treated biologically, which is equivalent to 112 million tonnes a year (figures rounded to nearest integer and not taking into account growth in waste arisings).

Although well designed and well run separate organic waste collection schemes can collect upwards of 85% of the total organic content in MSW, in practice, however, capture rates are likely to be lower across the OECD as a whole. Assuming an overall capture rate of 70%, this means that potentially 124 million tonnes a year could be collected for biological treatment, which equates to an additional 58 million tonnes a year over and above what is currently collected.

The potential for organic commercial and industrial wastes, crop residues and manures is unknown.

Potential nutrient and carbon value

Organic wastes are significant sources of both carbon and plant nutrients, however, estimating their potential value in waste streams is fraught with a number of uncertainties. In general, food wastes tend to be high in moisture and high in nutrients, whilst green wastes tend to have more carbon but lower nutrient and moisture levels, although this does vary according to the time of year. The relative proportion of these two main constituents of the organic fraction of MSW can thus vary significantly depending upon regional, climatic and socio-economic factors.

Using the data presented in Table 1, an estimate of the potential quantities of nutrients is shown in Table 2.

For comparative purposes, 20.9 million tonnes of nitrogen fertilizer was applied to agricultural land across 23 OECD countries in 2009.[19] This means that the organic fraction of MSW alone could potentially account for anywhere up to 14% of the total N applied to OECD agricultural land in 2009.

[c] This is defined by the OECD as being treated in a 'biological process that submits biodegradable waste to anaerobic or aerobic decomposition, and that results in a product that is recovered'.

[d] Minima and maxima values used in the calculation were: total N 1-4% (mass on a dry matter basis); total C 35 – 55% (mass on a dry matter basis); dry matter content 10 – 60 % (of total wet mass). This wide range of variables reflects the diversity in organic waste composition, which can vary significantly depending upon source, location and time of year. In practice, actual values will lie somewhere between the minimum and maximum values quoted.

Tab. 2 | Estimated nutrient quantities in different organic wastes

WASTE TYPE	REGION	ESTIMATED ANNUAL ARISING	NPK* NUTRIENT CONTENT	NOTES
Organic fraction of MSW	OECD countries	177 million tonnes	0.2 - 4.2 million tonnes of N 6.2 to 58.4 million tonnes of C	Based on indicative ranges of N and C content in feedstocks used for composting[d] quoted in reference.[17]
Organic fraction of MSW at 70% capture	OECD countries	124 million tonnes	0.1 - 3.0 million tonnes of N 4.3 - 40.9 million tonnes of C	Assuming 70% of the organic waste fraction is captured for recycling.
Manures	Global	Unknown	128.3 million tonnes of N and 24.3 million tonnes of P	Quoted in[18], which focussed on the spatial distribution of fertilizer and manure application. Total global quantities were not stated.
Crop residues	Global	4 billion tonnes	81 million tonnes (NPK in total)	[15]

* N = nitrogen; P = phosphorus; K = potassium; and, C = carbon

Organic waste derived products

Product categories

The carbon and nutrient content of organic wastes can be extracted, modified, or transformed into a range of different products. As the carbon is present as 'organic carbon' (that is, it contains carbon-carbon bonds) forming complex macromolecules, it has significant potential to be used to manufacture a range of products traditionally derived from fossil fuel precursors. These activities fall under the banner of industrial biotechnology, which seeks to use biological resources to produce materials, chemicals and energy.

Some industrial biotechnology processes are well-established, whilst others are still at the research phase or in the early stage of commercialisation. It is an area that is receiving considerable investment and development, with some large multi-national companies diversifying their business interests (for example, the Spanish company Abengoa, BASF in Germany, Mossi Ghisolfi and Novamont in Italy, and Natureworks in the USA).

Some biotechnological processes use primary raw materials (e.g. corn or sugar cane), industrial or agricultural by-products (e.g. bagasse or straw), and there is now increasing interest to use waste materials. Not only does this extract value and create resources from waste, it also reduces competition on agricultural land to grow crops for human consumption.

Extracting value in the form of chemicals from waste is called waste biorefining and is currently receiving considerable attention as part of the circular economy concept[20]. It is analogous to petroleum refining, where a number of products are derived from organic wastes instead of petroleum. It can employ a range of techniques, including thermal treatment, biologically-mediated processes, enzymatic conversions, and even synthetic biology. Broadly speaking, organic waste-derived products can be classed into three broad categories, as shown in Figure 2; each is discussed separately below.

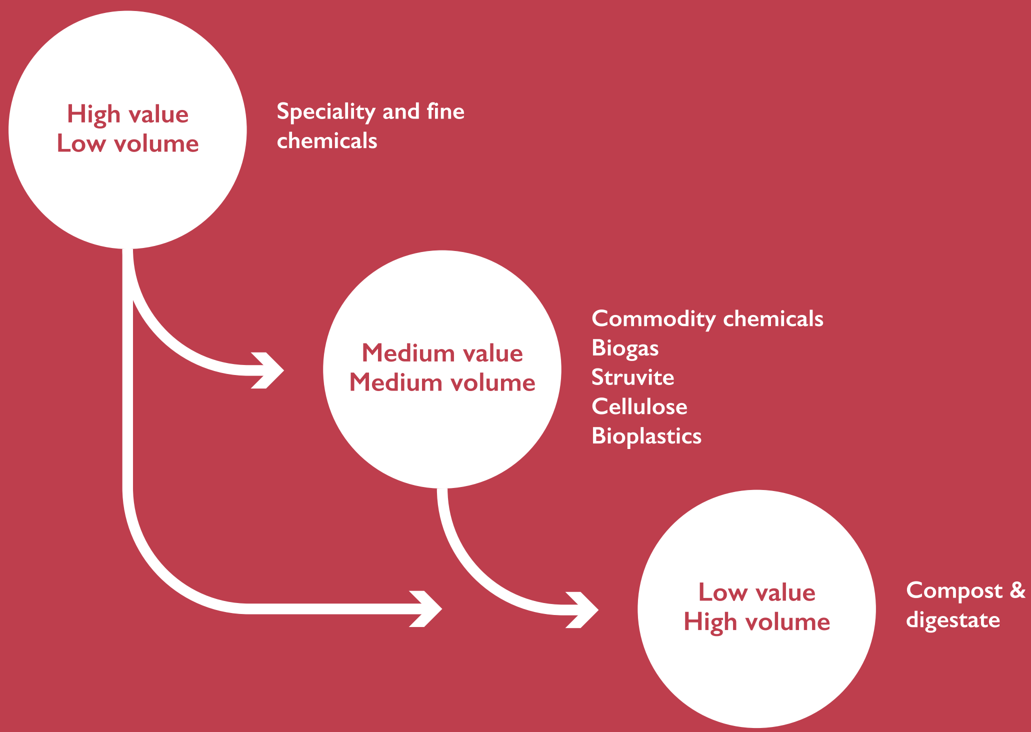
High value, low volume products

This category includes bio-based fine and speciality chemicals which are used in relatively small amounts for high-technology applications. Some products are well-established with defined markets, including, for example:

- the extraction of serum albumins (which are used in laboratory research) from slaughterhouse blood; and
- the extraction of limonene (which is used in cosmetics, as a flavouring and as a cleaning solvent) from citrus fruits.

Although these products are the focus of much scientific research, few are manufactured directly from organic wastes.

Fig. 2 | Value chain for organic waste-derived products



Medium value, medium volume products

These products fall into three main categories:

1. Transformation of specific components in waste into new chemicals for direct application, or as precursors for the synthesis of new products;

2. Physical re-formulation of components in the wastes into new products; and

3. Extraction of energy embedded in the waste, either directly or indirectly.

The main product categories are described below.

Commodity chemicals

Commodity chemicals are produced on a large scale to satisfy the needs of a range of markets. Although manufacture from wastes forms a very small part of this at present, potential for expansion exists (see, for example[21]).

Examples of commodity chemicals that can be derived from waste feedstocks include:

- polyhydroxybutryrate (PHB) and polyhydroxyalkanoate (PHA) – these are bio-based biodegradable plastics that can be used in a range of applications. They are manufactured through microbial fermentation, although production costs are high due to high feedstock (glucose or starch) costs. Alternative precursors have been investigated, including hydrolysed corn starch and soybean oil[22], pre-treated food wastes, waste glycerol, surplus whey[23] and fruit waste[24].

- polylactic acid (PLA) – this is also a bio-based biodegradable polymer that is widely used and typically manufactured from corn starch or sugar cane. PLA production from food wastes[25] has been described.

- in-Butanol and Acetone – these can be manufactured commercially through a *Clostridium* fermentation using agricultural by-products[26].

- other biodegradable plastics – although the polymer composition is not specified, Italian researchers described manufacturing biodegradable plastics from a range of vegetable wastes, including parsley and spinach stems, cocoa pod husks and rice hulls[27].

- lignin derivatives – these are based on the aromatic structures present in wood and by-products from the pulp and paper industry[28]. They may be converted into a range of products, including phenolic resins, wood adhesives[29] and other precursors for chemical syntheses, such as the flavour vanillin and benzene, toluene and xylene (BTX)[28].

- humic acid-derived surfactants – these have been extracted from compost and shown to have good surfactant properties[30].

- C5 and C6 sugars – these are important pre-cursors for a range of products, and are derived from biomass by enzymatic treatment and hydrolysis[31].

The manufacture of bio-based chemicals, whether through traditional synthetic chemistry routes or biologically-mediated reactions, requires 'clean' and chemically pure reactants. This means that, for wastes to be used as a viable alternative to non-waste feedstocks, they will need to be pre-treated effectively so that they contain the correct quantities and concentrations of precursor chemicals. For example, the manufacture of PHA from food wastes requires controlled hydrolysis followed by acetolysis in order to create volatile fatty acids of the correct composition and concentration[25].

Carbon fibre and cellulosic materials

The structural components of woody wastes (cellulose, ligno-celluloses and lignins) can be either chemically extracted and formulated into new products, or reformed mechanically. Some of these are established industries, whilst others are emergent, and include:

- fibreboard/particle board manufacture – this is an established industry, manufacturing a range of structural products (such as plywood, particleboard and fibre boards) which are used in the construction industry. They are produced from either virgin or recycled wood.

- crystalline cellulose – the cellulosic content of certain wastes can be extracted and formulated into specific products. For example, researchers in Thailand described extracting crystalline cellulose from cotton wastes and formulating into a film with PVC[32].

- carbon fibres from lignin – carbon fibres are expensive to manufacture, as they are derived from polyacrylonitrile. There is interest in manufacturing carbon fibres directly from wood lignin as an alternative to polyacrylonitrile, as it is much cheaper and from renewable sources. These carbon fibres are currently used in a range of industries, such as industrial (e.g. automotive), aerospace and sports goods[28], and there is also interest in using them to manufacture wind turbine blades[33].

Bioenergy

The examples cited above rely upon using the carbon-based macromolecules present in wastes, and either chemically or mechanically transforming them into a number of different specialised products. An alternative to this, is to release the chemical energy contained in the carbon-carbon bonds through either direct combustion as heat energy (e.g. biomass and solid recovered fuels), or by transforming some of the carbon-based compounds present in wastes into specific chemical fuels, that can then be used in precision applications (such as biogas from anaerobic digesters, bioethanol produced by microbial fermentation, or biodiesel produced from waste fats and oils).

Energy from waste materials is discussed in much greater detail in the companion report on Energy and Fuels.

Fertilizers

The nutrient content in some organic wastes has been processed into plant fertilizers for many decades. In addition, there are a number of commercially-emerging technologies that create refined products with similar characteristics to conventional inorganic fertilizers. Examples include:

- meat and bone meal – this is a product of the animal rendering industry, and can be manufactured into a phosphorus-rich product.

- struvite – this is magnesium ammonium phosphate and forms in anaerobic digesters and sewage treatment plants, especially if magnesium is supplied as an additive. There are a number of commercial recovery processes in operation (see for example[34]), creating a slow release fertilizer.

High volume, low value products

In general, these high volume, low value products include wood chips and bark residues (forestry by-products), as well as composts and anaerobic digestate. They are typically applied to land as a range of different product types, including *inter alia*:

- mulches – these are spread onto the surface of cultivated soils to help retain moisture and reduce weed growth;
- soil conditioners – these are either spread onto, or dug into, soil to add organic matter and thereby help improve soil structure and function;
- biofertilizers – these are applied to soils primarily to supply plant nutrients; and
- growing medium constituents – these are blended with a range of different materials for containerised plant growth.

The main organic waste-derived products are compost and digestate, which are discussed in greater detail below.

Compost and digestate

Compost and digestate are the two main outputs from the composting and anaerobic digestion processes, respectively. They both contain useful quantities of carbon and plant nutrients, but differ physically, chemically and biologically in important ways.

The composting process involves oxidative metabolism of a range of different organic wastes by a wide range of naturally-occurring bacteria and fungi. Relatively simple compounds, such as carbohydrates, fats and proteins are metabolised to provide energy and building blocks for microbial growth. Other macromolecules, primarily those present in woody materials, such as lignin, ligno-cellulose and cellulose, are metabolised through a series of oxidation, demethylation and condensation reactions to produce 'humus' (which is a mixture of humins, humic acids and fulvic acids). The precise biochemical mechanisms involved are relatively poorly understood (see for example[35]). Research has suggested that the humic acid content of a range of composts may be as high as 54% of the organic dry matter content, which indicates that it is a particularly good source of stable carbon[36]. The humus content in compost is recognised as providing a stable form of carbon that can increase soil organic matter and contribute towards carbon sequestration.

Digestate, on the other hand, is the result of anaerobic digestion (AD), which is carried out in the absence of oxygen. As such, it uses more readily degradable feedstocks, such as food wastes, manures and crops. The main economic impetus for the AD process is to maximise biogas generation and recovery for energy purposes, meaning that it is in an operator's interest to maximise degradation and conversion of carbon compounds into methane by methanogenic bacteria. AD operators do not generally accept lignin containing woody wastes, as they are not suitable feedstocks. Where they are present in incoming feedstocks, spectroscopic analysis suggests that they are not degraded during the digestion process[37].

Both compost and digestate also contain useful quantities of plant nutrients, which is discussed below.

Definitions

Composting
This is the process of controlled biological decomposition of biodegradable materials under managed conditions that are predominantly aerobic and that allow the development of thermophilic temperatures as a result of biologically produced heat

Compost
This is the solid particulate material that is the result of composting, that has been sanitized and stabilized and that confers beneficial effects when added to soil, used as a component of a growing medium, or is used in another way in conjunction with plants

Anaerobic digestion
This is the process of controlled decomposition of biodegradable materials under managed conditions where free oxygen is absent, at temperatures suitable for naturally occurring mesophilic or thermophilic anaerobic and facultative bacteria species, that convert the inputs to biogas and digestate

Digestate
This is material resulting from a digestion process and that has not undergone a post-digestion separation step to derive separated liquor and separated fibre

Nutrient content and availability

Compost and digestate differ in the total nutrient content and the availability for uptake by crops.

The total nutrient content is largely dependent upon the feedstocks from which they are derived: for example, food wastes, which contain higher levels of protein, are more likely to contain greater nutrients levels than woody wastes, which are intrinsically lower in nitrogen.

Similarly, the availability of nitrogen in compost also depends upon the feedstocks from which it is manufactured; they not only affect the extent to which the nitrogen is complexed with the humic acid fraction[36], but also the rate at which it is released (mineralised) for plant uptake. In general, nitrogen availability in composts for crop uptake is somewhere between 0-20% in the first year, and between 0-8% in subsequent years[38]. Although this slow-release of nitrogen may be insufficient to meet a crop's entire nitrogen demand, it means that it is unlikely to leach from the soil; instead it provides a 'nutrient bank' which can be mobilised by soil organisms over time.

By comparison, the nitrogen in digestate is much more labile (up to 80% of the total N content), meaning it performs more akin to conventional fertilizers, and can be better integrated into crop nutrient planning regimes. It also means that it has a greater potential to leach out of soils.

The availability of phosphorus from both compost and digestate is thought to be somewhere in the region of 50% in the first year[39], however, this is also dependent upon the feedstock. Like nitrogen, the release of phosphorus from compost is thought to be slow, and less prone to leaching[40].

Potassium (as potash; K_2O) is thought to be readily available in both compost and digestate, somewhere in the region of 80% availability in the first year of application.

Effect on soil

The beneficial effects of applying quality compost to soil have been widely documented and have important climate change and agricultural productivity implications.

Globally there has been a trend towards loss of soil organic matter, which reduces the soil's resilience and function, as well as releasing significant quantities of carbon dioxide into the atmosphere. It is the focus of the FAO's International Year of

Soils 2015, and is discussed further below.

Regularly applying quality compost to soils can result in the following physical, chemical and biological benefits[41]:

- increasing soil organic matter content – this principally stems from the 'stable' humus fraction in compost. This helps reduce organic matter loss and erosion effects and improves tillage;
- increasing cation exchange capacity – this helps bind nutrients and reduce inorganic fertilizer run-off losses;
- improving water retention – this helps buffer against droughts and is particularly important in parts of the world that are prone to desertification. It also helps reduce flooding during wet weather episodes, as the soil's capacity to retain water is improved;
- improving soil temperature regulation – this helps reduce the variability of temperature extremes, which is beneficial for soil organisms and crops;
- increasing biological activity – increases in both micro- and macro-fauna have been noted, due, in part, to improved soil physical structure, but also to increased carbon and nutrient availability for food and growth. This has add-on beneficial effects, as it helps improve nutrient cycling and availability to crops for uptake.
- suppression of plant pathogens – there is good evidence that some composts can help suppress the growth of some phytopathogens. Although the mechanisms by which this is achieved are complex, notable decreases in commercially significant pathogens, such as *Fusarium oxysporum* and *Pythium* spp. have been documented[42].
- increasing soil pH (liming effect) – composts can reduce the acidity of soils, which helps release micronutrients, making them available for plant uptake.

These beneficial effects have been highlighted recently by the FAO as part of its International Year of Soils[43], and have been summarised in a number of literature reviews[44–46], as well as UK-based trails[47].

Importantly, as the stable humus fraction in soils is estimated to have a turnover rate of between 20 to 1000 years, one estimate for the potential annual sequestration potential for compost alone across Europe (EU15) suggests that it is in the region of 11 million tonnes CO_2 per annum[48]. Despite there being a huge uncertainty surrounding this estimate, it illustrates the significant carbon sequestration potential of compost and its potential to mitigate greenhouse gas emissions. This is a complex area that could benefit from further research, which ISWA would be willing to undertake.

Compared to compost, the long-term effect on soil organic matter and structure through repeated applications of digestate to soil has been less well characterised. In general, due to the nature of the feedstocks digested, the organic matter content in digestate is more labile (and therefore less stable, in terms of its humus content). However, research has suggested that aerobically post-composting anaerobic digestate with woody wastes has been shown to increase humic acid content in the compost[36,49]. Notwithstanding, the carbon in digestate is likely to contribute towards increasing the soil's biological activity, and may also potentially aid *in situ* humus formation.

The relative benefits of compost and digestate relate to the requirements of farmers to meet immediate nutrient demands by crops set against longer term impacts on soil organic matter content and improved soil function. In general, digestate is better viewed as a biofertilizer, whilst compost has superior soil improving properties.

The importance of soils

About soils

Soils are the main receptor for compost and digestate derived from organic wastes and play an important role soils in providing humans with a medium to grow food as well as a number of important ecological services. Soils cover most of the top surface of our planet, and are fundamental for supporting almost all terrestrial life on earth. They are a complex mixture of inorganic substances (minerals), organic matter, gases, liquids, macro- and micro-organisms. Soils are formed over long periods of time through the interaction of underlying parent material with organic matter. It is a complex process influenced by climate, topography and organisms, including man.

Soils serve a number of important functions. In recognition of this, the Food and Agriculture Organization of the United Nations (FAO) has designated 2015 as the International Year of Soils, setting out the important role soils play[43]:

- 'healthy soils are the basis for healthy food production;
- soils are the foundation for vegetation which is cultivated or managed for feed, fibre, fuel and medicinal products;
- soils support our planet's biodiversity and they host a quarter of the total;
- soils help to combat and adapt to climate change by playing a key role in the carbon cycle;
- soils store and filter water, improving our resilience to floods and droughts;
- soil is a non-renewable resource; its preservation is essential for food security and our sustainable future'.

Soil organic matter

Soil organic matter (SOM) is derived from both plant and animal material that has been returned to the soil and decomposed. SOM can be roughly divided into two fractions: an active fraction (accounting for between 10-40 %), and; a stable fraction (40-60 %), which is called 'humus' and is formed by a process called 'humification'[50]. Humus is made up of a complex mixture of humic acids, fulvic acids and humins.

The importance of soil organic matter cannot be overstated. The FAO[50] has suggested that, in terms of agriculture, it:

- serves as a 'revolving nutrient fund', providing all the major plant nutrients, whilst the humus fraction (the stable organic fraction) adsorbs and holds nutrients in a plant available form; and
- improves soil structure, reduces erosion and helps maintain soil tilth.

SOM, and the stable fraction, in particular, serves as an important store of carbon. Globally, it is thought to account for about three times as much carbon as that contained in both the atmosphere and terrestrial plants (quoted in[51]). This is equivalent to somewhere around 1500 billion tonnes of carbon, although estimates vary depending upon estimation techniques employed[52]. Loss of SOM is acknowledged to be a major emitter of greenhouse gases, second only to fossil fuels[52].

The turn-over rate of SOM can vary considerably, from years, decades to millennia. Conventional wisdom suggests that complex aromatic molecules (such as humic substances and wood-derived combustion products such as biochar) are intrinsically more stable in soils than simpler aliphatic molecules. However, this may be more complex, depending upon the biotic and abiotic environment within the soil[51].

Changes to land use and land cover change (LULCC) is an important factor in affecting the dynamics of SOM formation and decomposition[53]. In particular, agriculture has been shown to reduce SOM, primarily due to ploughing and tillage practices. Scharlemann *et al.*[52] noted that by converting native vegetation to cropland, losses of between 25–50% soil organic carbon in the top one metre have been measured. As such, a number of management approaches have been adopted in an attempt to reduce SOM losses.

Notably, regular applications of organic fertilizers, such as manures and composts, have shown to increase SOM levels. Long term (160 year) field experiments at Rothamsted in England showed significant increases in SOM following annual applications of farmyard manures, especially in the early years (quoted in[54]). Similarly, repeated applications of compost was also shown to increase SOM (summarised in[44,45,47]). The potential for compost to maintain or increase SOM was also noted in a report published by the European Commission investigating the effects of soils on climate change[55].

Threats to soils

The FAO has indicated that '33 percent of soil is moderately to highly degraded due to erosion, nutrient depletion, acidification, salinization, compaction and chemical pollution'[6]. In addition to this, loss of soil availability through construction projects (so-called 'soil sealing', for example, through the building of roads and houses) is significant in areas of high economic growth as experienced in some OECD countries.

Soil organic matter losses are particularly acute in certain parts of the world, especially those that have been intensively farmed. Ploughing of soils over decades in temperate regions has resulted in a steady decline of soil organic matter levels[55]. In hotter climates, degradation of dry soils as a result of vegetation removal or livestock overgrazing is termed 'desertification', and has significant negative environmental impacts.

Within the OECD, both Poland and the Slovak Republic have indicated that 55% of their agricultural land is classified as having moderate to severe water erosion risk[19]. More recently, the UK's Committee on Climate Change noted that: 'Soil organic carbon levels are deteriorating nationally in arable soils … putting at risk some of England's most productive agricultural land'[56]. Collectively they all have important implications for the way in which soils are able to continue to support crop growth, adapt to climate change and carry out the myriad of functions necessary to support life on earth.

Compost and digestate quality

The benefits of applying compost and digestate to soils can only be realised if they do not concurrently introduce unwanted contaminants that might impair soil function, harm animals or plants. Contaminants in compost and digestate may be either physical, chemical or biological and have been reviewed in detail within Europe, as part of the European Commission's desire to establish end-of-waste criteria. This work was carried out by the Commission's Joint Research Centre (JRC), and involved a detailed investigation of potential contaminants in compost and digestate, as well as a review of extant standards and certification schemes[57].

In its third report, the JRC set out conditions for end-of-waste criteria for compost and digestate, as well as suggested quality criteria, which are summarised in Figure 3 and Table 3. End-of-waste criteria are particularly important in that they set boundaries where recovered wastes meet quality standards so similar to non-waste materials that waste management legislation need no longer apply. This is an important concept when considering secondary resources and the role they may play in substituting primary raw materials. This is discussed further in the report.

One of the fundamental principles of the draft European end-of-waste proposals is that organic wastes must be collected separately from other wastes (that is, mixed organic wastes are not permitted) and treated in a quality assured composting/anaerobic digestion process. The European Compost Network's Compost and Digestate Quality Assurance Scheme was referenced as an exemplar. This scheme has been in operation since 2010 and aims to provide a baseline across Europe in terms of compost and digestate quality so that it is produced consistently and homogeneously, setting criteria for:

- requirements to be met by a national quality assurance organisation for composting/digestion plants; and
- quality criteria for composts and digestate.

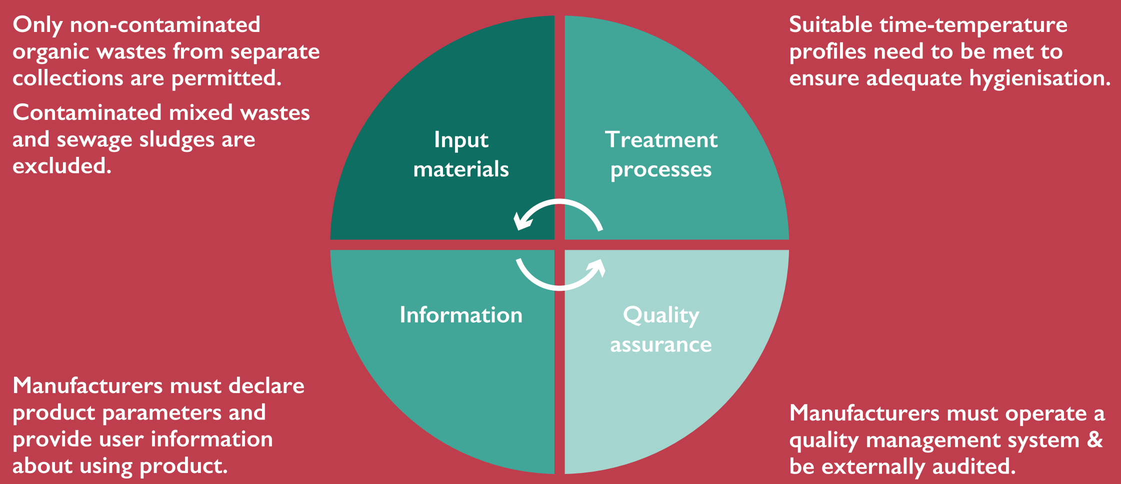
At the time of writing (Summer 2015), the ECN-QAS has awarded conformity labels to four national compost quality organisations.

Outside of Europe additional compost standards exist, for example those in Australia (AS4454) and New Zealand (NZS 4454:2005). Notably, the USA does not have a nation-wide compost or digestate standard, although the US Composting Council operates a Seal of Testing Assurance Program, which covers compost testing, labelling and information. The situation is similar in Canada, where some provinces have adopted the Canadian Council of Ministers of the Environment Guidelines for Compost Quality, although the Standards Council of Canada and their agency, the Bureau de normalisation du Québec, were publicly consulting on a draft standard during Summer 2015.

End-of-waste (EoW) criteria set important milestones as far as processing waste materials into marketable products are concerned. First and foremost they set criteria where waste legislation ceases to take effect, which means that waste-derived materials, if manufactured to defined quality standards, need no longer be subjected to restrictive waste controls. They may instead be marketed as products, in line with other similar non-waste materials. EoW criteria also provide a framework to promote standardisation and product quality.

This is an important concept within the circular economy concept, where remanufacture and recycling of wastes into products need to be of at least equal quality to those manufactured from primary materials.

Fig. 3 | Proposed European end-of-waste principles



Tab. 3 | Proposed European end-of-waste quality criteria for compost and digestate

PARAMETER	REGION
Organic matter content	Compost and digestate must contain a minimum amount of organic matter (15% on a dry matter mass basis).
Stability	Compost and digestate must be processed so that they have decomposed sufficiently. Two stability criteria are proposed for compost and three for digestate.
Pathogens	Compost and digestate must be free from Salmonella species. Levels of E. coli (if present) must be low.
Weed seeds & plant propagules	Compost and digestate must contain less than two viable weed seeds per litre.
Macroscopic impurities	Maximum limits for glass, metal and plastic contaminants have been set.
Heavy metals and persistent organic compounds	Maximum limit levels are proposed for a range of heavy metals (Cd, Cr, Cu, Hg, Ni, Pb and Zn) and 16 polycyclic aromatic hydrocarbons organic pollutants.

Compost and digestate market sectors

Across OECD countries, it is estimated that 66 million tonnes of municipal waste was composted in 2013[12], which would result in approximately 22 million tonnes per annum of compost / digestate.[e] By comparison, across the EU 27, an estimated 11.3 million tonnes of food and green waste compost was produced annually (based on data for 2008 and 2010).[57]

Data for compost/digestate use across OECD countries are not available; however, the JRC notes that within the EU, agriculture accounts for the largest market sector, followed by hobby gardening, horticulture and landscaping.[57] This is shown in Figure 4.

Although agriculture is the largest market sector within the EU, this does not always hold true in other OECD countries. For example, in the state of Victoria, Australia, the urban amenity market (including landscaping, retail nursery and special projects) accounted for 73%, followed by intensive agriculture at 9%, rehabilitation at 6% and enviro-remediation at 4% by volume of compost markets in 2013-14.[58]

Although agriculture is the dominant market sector within the EU, the potential maximum supply of all manufactured compost / digestate is well below the theoretical land bank needed to accommodate these products. The JRC estimated that current compost production in the EU required 1.5% of the total arable land across the EU27, rising to 3.2% of all arable land should a theoretical maximum of 40 million tonnes per annum be produced[57]. Potential demand therefore far exceeds potential supply.

Similarly, within OECD countries, there is an estimated 1.2 billion hectares of agricultural land, with 58% being arable and permanent cropland, and 42% under permanent pastureland[19], meaning that the potential land bank far exceeds potential compost / digestate supply.

Sales of both compost and digestate are dependent upon a number of factors, including:

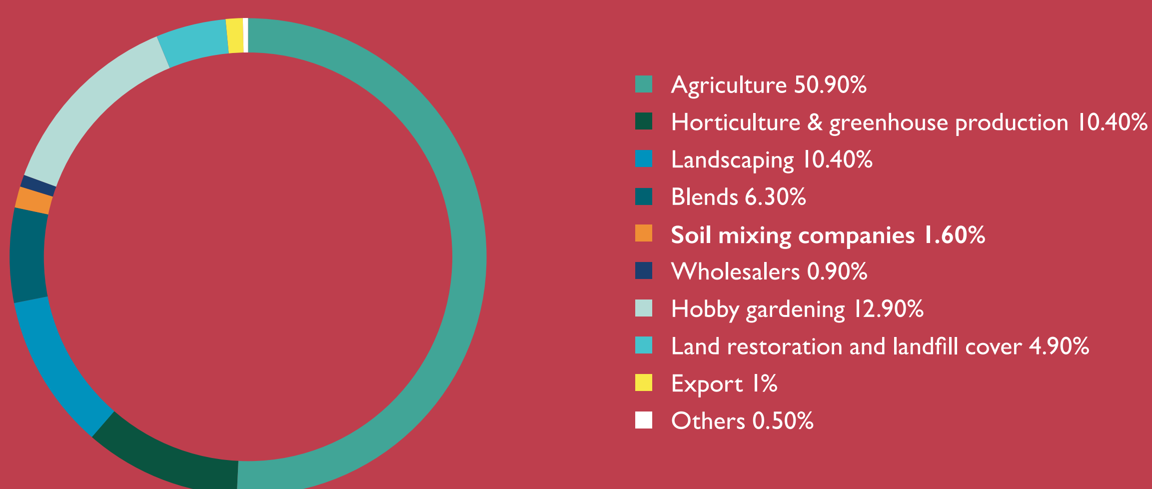
- the relative price of inorganic fertilizers;
- the season, as they may only be spread when soil conditions are suitable and in accordance with crop nutrient demand;[f]
- the quality of the product, marketing and sales techniques employed (e.g. bulk supply vs. blended and bagged products, market sectors targeted);
- transport distances from the place of manufacture to the place of end use, as it is generally uneconomic to transport compost or digestate further than 100 km; and
- spreading costs.

Blended and bagged compost sold to hobby gardeners as part of a growing medium can attract premium prices, and may sell for up to USD 300/tonne. However, this represents only a very small fraction of the total and is not typical of the majority of compost sales. Bulk sales of screened compost to landscapers, horticulture and gardeners may sell anywhere in the region of USD 5 - 15/tonne, although, again this can vary considerably.

As far as agricultural applications are concerned, these do not command premium prices, with the majority sold for somewhere between USD 1- 5/tonne. Some compost manufacturers may offer a spreading service to farmers, in which case prices can be as low as USD 1-2/tonne. In some instances, compost and digestate may be given away free of charge, with the facilities' income being derived from gate fee charges and sale of renewable energy. This generally occurs where compost plant managers do not understand the needs of the various potential markets they can serve.

[e] This assumes that 33% of the incoming feedstocks will be converted into product.
[f] This is also the case for inorganic fertilizers.

Fig. 4 | Compost use in major EU compost producing countries



% of weighted mean; quoted in[57]

Market potential

The bioeconomy

The products described in the previous section all form part of the 'bioeconomy'. Whilst some products are currently established and market sizes can be estimated relatively easily, others are at pilot stages or are only manufactured on a small scale, meaning that market analysis is much harder. In addition, there remain fundamental challenges when attempting to value products that may not be traded directly, but are used to maintain and enhance natural capital. This is particularly significant for compost (and to a lesser extent digestate), where stable organic carbon can reduce soil erosion and improve soil organic matter; the overall benefits to society in terms of carbon sequestration and improved soil structure and function are far harder to monetise, but are significant nonetheless.

The European Commission estimates that the European bioeconomy sectors are worth in the region of EURO 2 trillion (USD 2.2 trillion) a year (turnover), accounting for more than 22 million jobs and approximately 9% of the workforce[59], although this includes materials other than wastes.

In a 2009 report, the OECD noted that 'The bioeconomy will be global … especially in agricultural and industrial applications. Approximately 75 percent of the future economic contribution of biotechnology and large environmental benefits are likely to come from these two areas'[60].

High and medium value products

Estimating potential market sizes is complex, with different valuation techniques being used to arrive at different figures. Consequently, care therefore needs to be taken to prevent un-meaningful conclusions being drawn. This section illustrates some estimates which are useful for benchmarking purposes.

The World Economic Forum[61] estimated global potential revenues from the biomass value chain could be in the region of USD 295 billion by 2020, whilst overall demand for bio-based chemicals is thought to be increasing, with bio-based plastics offering the greatest potential (Table 4).

In addition, Frost & Sullivan[28] estimated that the market potential for lignin-derived chemicals (benzene, toluene, xylene [BTX], phenol, vanillin & carbon fibre) to be over USD 130 billion, and is projected to reach USD 208 billion by 2020.

Despite this significant potential, one of the overriding factors affecting market potential for this sector is the relative cost of manufacture from fossil fuels and the subsidies they receive. For example, one estimate suggests that the feedstock cost of producing 'average bulk chemicals' from fossil feedstocks is in the region of USD 33 / GJ energy, whilst its equivalent from biomass costs USD 83 / GJ end product (quoted in[62]).

High volume, low value products

Nutrient content in compost and digestate

The nutrient content in compost and digestate can be calculated relatively easily and compared against their inorganic counterparts. The UK's Waste and Resources Action Programme (WRAP) has developed a web-based 'nutrient calculator' to enable quick calculations to be made[63]. This is reproduced below for compost and digestate (based on fresh weights) and shows that fertilizer equivalent values during the first year of application are somewhere in the region of USD 4-7 for fresh compost and digestate (Table 5).

It is worth noting that these calculations are not only dependent on the price of inorganic fertilizers, but also on the assumption about availability of nutrients for plant uptake. The WRAP nutrient calculator assumes that the nitrogen availability in the first year for green waste-derived compost is zero, however, Prasad has noted that it would lie somewhere between 0-20% in the first year[38].

The Italian Composting and Biogas Association (CIC) has developed a similar tool, which assumes that 30% of total N would be available (M. Centemero, *Personal Communication*). Using different

Tab. 4 | Estimated relative increase in production of bio-based chemicals between 2010 and 2020

PRODUCT CATEGORY	MARKET IN 2010 (THOUSAND TONNES)	ESTIMATED MARKET IN 2020 (THOUSAND TONNES)
Bio-based plastics	260	2,810
Biodegradable and bio-based plastics	35	333
Bio-lubricants	137	420
Bio-composites	372	920
Bio-based platform and fine chemicals	1,100	1,340

Source: [62]

Tab. 5 | Fertilizer value of fresh compost and digestate

	NITROGEN (N)	PHOSPHATE (P_2O_5)	POTASH (K_2O)	TOTAL GBP/ TONNE	TOTAL EURO/ TONNE	TOTAL USD/ TONNE
Market price of fertilizers (GBP/kg)	0.74	0.59	0.44			
GREEN WASTE DERIVED COMPOST						
Readily available nutrient content (kg/tonne compost)	0.00	1.50	4.40			
Financial value of readily available nutrient content (per tonne compost)	0.00	0.88	1.95	2.83	4.00	4.36
GREEN/FOOD WASTE DERIVED COMPOST						
Readily available nutrient content (kg/tonne compost)	0.55	1.90	6.40			
Financial value of readily available nutrient content (per tonne compost)	0.40	1.12	2.84	4.36	6.15	6.71
GREEN/FOOD WASTE DERIVED DIGESTATE						
Readily available nutrient content (kg/tonne digestate)	4.00	0.25	1.60			
Financial value of readily available nutrients (per tonne digestate)	2.94	0.15	0.71	3.80	5.36	5.85

Source: WRAP http://www.wrap.org.uk/content/compost-calculator [accessed 9 July 2015] with fertilizer prices based on current market prices provided by FARM BRIEF. Exchange rates as of 8 July 2015.

fertilizer prices, CIC calculates that each tonne of green and food waste-derived compost has a value of USD 31.50.

The fertilizer benefits of applying compost and digestate to soils is not only realised in the first year following application, but also in subsequent years, because they act as a slow-release nutrient bank. For example, calculations by Defra in England, indicate that potential fertilizer savings of USD 237/hectare of arable land sown with winter barley can be realised by spreading 30 tonnes per hectare of green waste-derived compost. This benefit is transferred into future years, where the actual savings on inorganic fertilizer costs[g] in subsequent years due to compost application is USD 153/hectare[64].

Across the OECD, taking into account actual compost/digestate production, somewhere in the region of USD 121 million in nutrient value is currently being realised annually; this could increase to USD 227 million per annum (Table 6). Notably, this is higher than the actual values being realised, which implies that both compost and digestate is being undersold. This may be because the waste management industry lacks the necessary marketing expertise, or that farmers are unwilling to recognise the true value of compost and digestate; although it probably also accounts for storage, transport and spreading costs, which would be additional to the ex-works prices suggested.

Valuing natural capital enhancement

Whilst the nutrient content in compost and digestate can be calculated relative to the price of inorganic fertilizers, the carbon content is far harder to quantify in monetary terms. The value of the long-term, stable carbon in soils cannot be underestimated, delivering wide ranging benefits, such as carbon sequestration and improving drought tolerance (as noted previously).

An estimate of the quantity of humic substances in compost and digestate produced in OECD countries is shown below (Table 7).

This suggests that at present somewhere in the order of five million tonnes of stable carbon (and ten million tonnes of carbon in total) is applied to OECD soils every year, which could rise to six million tonnes and 12 million tonnes, respectively, if all of the potential municipal organic waste was composted/digested. This would be far greater if commercial and industrial organic wastes are taken into account.

Improved soil structure and function following long term compost application has been well documented, however, there are underlying difficulties in calculating this benefit to farmers (e.g. through reduced/improved tillage, reduced irrigation etc.). At present, this carbon isn't valued in monetary terms, nor is its potential accurately taken into account in life cycle assessment calculations; as such, it is an important area that requires further research.

[G] Assumed to be: Nitrogen USD 0.93 / kg, phosphate at USD 0.93 / kg and potash at USD 0.93 / kg.

Tab. 6 Estimates for actual and potential nutrient values in compost / digestate compared with realised value

	ORGANIC WASTE COMPOSTED (MILLION TONNES PER ANNUM)	COMPOST / DIGESTATE PRODUCTION* (MILLION TONNES PER ANNUM)	FERTILIZER EQUIVALENT USD MILLIONS**	SALES ASSUMING COMPOST / DIGESTATE SOLD AT USD 3 / TONNE*** USD MILLIONS
OECD Actual	66	22	121	66
OECD Potential****	124	41	227	124

* Assuming 33% product manufactured from incoming feedstocks, taking into account process losses
** Assuming fertilizer value in compost/digestate of $5.50 per tonne (mean of USD 4-7/tonne)
*** Assuming compost/digestate is sold at between USD 1-5/tonne, mean is USD 3
**** Assumes that 70% of the organic fraction of municipal waste can be collected separately for composting and AD.

Tab. 7 | Estimate of humic substances in compost/digestate

	TOTAL ORGANIC C IN COMPOST* (DRY MATER BASIS)	TOTAL % HUMIC ACIDS IN COMPOST (DRY MATTER BASIS)	COMPOST / DIGESTATE PRODUCTION (MILLION TONNES PER ANNUM, FRESH MASS)	COMPOST / DIGESTATE PRODUCTION (MILLION TONNES PER ANNUM, DRY MATTER)**	ESTIMATE OF TOTAL ORGANIC C IN COMPOST / DIGESTATE (MILLION TONNES PER ANNUM, DRY MATTER)	ESTIMATE OF HUMIC SUBSTANCES IN COMPOST / DIGESTATE (MILLION TONNES PER ANNUM, DRY MATTER)
OECD Actual	50%	25%	33	20	10	5
OECD Potential******	50%	25%	41	25	12	6

* See, for example[36]
** Assuming the dry matter content is 60%

Current role of the waste management sector

Core competencies

Within OECD countries, the formal waste management sector has established efficient and effective waste collection and transportation infrastructures, moving wastes from the point at which they arise to the point of treatment or disposal. It also has capabilities in the treatment of wastes, to manufacture products such as compost or digestate, or fuels such as biogas and solid recovered fuels.

Organic waste collection methods

There are a variety of ways in which solid wastes can be collected, including: house-to-house collections, community bins, kerbside pick-up, self-delivered, and contracted or delegated services[16]. The chosen option(s) are necessarily dependent upon a variety of factors such as: road infrastructure; business or housing types (such as single or multi-occupancy dwellings); rural, urban or city locations; legal structures and charging mechanisms; municipality (local authority) and private sector involvement.

In general, there are two approaches towards collecting organic wastes, especially those from the municipal solid waste (MSW) fraction:

- separate collections – where organic wastes are stored separately from other wastes at the point at which they arise, and are then collected and sent for recycling as an organics-only fraction; and
- mixed waste collections – where wastes of different types (e.g. paper/card, metals, plastics and organics) are not separated at source, but are collected all together and the different fractions subsequently separated at facilities often referred to as mechanical biological treatment (MBT) plants, or dirty Materials Recovery Facilities (dirty MRFs).

The choice of whether or not to collect organic wastes separately has important implications in terms of integration with residual waste collection services and, most importantly, the quality of wastes. Data collected on behalf of the JRC during the development of European end-of-waste proposals for compost and digestate, indicated that only separately collected organic wastes could be used as feedstocks to manufacture quality products.[57] The contamination levels in mixed waste-derived composts and digestate was deemed to be too high for unrestricted use as a product.

Organic wastes cover a wide range of materials, with highly variable density and moisture contents. (For example, woody green wastes are low in moisture and, due to their branchy nature, are not very dense; on the other hand, food wastes have high moisture contents, are highly putrescible, and have high densities.) Both the density and moisture content of the waste are the primary variables that dictate the frequency and type of collection method employed. Considerations regarding hygiene, biosecurity and human health also need to be taken into account.

Organic waste collection methods

Garden / green waste collections
Botanical garden waste (so-called green wastes) may arise at a number of different places, including, gardens (backyards), parks, schools, hotels, country clubs and landscaped verges. Quantities and composition are primarily dictated by the season, climate and horticultural practices, meaning that they can vary significantly both temporally and spatially.

Some green wastes may be treated in situ, by either home (backyard), onsite or community composting schemes, by chipping and using the wood chips directly as surface mulches, or by burning. However, a significant proportion is collected separately for *ex situ* treatment, primarily at composting facilities, or for biomass production.

Successful collection schemes have been established widely across OECD countries involving a range of kerbside collections, community bins, self-delivery and contracted services. A wide range of collection receptacles may also be used and include 240 and 1,100 litre wheeled bins, paper sacks, reusable polypropylene bags, skips and road containers. Collection frequencies can also vary from daily (for self-delivered wastes), to weekly, fortnightly or monthly collection, especially those from domestic dwellings.

Food waste collections
Food wastes may arise at a wide range of places, including food manufacturing and preparation premises, catering establishments (such as cafes, restaurants and hotels), schools, hospitals, supermarkets and households. The massive quantities of food waste generated by consumers has been the focus of much recent publicity, including the FAO[65]. National and local campaigns (such as the UK's Love Food Hate Waste) have focussed on reducing the quantities of avoidable food waste generated, whilst campaigns such as Fair Share in the UK and Annakshetra[66] in India redistribute unwanted edible food to those who need it.

For food wastes that cannot be prevented or re-distributed, separate collection schemes have been widely established, especially in Europe, including high-density cities, such as Milan in Italy and Seattle in the USA. These generally involve house-to-house or kerbside collections from domestic or small business properties, or contracted collections from larger business premises.

The wet and putrescible nature of food waste means that specialised bins and receptacles are needed to contain the waste at-source prior to collection, whilst dedicated vehicles are need to transport the material to treatment facilities. In particular, some food wastes from commercial and industrial sources may be liquids or slurries, such as those from food manufacturing premises, hence they require dedicated tankers for storage and transportation.

Small scale desk-top kitchen caddies are often distributed to householders by municipalities, to use in conjunction with larger lidded bins, which are set out for collection. Many municipalities either promote or distribute caddy liners, to help reduce potential nuisance and to make collection more efficient. These are usually made out of paper or compostable polymers such as starch or PLA. The ISWA issue paper[67] contains further information about food waste, its collection and treatment, whilst WRAP guidance explains some of the factors relevant to food waste collection in the UK[68].

Most food waste schemes collect from premises at least once a week, if not more frequently. This has the benefit of reducing odours and potential nuisance factors, as well as reducing the frequency of residual waste. Central to the success of these schemes is design (frequency and the type of collection receptacles), as well as communication.

Other wastes
There are a range of organic wastes, other than garden and food wastes, that are suitable carbon and nutrient sources. These include, for example, crop residues, wastes from processing / manufacturing industries, such as spent hops from the brewing process and waste vegetables from horticultural operations. Some of these may be collected and transported in tankers or dedicated vessels, which may or may not involve third party hauliers or the formal waste sector.

Organic waste treatment methods

At present, the main methods for processing and treating organic wastes centre around two main activities:

- physical processing – such as size reduction through maceration, shredding or pulping, contaminant removal and compaction, or heat treatment; and

- biological treatment – by either aerobic processes (primarily through composting, although thermophilic aerobic digestion processes can be employed for slurries and liquid wastes), and/or anaerobic digestion.

Physical processes are used extensively, for example, in the manufacture of particle boards from wood wastes. Most biological treatment processes also involve an element of physical processing, especially for municipal wastes and packaged end-of-life food wastes. Mechanical biological treatment methods seek to extract value from mixed waste streams. These employ a range of physical sorting and separation techniques to extract dry recyclables and the organic fraction, although the contamination issues discussed previously impair quality and restrict final end use of the organic material.

The removal of contaminants remains a critical issue for most treatment operations. Whilst shredding, screening and de-packaging equipment have developed considerably over the past decade, issues relating to grit (in slurries) and plastic bag removal remain problematic. For organic wastes to be considered potentially useful substrates for conversion into higher value products, consistent communication to prevent contamination in the first place by waste producers, coupled with more sophisticated and effective pre-treatment methods need to be more widely adopted.

At present, there appear to be few large scale pre-treatment facilities refining and upgrading organic wastes for use as substrates for conversion into higher value products. This probably illustrates the disconnect between demand for conventionally sourced chemicals and the potential for the waste sector to 'biorefine' feedstocks in sufficient quantities and to (as yet undefined) quality specifications in order to partially meet this potential demand.

Challenges for the waste sector

Macro-economic challenges

The waste sector faces a number of significant challenges if it is to move its core competence from one involving the collection and transportation of low value wastes, into one that is capable of selectively collecting a range of different wastes and treating them to a sufficiently high specification so that they can be used as substrates to manufacture a range of high value products. In doing so, the waste sector also faces significant macro-economic constraints that currently favour the manufacture of products from primary, rather than secondary raw materials.

Relative cost of fossil fuels

In the majority of cases, bio-based products need to compete with products derived from primary materials, which are usually petroleum based, or are dependent upon fossil fuel-reliant processes. This means that they are directly affected by the relative price of crude oil, which has dropped significantly during 2015, from over USD 100/barrel in mid-2014 to below USD 50/barrel by mid-2015. The collection, conditioning and processing costs of using organic wastes as precursors for high-value products means that it is difficult for the waste sector to compete economically with traditional non-waste substrates which have established supply routes and benefit from economies of scale. The example quoted by Nita *et al.* highlights the magnitude of the challenge: where the feedstock cost of producing 'average bulk chemicals' from biomass is over two-and-a-half times more expensive than those derived from fossil feedstocks[62].

An additional impediment relates to fossil fuel-based energy subsidies[69] which further distort the cost competiveness of secondary materials-based products. Bio-based products, and especially those derived from organic wastes, need to be able to compete on a level playing field with traditionally sourced precursors. Without subsidies or other fiscal incentives to redress this imbalance, it appears that these products will remain niche.

Legislative framework

Across all OECD countries, wastes are defined and regulated to ensure they do not harm human health or the environment. These principles serve society well for their intended purpose, but act as a barrier when considering waste as a resource and how its components can be integrated into a materials-based economy.

The stringent controls placed on the owners, transporters and processors of organic wastes are, in general, not applied to non-waste primary materials. These controls carry an administrative cost that further weighs against their conversion into higher value products.

In particular, the restrictions placed on the movement and use of wastes specifically impedes their integration into established non-waste processes. This uncertainty of using waste-derived precursors needs to be addressed. New quality specifications and end-of-waste criteria need to be developed throughout the value chain, so that converters and manufacturers of high value products are confident about their effectiveness and consistency.

Infrastructure

In addition to fiscal and legislative barriers, a lack of extant processing infrastructure presents an operational barrier. New capital equipment and infrastructure need to dovetail with collection, processing and manufacturing capabilities, creating integrated facilities. Significant benefits could be achieved by developing integrated sites involving pre-processing and refining of wastes for high level applications, as well as anaerobic digestion and composting, enabling cost effective cascading of resources. This was highlighted in a report by Dalberg[70], which suggested that co-locating biorefineries with existing facilities could realise new capital savings of between 20-80% depending upon the level of synergy realised.

Service challenges

The waste management sector also faces challenges in the way it designs and operates its services. These are summarised in Figure 5 and are discussed below.

Improving waste capture rates

As noted previously in this report, an estimated 56 million tonnes of organic wastes a year from the municipal waste stream alone is not collected separately for biological treatment, whilst the potential from the commercial, industrial and agricultural sectors is largely unknown, but significant.

In order to maximise these untapped resources, separate collection schemes will need to be both extended and improved across OECD countries. This will, in many cases, involve co-ordination of activities between private and public sectors, civil society and private individuals. Ultimately, the number and effectiveness of collection schemes will need to be increased.

Although these will inevitably incur upfront capital costs, their cost effectiveness has been demonstrated when the impact on dry recyclables and residual waste is taken into account. Sharing information, good practice and data between municipalities, non-municipal waste producers, and the waste sector will be pivotal to help achieve this.

Delivering clean, homogeneous organic wastes

Delivering organic wastes of sufficiently high quality and consistency so that they may be converted into high value products relies upon well managed separate collection schemes. The effectiveness of these not only depends upon design, but also on the level of communication between the processor, collector and producer of the waste itself. Consistent, effective communication in needed to educate and motivate waste producers about quality, whilst collectors and processors (in particular where third-parties are involved) need to be knowledgeable about acceptance/re-

Fig. 5 | Service challenges for the waste sector

jection criteria. Effective and up-to-date communication along the value chain is essential.

Coupled with this, is the need to improve waste pre-treatment techniques, not only to reduce contamination but also to convert and extract certain waste components as product precursors. Further research and development is needed to improve the effectiveness of pre-treatment techniques, and to adopt those currently employed in comparable industry sectors.

Managing variable, heterogeneous wastes remains a significant challenge for the sector.

Improving waste statistics

Despite improvements in municipal waste data, there remain considerable uncertainties in waste statistics for commercial, industrial and agricultural wastes; this is due, in part, to classification as well as the practical difficulties of quantifying arisings, especially where they treated or disposed of *in situ*. This means that it can be challenging to accurately predict growth in waste arisings and changes in its composition. Improved data classification and collection would promote better resource planning and management. Initiatives, such as the EU-funded FUSIONS project, aims to contribute towards harmonised food waste monitoring across the EU[71].

Increasing the sector's core competencies

The waste sector employs a large number of individuals with specific knowledge and skills, whose competencies centre on collecting, transporting and treating wastes. If it is to embrace the circular economy and become a provider of a range of carbon and nutrient-based products, then it cannot act in isolation. To realise this potential, the waste sector will need to integrate its services with those in parallel industries, such as oil and gas, chemicals and agriculture. To achieve this, competency standards and qualifications will need to be extended, so that they reflect the increasing technical requirements of a range of managerial and operative occupations.

Similarly, improved marketing and communication skills will be needed, so that the sector can better promote the range of services and products it offers.All of these need to be underpinned by high quality training.

Conclusions

Organic wastes contain significant quantities of both carbon and plant nutrients. These valuable resources can be either recycled into bio-fertilizers and soil improvers using traditional composting and anaerobic digestion techniques, or transformed into new bio-based materials using sophisticated biorefinery processes. A conducive macro-economic environment, coupled with effective capture and treatment of organic wastes, is key to unlock the potential these resources contain within them.

The markets for high and medium value bio-based products are potentially massive, with estimates in the billions of US dollars annually. However, in most cases, their competitiveness will be linked to the relative cost of manufacture from petroleum-based precursors, against which they will need to compete.

Currently, the cost of crude oil dictates the relative price of non-waste substrates; given the current low price of oil (< USD 50/barrel), this is significant. In addition to this, subsidies for fossil fuels, established supply networks and economies of scale for primary resources all weigh against the development of new infrastructure and processing capacity to exploit secondary waste-derived resources. Policy and fiscal incentives to stimulate demand and overcome investment and technical barriers to supply could usefully be developed.

Similarly, extant waste legislation also serves to act as a barrier to integrating waste-derived resources into a materials-based economy, both logistically and economically. This uncertainty needs to be addressed through an enabling legislative framework coupled with the development of new quality specifications and end-of-waste criteria throughout the biomass value chain. Manufacturers and consumers of waste-derived products need to be confident about their safety, effectiveness and consistency.

The waste management industry also has an important role to play in helping make this a reality, acting as a provider of waste-derived substrates for conversion into potentially high value products. For this to work, however, the waste sector's core competence as a collector, transporter and converter of wastes will need to be broadened.

The manufacture of speciality bio-based chemicals and materials necessarily relies upon technically demanding transformational processes, which, in turn, require chemically defined substrates. At present, agricultural by- and co-products are often used, as these are more homogeneous and of known composition when compared to wastes (especially those of municipal origin). Wastes, by their very nature, are heterogeneous, relatively ill-defined and can carry varying levels of contamination, which presents significant challenges for the sector. Research and development to improve organic waste pre-treatment and conditioning needs to be carried out in order to deliver feedstocks of equal quality to those that are sourced conventionally (i.e. agricultural by- and co-products).

Within OECD countries, the waste management industry has a strong network collecting and recycling/disposing of municipal organic wastes. However, despite this, only 53% of the total realistic potential from the municipal stream alone is composted or anaerobically digested; this leaves an estimated 58 million tonnes of untapped resources from municipal wastes that could be recycled to recover the carbon and nutrients to create a range of products and improve soils.

Links with commercial and industrial wastes appear to be less well developed. Compared with the municipal sector, data are less well defined, hence it can be challenging to understand supply dynamics (e.g. sources and quantities) and predict growth rates and changes in composition. Improved data categorisation, collection and analysis for commercial and industrial wastes is desperately needed, so as to better assess the potential to source these comparatively homogenous organic wastes.

The waste management industry is competent in collecting and managing well-established recycling processes, such as composting and anaerobic digestion, however, if it is to grow and diversify its operations, it cannot work in isolation. It will need to build partnerships with other complementary sectors and expand its core competencies, by diversifying its competency standards and qualifications, and extend training across all occupational levels.

In order to fully embrace the potential opportunities available through manufacturing higher value products, synergies could be realised by co-locating waste processing plants alongside more sophisticated biorefinery operations. A lack of extant processing infrastructure currently presents an operational barrier. New capital equipment and infrastructure will need to dovetail with collection, processing and manufacturing capabilities, creating integrated facilities where economies of scale and synergies can be realised. This has the potential to realise significant capital and operational cost savings, which would allow for more cost effective cascading of resources. It would also require the sector to develop and improve its communications and marketing skills.

The markets for high volume, low value compost and digestate products are currently established, although they are by no means saturated. The nutrient value of compost and digestate can be calculated relative to its equivalent for inorganic fertilizer, which is pegged against the price of energy. Using a UK web-based nutrient calculator, on average, each tonne of compost/digestate will have a nutrient value of USD 5.50 (fresh product). This represents only crop available nutrients and not those that remain in the soil and are gradually released in subsequent years.

Applying compost to soil over a number of years has been shown to increase organic matter levels, thereby improving soil properties and function, as well as contributing towards long term carbon storage. The impact of repeated applications of digestate is less well understood, and could benefit from further research. By creating combined products, where anaerobic digestate is post-composted with green wastes, there is some evidence that humic acid content is increased, which would contribute towards stable carbon formation. This practice is widely adopted in Italy, but is uncommon in most other OECD countries. Again, synergies can be realised by combining aerobic and anaerobic biological treatment processes.

Although the nutrient value of compost and digestate can be calculated with relative ease, the benefit of organic carbon and its effect on soil organic matter is currently not valued in monetary terms. Soil organic matter represents a finite and vulnerable resource, acting as a substantial carbon sink globally. As most cultivated arable soils are showing signs of organic matter loss, this not only has the potential to reduce productivity, but also has important climate change implications.

The monetary value to farmers of improving soil structure and function through long term compost and digestate application needs to be assessed, encompassing, for example, savings through reduced/improved tillage, reduced irrigation, improved fertilizer utilization and reduced soil erosion. Although it is inherently complex, it is an important area that requires further research so that the true value of these products can be used for marketing and policy appraisal purposes (e.g. life cycle assessment calculations). Integration of these benefits into national and regional agricultural policies would create a powerful driver.

In conclusion, the carbon and nutrient value in organic waste is currently being realised, at least in part. Significant potential exists to maximise collection and recovery of organic wastes across OECD countries, and to use these to manufacture high-value bio-based products, as well as to recycle nutrients and improve soils through the application of quality compost and digestate. Current macro-economic policies, a lack of processing infrastructure and operational standards effectively impede development of this sector. The waste management sector also has a pivotal role to play, but will necessarily need to diverse its operations, core competencies and business models. Co-locating treatment and manufacturing processes at single sites, overcoming technical barriers, and valuing the benefits of improving natural capital all need to be addressed.

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